CRYSTAL SETS TO SIDEBAND

A guide to building your own amateur radio station

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Chapter 1

THE FASCINATION OF RADIO

Radio produces action at immense distances with no physical connection that can be perceived by our senses. A modern way to demystify radio is to say that radio is simply a kind of light that our eyes cannot see. To those of us addicted to shortwave radio, it's an adventurous realm that can be explored. When we listen to our radio receivers it is comparable to using the Hubble telescope to explore the heavens. Shortwave is fascinating because you can't predict what you are going to hear. You might hear a radio broadcast from an exotic foreign capitol. You might pick up an SOS from a ship sinking in a storm or maybe weather reports from a radio amateur on Pitcairn Island. The next evening the same frequency band might be completely

empty except for two hams on the other side of your own town discussing the Super Bowl. Or you might receive coded messages intended for some undercover spy lurking in our country.

I'm not kidding. I routinely hear such coded messages consisting of groups of letters on the 10.1 and 28.1 MHz ham bands. The codes are usually sent in Morse code, but sometimes you will hear a voice reciting the letter groups. Sometimes the woman announcer finishes by saying, "Thank you for decoding this message!" Since hams are forbidden to use codes or modulation modes that are not easily decoded, these communications are at least illegal.

Yes, it's true that shortwave isn't as vital to world activities as it once was, but if there's any romance in your soul, shortwave is still entrancing and always will be. This book is about using amateur radio to recapture the adventure of early day radio and bring it into the present. It is also about learning electronics and radio technology. If you can get through this book, shortwave radio will still be fascinating, but no longer mysterious.

Admiral Byrd at the South Pole

I first became intrigued by shortwave when I read Admiral Byrd's book on his last expedition to the Antarctic. Admiral Richard Byrd was in the business of launching expeditions to explore the Earth's poles. These expeditions had no inherent commercial value except for book sales and sponsoring grants from companies hoping to gain visibility for their products. In order for Byrd to get those grants, the public had to be sufficiently interested in the expeditions to generate advertising value. With each polar expedition, finding new expedition goals that would be exciting to the public became increasingly difficult. Studying rocks, glaciers and penguins was scientifically important, but not particularly interesting to the public. By the 1940's all the neat stuff, like walking to the North and South Poles had been done decades before.

On his last expedition to Antarctica, Byrd established a base on the Antarctic coast like all previous large expeditions. However, he succeeded in maintaining public interest by setting up a tiny second outpost on the polar icecap hundreds of miles south of the coast. Then he attempted to spend the Antarctic winter alone in his little under-snow cabin totally isolated from the world in the cold and dark. His one connection with his base camp at "Little America" and the outside world was Morse code radio contact. Other than producing some interesting weather reports, the outpost had little real value. However, it did attract attention. Who could help but be captivated by the ordeal of a man totally isolated, hundreds of miles from the nearest humans? It was like being marooned on the moon, utterly alone.

Byrd's messages were relayed from his big base back out to the rest of the world. As a boy I was fascinated by Byrd's lonely vigil. I imagined what it would be like to be shut off from the world for months on end. I pictured Byrd bundled up in a fur parka huddled over his little table sending and receiving Morse code. His connection with the world was reduced to musical notes barely audible above the soft purring static of the polar night. The Morse tones came into his headphones and he wrote down their meaning, one letter at a time. The decoded messages appeared on his pad, one word at time. He fumbled with his pencil. "Was that a 'C' or a 'K?'" he asked himself. He pushed his indecision aside and kept writing down the new letters. Fretting about one letter can destroy the whole sentence. A radiotelegraph operator learns to focus on the stream of characters and not dwell on each one.

After a few weeks in his frozen prison, Byrd began to suffer from headaches, nausea

weakness and confusion. His Morse code became harder and harder to read and his team back at Little America became greatly concerned. Unknown to Byrd, his cabin heater was leaking carbon monoxide and was slowly killing him. Finally, when Byrd's condition became desperate, his crew drove hundreds of miles over the ice cap through winter darkness, howling wind and below zero temperatures to rescue him.

Growing up at the end of the Morse code age

As late as 1960, Morse code was still commonly used commercially and by the military. Since Morse code had an exotic sound, news broadcasts were routinely introduced by snippets of code. When the word "NEWS" is spelled out in Morse and repeated rapidly, it makes a pleasant, rhythmic, musical phrase that blends in well with Hollywood-style introduction music. The public often assumed that messages from the other side of the world arrived by Morse code, although in reality its importance had been fading since the 1930s.

The Morse code used for radio communications in the English language

The "dashes" are three times longer in duration than the "dots."

A ._	**G** _ _ .	**M** _ _	**S** . . .	**Y** _ . _ _
B _ . . .	**H**	**N** _ .	**T** _	**Z** _ _ . .
C _ . _ .	**I** . .	**O** _ _ _	**U** . . _	
D _ . .	**J** . _ _ _	**P** . _ _ .	**V** . . . _	
E .	**K** _ . _	**Q** _ _ . _	**W** . _ _	
F . . _ .	**L** . _ . .	**R** . _ .	**X** _ . . _	

Numbers and Commonly Used Punctuation

1 . _ _ _ _	**3** . . . _ _	**5**	**7** _ _ . . .	**9** _ _ _ _ .
2 . . _ _ _	**4** . . . . _	**6** _	**8** _ _ _ . .	

Ø(zero) _ _ _ _ _   **(, comma)** _ _ . . _ _   **(. Period)** . _ . _ . _   **(/ slash)** _ . . _ .

My introduction to ham radio was through Alexander ("Mac") McKenzie. When I was a kid, Mac was the father of my best friend, Garth McKenzie. Garth's dad was a ham and had an alcove off the dining room crammed with radio gear. In the 1940s, quality radio equipment was packaged behind somber black aluminum panels 22 inches wide, eight inches high and mounted in tall racks. The controls were enigmatic black knobs with strange labels like "grid drive" and "loading." The displays were usually just meters with equally arcane titles such as "S-meter" and "plate current."

The McKenzie family had a cabin up in New Hampshire. Mrs. McKenzie and the kids spent most of every summer up at the cabin. Mac went up to New Hampshire on weekends when he could, but most of the time he stayed in touch with his family by radio. A friend of Garth's

dad, Mr. Henny, lived near the McKenzies' cabin. He was also a ham, so on Saturday mornings Mac had a regular schedule to talk with Mr. Henny using Morse code, or "CW" (continuous wave) as it is still known. I was intrigued when I heard about these scheduled contacts and wanted to see Mac operate his station. I arrived at the McKenzie house at the appointed time. Sure enough, right on schedule, Morse code appeared over the static. Garth's dad wrote down the letters on a pad. I watched over his shoulder and stared at his pencil tip. It was mesmerizing to hear the code and watch the words and sentences appear on the paper. Unfortunately I couldn't understand even one letter of what Mr. McKenzie was sending, so I quickly tired of the one-sided conversation. In spite of that, Morse code had a mysterious, other-world quality and I was hooked.

Among the other equipment in Mr. McKenzie's radio shack was a Loran set. Loran was a long-range direction finder, the 1950 version of today's global positioning system (GPS). Mac demonstrated for me how to find latitude and longitude using a tiny green oscilloscope screen. The little round screen was only 2 or 3 inches wide and peered out from another one of those black, 22-inch wide black rack panels. Mac had it set up just for fun, of course. The Loran was designed for use on a ship and the McKenzie's house certainly wasn't going anywhere.

The joy of building it yourself

It was hard for an eight year old like me to imagine getting a ham license and affording all that massive equipment. The Loran was even more alien. What really turned me on was Mac McKenzie's television set. In the late 1940s, television stations were on the air, but no one I knew other than Mac actually owned a TV. That wasn't surprising. TVs cost as much as an automobile. Talk about a luxury! Undaunted, Mac built his own television from old radio parts and an army surplus, five-inch diameter, green oscilloscope tube.

A real, white phosphor, (black and white) TV cathode ray tube cost a fortune back then, so Mac couldn't even afford the picture tube. And because the TV tubes were designed for magnetic deflection and the oscilloscope tube used electric deflection, Mac couldn't just copy the deflection circuits from an RCA TV. Instead, he had to design his own custom picture tube drive and sweep circuits. Perfecting a new circuit meant that it had to be built and tested one small piece at a time. Since Mac had little idea how large the final circuit would be, he couldn't assemble his TV in a cabinet right away. Instead, he built his TV as a giant "breadboard" circuit with all the glowing tubes, wires, resistors, transformers, capacitors and components all laid out in a huge spider-web matrix.

A TV is extremely complicated and a large breadboard was needed. Fortunately Barbara McKenzie was a tolerant woman. For about a year the dining room table, including the extension leaves, was completely covered with about four by eight feet of television circuitry. Toward the end of the year the TV began to work. We kids used to come home from school and sit on the floor and watch programs on the tiny five inch picture tube dangling off the end of the table. The pictures were in living "black and green." We watched "Zoo parade" with Marlin Perkins and our favorite program, "Flash Gordon." TV was different back then. Flash Gordon was 15 minute film clips but most other programs were live. Even the commercials were live. I remember laughing silly over a commercial for a vacuum cleaner in which the fellow plugged the hose into the wrong end of the cleaner. The machine blew the dust all over the room while the announcer tried to pretend it was working perfectly.

Eventually Mac installed his TV in an old record player cabinet. To make the picture larger, he put a big magnifying lens in front of the screen. When he watched TV, he propped up the hinged lid of the cabinet up at a 45 degree angle and watched the enlarged picture in a mirror mounted on the underside of the lid. Mac McKenzie demonstrated to me that, with patience, you can build almost anything. And, in the long run, it's usually much more rewarding to build a possession rather than to buy it. He also taught me that projects must be built and tested one tiny part at a time. ***If you build it all at once without testing the parts as you go, it might fit in the cabinet, but it almost certainly won't work***. There are very few short cuts.

The complete radio amateur

This book is about building ham radio equipment. To be sure, it's much, much easier to buy the equipment. In fact, commercial ham equipment today is so cheap, that buying it is far less expensive than buying the parts one at a time. The good news is that equipment you build yourself will have a value and meaning for you that can't be purchased. Along the way you'll learn much more about electricity, then you ever will learn reading the operator's manual of commercial equipment. Most of us will never be an Edison, Marconi or Armstrong, but we can learn what they knew and we can share some of the thrill they felt when their inventions began to work. When your homemade station is finally on the air, you'll have all the same fun the other hams are having. But unlike the rest of the herd, you will be the ***"The Complete Radio Amateur."***

A brief history of radio communication

Radio is based on phenomena that have been known since ancient times, namely static electricity and magnets. These phenomena also produce action at a distance with no visible connection, but only over extremely short distances. In 600 BC the philosopher Thales of Melitus described how, after rubbing amber with cloth, the amber could attract bits of straw. Sometime back in antiquity it was observed that natural magnetite ore (iron oxide, Fe_3O_4) could attract other bits of magnetite rock. Knowledge of natural magnets eventually led to the discovery of the magnetic compass. Compasses were a Godsend to sailors lost in fog and must have seemed astounding to those who first used them. The compass was in wide use in Europe by 1000 AD.

Magnets and electricity appeared to be separate phenomena until 1820 when Hans Christian Oersted noticed that an electric current in a wire generates a magnetic field that can move a compass needle. Faraday and Henry studied and quantified the generation of magnetic fields by coils of wire that we now call called "inductors." In one of the all-time greatest triumphs of theoretical physics, James Maxwell published four equations in 1884 that summarized the connection between magnetism and electrical force. Maxwell's equations not only quantified and connected what was already known about these forces, they also predicted that magnetism and electric force could be combined to form a free-flying radiation. From the equations it appeared that these radio waves should be able to propagate great distances through space, much like light and heat.

What exactly is a radio wave?

An electric field and a magnetic field both can temporarily store energy in free space. For example, a refrigerator magnet generates a magnetic field in the space surrounding it. This

magnetic energy hovers in "cloud" or "field" surrounding the metal magnet. Similarly, electric field energy is present in the space between the terminals of an ordinary flashlight battery. Suppose that magnets and charged batteries could be sent into outer space and turned loose to float in the void. These devices would still generate their magnetic and electric fields in the vacuum surrounding the devices. However, if the devices could suddenly disappear, the magnetic and electric fields would not be maintained. The fields would quickly collapse and the energy would dissipate in all directions at the speed of light.

A battery or a magnet can be compared to a glass of water on a table. The glass holds the water in place and the water will rest there indefinitely. But if the glass were to suddenly break or vanish, the water would flood out in all directions.

If either a magnet or battery floating in free space could be made to suddenly disappear, it would generate a radio wave that would propagate outward in all directions making a spherical shell of expanding waves. It turns out that *collapsing magnetic field energy in free space is converted into electric field energy.* Then, *a moment later, the electric field energy similarly collapses back into a magnetic field.* One way to look at it is that the collapsing magnetic field forces the storage of that same energy as an electric field in neighboring space. In other words, a collapsing field becomes a "device" that establishes the opposite kind of field in adjacent space. The end result is a wavefront of energy propagating across the void. As it travels, the energy oscillates back and forth between electric and magnet field forms. In the vacuum of space there is no dissipation of the original energy except that the energy becomes more dilute as it spreads out in all directions like ripples on a pond.

The water analogy has other similarities with radio waves. The crests of the ripples on the pond represent the storage of mechanical energy as *potential energy*. The potential energy is proportional to the height of the ripples or waves. The higher the wave, the more energy it stores. As the water falls back down, the energy from this descent is converted into *kinetic energy*, that is, the outward velocity   Then as the wave spreads outward, the water stacks up to form another wave crest, restoring the energy to its potential energy form.

In 1887 Heinrich Hertz, a professor at the University of Bonn, Germany, managed to demonstrate in his laboratory that Maxwell's radio waves actually existed. From then on other experimenters built "Hertzian apparatus" and tried to use it for communication or remote control. Experiments much like Hertz performed are described in Chapter 4. Using rocks, copper wire and other materials available in 1880, you can build a short-range communicator to send and receive radio waves from one end of your house to the other. You can even demonstrate "standing waves" on an antenna.

How inventions happen

Big inventions usually begin with a novel observation. Faraday first invented the AC transformer with independent coils. An alternating current (AC) introduced into one coil on the transformer causes a second current to appear in a tightly coupled similar coil a fraction of an inch away. Today we still routinely use transformers to convert the ratio of current to voltage. For example, inside your flashlight battery charger, there is a transformer that converts a tiny current at 120 volts AC into a large current at 1.5 volts AC. If you used 120 volts directly on your battery, it could be disastrous. Chargers would be quite impractical (or at least horribly inefficient) without transformers. We shall discuss these principles in detail in later chapters.

Getting back to Faraday, he must have marveled when he thought about the implications of electrical energy fed into one coil appearing in a neighboring coil. That is, the energy was "transmitted" across a gap. Yes, the gap may have only been a fraction of an inch, but certainly the thought must have occurred to him, "how far can it transmit?" In a letter in 1832 he proposed to a friend that electric energy could probably travel through space as waves. Unfortunately, he had no evidence, experiments or equations to support this idea.

Many early radio communication experiments began when the first high frequency transformers were made. Unlike low frequency, like our 60 Hz line current, high frequency transformers of 500 KHz and above readily couple energy several inches through air. At these higher frequencies couple from one coil to another and begin to resemble radio.

It's surprisingly easy to build a high frequency transformer and demonstrate a crude, short range "radio communications." All that's needed is a powerful battery, a large coil of wire and a second coil wrapped around the first coil. The second coil is arranged so that the two ends of the wire are fixed a tiny distance apart, perhaps a sixteenth of an inch. The two ends of the first coil of wire are scratched transiently across the terminals of the battery. Huge currents flow in the first coil establishing a magnetic field around that coil. Since the same space is shared with the second coil, the magnetic field induces voltage across the second coil and a spark appears in the gap on the second coil. In other words, electric current was converted into magnetic energy, jumped across a short distance, and then was reconverted back into electrical current. Now if the two coils are moved far apart, there will continue to be energy transmitted from one coil to other. However, with such a crude detection system, a spark will probably not be visible and a much more sensitive detector would be needed to prove that the energy was there.

Inventions appear when all the conditions are in place

New technologies appear whenever the necessary knowledge and affordable raw materials become available. For example, cell phones could have been built 50 years ago, but they would have been the size of suitcases, served few people, and would have only been available to the most wealthy. Even today it's possible to introduce useful technology too early to be profitable. The Iridium phone system is a world-wide direct satellite telephone system. Unfortunately, the iridium "phone" is big and clumsy and the phone calls cost a fortune. Sure, you can reliably talk to a guy on dog sled at the North Pole, but there aren't many people who actually need to do that. The result of this business miscalculation is that this year (2003) a network of satellites costing billions of dollars might be deliberately crashed into the Pacific Ocean.

Radio was invented between the years 1884 and 1910 in a time when all the pieces to make it practical were in place. Many inventors had the chance to pursue radio communication, but many turned it down. To be more than a parlor trick, radio had to have a commercial reason for its development. The concept of broadcasting voices, music and even motion pictures to the masses seems obvious to us now. But in 1900 it wasn't obvious that radio could be more than an unreliable way to send telegrams. Hardly anyone back then imagined that speech and music might be transmitted.

Nicola Tesla, the archetype "mad scientist"

Tesla was born in Serbia in 1856. In college he studied what was then the exotic field of

electrical engineering. He once proposed to his professor that an AC generator could be built that would be simpler than DC power generation and which would have several other advantages. The professor ridiculed his idea mercilessly. Today we call these "alternators." We use giant alternators to generate electricity in all large power plants. And we use little ones in our cars to recharge our batteries. When Tesla's father died, Nicola was forced to leave school and go to work. Like most electrical engineers of his time, he worked on DC motors and DC generators. At that time the DC motor was beginning to replace the belt and pulley as a means of powering industrial machinery such as looms and mine hoists.

Tesla migrated to America and arrived almost penniless. He even worked briefly as a ditch digger in order to eat. He applied for work with Edison who tested his skills by assigning him to fix a DC generator on a ship. Tesla rebuilt the generator right on the ship and made it produce more electricity than its original design. Tesla worked briefly for Edison, then he struck out on his own. He built his own small laboratory and worked on gadgets of all sorts. He soon acquired a reputation as a "science wizard." He enjoyed putting on "magic shows" with giant sparks flying off his fingers and whirling fluorescent light bulbs. His reputation as a science magician encouraged him to put show business into everything he did. After reading his biography, it appears to me that his ability to gain awe and respect through showmanship eventually ruined his career.

As money ran short, Tesla got a job with Westinghouse and developed the alternator into a practical power generator. Tesla's greatest contribution to the world was the power generation and distribution system he demonstrated at a brand new power plant at Niagara Falls. He invented three phase AC alternators, transformers and high-tension power lines that are still in use world-wide. After Tesla left Westinghouse, he set up his own laboratory in New York City to experiment with uses for radio frequency current.

The missed opportunity

Ship owners have probably always wished they could communicate with ships at sea. Until the late 19th century the fate of a ship might be totally unknown for months or even a year. When the ship finally sailed into homeport, the owner might suddenly learn that he was extremely wealthy. Or the ship might never return and the owner would have lost a huge investment. Being able to communicate a few hundred miles or even a dozen miles out to sea might be life saving in an emergency.

By 1900 scientists knew that "wireless telegraph" could communicate across the English channel using giant transmitters and antennas, but no one had been able to receive a message from much farther than that. Among his empire of enterprises, the multimillionaire / financier J.P. Morgan owned a fleet of ships. If practical long-range telegraph could be developed, he wanted it on his ships. Marconi already had a good start on a ship-to-shore radio and had already demonstrated short-range ship-to-shore communication, both in England and America. In spite of that lead, Morgan approached Tesla who certainly had the knowledge and experience to develop practical radio communications. J.P. Morgan gave Tesla a big financial grant to do this work. Tesla set up a laboratory in Colorado Springs to invent long distance radio, or so he allowed Morgan believe.

Unfortunately, merely talking to ships was boring to Tesla. Tesla preferred to develop what he called "The World Telegraphy Center." Tesla wanted to set up a communications center

that could not only talk to ships, but also to everyone else on earth. His vision of what he was trying to build sounds to modern ears like a one-way Internet or perhaps CNN. He doesn't seem to have thought about the difficulties of handling all the messages in the world through one single gigantic low frequency transmitter. Back then, there were no Internet servers to organize all that message traffic into digital streams of information. Considering the operating frequency of his transmitters, his data rate would have been limited to a few kilobytes per second rather than the terabytes handled today by a single node on the Internet.

Tesla's radio transmitters were certainly adequate for transoceanic communication. But instead of also developing a sensitive radio receiver, Tesla spent nearly all his effort on developing huge low frequency radio transmitters. His transmitters were so powerful, he experimented with transmitting electric power as well as information. Tesla proposed using tuned coils to light fluorescent light bulbs miles away from his transmitter. Yes, his idea worked but only at an extremely low efficiency. Yes, the lights would go on, but damp soil, cows, people, barbed wire fences and every other electric conductor within range would be heated with the wasted energy, just like a microwave oven.

Tesla built a gigantic "Tesla coil" that produced radio frequency sparks 60 feet long. Always the showman, Tesla liked to be photographed sitting among the sparks and fire, while calmly reading a book. Actually, he used double exposures to create the illusion of sitting among the sparks. Tesla's machine was so huge and had such unique capability that the U.S. Air Force built a copy of it 80 years later for research.

With all this dramatic, futuristic activity, Tesla never got around to building the dinky ship-to-shore radio that Morgan was paying him to develop. When he gave Morgan a progress report, Tesla tried to sell Morgan on his futuristic schemes. Morgan was furious at him for not sticking to the assignment and had little interest in any of Tesla's ideas. Morgan did however force Tesla to assign him the ownership of any useful patents that might arise out of the work. Morgan was not known for generosity.

After Morgan gave Tesla a tongue lashing, he gave him a second chance. But instead of getting serious about ship-to-shore communication, Tesla blew the money on building his "World Telegraphy Center" out at Wardenclyff, Long Island, New York. It was an imposing building with a huge tower housing the Tesla coil transmitter. The communications center came to nothing and Morgan stopped the funds. Tesla lived at the Waldorf Astoria Hotel in New York City and became a sort of self-absorbed lounge lizard. He dressed in Tuxedos and top hat and mooched off his friends.

In the following decades Tesla dabbled in inventing and came up with several interesting devices that were almost good enough to become standard technology. For example, he designed a "bladeless turbine" heat engine, on the order of a steam engine or the internal combustion engine. There are few successful heat engine designs that are fundamentally different, so inventing a new one was an intellectual triumph. Unfortunately, Tesla's heat engine was not as efficient as other methods and, so far, there have been no good uses for it. He also developed a speedometer gauge that was excellent and was used in several luxury cars. Converting the speed of a rotating shaft into a smooth, linear needle movement is much harder than it looks. However, Tesla's method was more expensive than the meter design that eventually became universally used for that purpose.

Tesla ended up as a lonely old man feeding pigeons in a third rate hotel in New York. After he died in 1943, it turned out that he had paid his rent for several months by giving the hotel manager a "death ray" to hold as collateral. Tesla told the manager the death ray was worth $10,000. The ray gun was actually a Wheatstone bridge, a sensitive resistance-measuring device commonly found in electrical labs.

Marconi gets the job done

Guglielmo Marconi was born into a prosperous family in Bologna, Italy on April 25, 1874. He was educated in Bologna then later in Florence. He studied physics at Leghorn College. He was fascinated by Hertz's discovery of radio waves and he became interested in wireless telegraphy in 1890. Starting in 1894, Marconi worked at home building prototypes in his basement.

Today most of us think of a radio receiver as a kind of amplified stethoscope that lets us listen in on the hidden world of the radio spectrum. In Marconi's time the main precedent for radio was telegraphy. This concept of one telegraph operator banging out telegrams to another operator using Morse code influenced Marconi's vision of what he was trying to build. In conventional telegraphy the signal over the wire triggered a "sounder" which was a kind of electro-magnetic relay. The sounder made clickity-clack noises that the receiving operator interpreted as dots and dashes.

Similarly, Marconi's first radio transmission to another room in the house rang a bell when the signal was detected. There were no headphones that a person listened to. Most early experimenters built radios that resembled radio control systems rather than listening devices. As the technology developed, the radio operator gradually became a vital part of the system. The operator's skill and trained ears became responsible for most of the range and practicality of the system. A trained operator can hear Morse code signals that are no stronger than the atmospheric static. Unlike a simple bell system, an operator can copy one Morse code signal while ignoring another. It took a hundred years for computerized digital signal processing to exceed the ability of a trained radio operator and return to Marconi's vision of a robotic receiver.

Radio detectors – An early challenge

The most popular early radio detector, the "coherer," was invented by the English physicist Lodge. Coherer's were first used with long distance wire telegraph lines. They greatly extended the practical range of a telegraph wire and it was natural that they would be applied to the earliest radio experiments.

A coherer was a small glass vial containing loose powdered carbon or iron filings. This powder contacted two electrodes in the vial. When a small voltage appeared across the powder, it would break down the contact resistance between the powder granules and cause the resistance of the coherer to suddenly drop. The drop in resistance was used to cause current to flow through the sounder relay. Coherers were often built onto the frame of a sounder so that the vibration of the sounder would keep the powder loose, thereby continually resetting the coherer to its original state.

The set - reset action of a coherer resembles a modern silicon controlled rectifier. A small input current causes a much bigger current to flow. Unfortunately, like a silicon-controlled rectifier, the current through the coherer doesn't shut off by itself when the input is turned off.

Because coherers turned on and off at rates well below 20 cycles per second, the output from a coherer wasn't an audio signal that someone could listen to directly.

At first Marconi's receiver sat on the table next to the transmitter. Then he was able to transmit across the room, then to other rooms in the house. As his range increased, he moved his operation into an unused granary behind his parents' house where he could string up antennas. His next triumph was a transmission from the granary to the end of the garden, 100 meters away. During these years the existence of radio was widely known to scientists, but it was believed that radio waves were inherently line-of-sight, much like a signal lantern. Marconi had already observed that he was able to transmit to the receiver when it was behind walls and trees. Since he already knew the experts were wrong, he worked on the big question of whether radio waves could travel over mountains and perhaps over the horizon.

About this time Marconi must have graduated from coherers to some kind of rectifier detector. This detector produced an audio output that an operator could listen to directly with earphones. The earliest detectors consisted of "crystals" which consisted of a piece of wire pressed against a crystalline chunk of sulfide ore. Crystal detectors are described in detail in chapter 4.

Marconi had a servant named Mignani. To test his receiver over distances, Mignani manned the receiver while Marconi sent test signals. One of Marconi's breakthrough improvements was a directional antenna that focused his weak transmitter output directly toward the feeble receiver and thereby extended the range. Radio stopped being a toy the day that Marconi transmitted a test signal two miles over a hill. Mignani signaled back to Marconi that he had received the Morse code letter "S," by firing a rifle into the air from the hilltop.

Radio reaches across the Atlantic

Following the success of his experiments at home, Marconi became obsessed with the possibility of transmitting a signal across the Atlantic. If he could do that, radio communication could cover the world. There was essentially no interest in radio in Italy. He was even unable to get a patent for his device. An Italian government minister told him that radiotelegraphy "was not suitable for communications." Marconi moved to England where he patented his method of transmitting signals in 1895. In 1897 he was financed by the British Post Office to continue his experiments. Gradually the range of his transmissions was extended to 8, 15, 30 and 100 kilometers. In 1897 he founded the Marconi Wireless Telegraph Company, Ltd. in London. In 1899 he established a communications service across the English Channel.

Marconi built a huge transmitter, 100 times more powerful than any earlier transmitter and set it up at Plodu, Cornwall in South West England. One approach to building very large transmitters was to construct large, high-speed AC alternators. These resembled Tesla's power generation alternators but ran at such high speeds that they produced a sinewave, not at 60 cycles per second like a modern power plant, but at low radio frequencies, 20,000 cycles per second. Marconi also built a complementary station at St. Johns, Newfoundland and on December 12, 1901, he received the first signals from across the ocean.

The British and Italian Navies soon adopted his system and ship-to-shore radio became reality. By 1907 his system was available to the public as a transatlantic radio telegram service. Marconi was awarded the Nobel physics prize for 1909. In his later life he continued to

experiment with short waves and microwaves. Marconi also briefly served as a statesmen. He was sent as a delegate to the Peace Conference in Paris after W.W.I where he signed the peace treaties with Austria and Bulgaria. He died in 1937.

Radio changes history

Until radios were put on ships, radio communication didn't make much difference to the course of history. Radio telegrams sent across the ocean or between cities were competing with undersea and overland cable telegrams. Ordinary hard-wired telegraph was just as fast as radio, but was not vulnerable to atmospheric conditions. However, once radio transmitters were placed on ships, it was only a matter of time before radio was used to rescue the passengers and crew from a sinking ship. This first happened during the sinking of the RMS Republic.

At 5:40 AM, Saturday January 24, 1909, the passenger steam ship RMS Republic was steaming off Nantucket, Massachusetts through thick fog. The Republic was outbound from New York. The Republic had a lot in common with the later Titanic. The Republic was owned by the same British White Star Line and was considered "unsinkable." Its hull was divided into multiple compartments by watertight bulkheads so that several compartments would have to flood before the ship could sink. Also like the Titanic, the Republic carried only half as many lifeboats as needed for her 800 passengers and crew.

As the Republic motored through the fog she sounded her foghorn periodically and ship's lookouts listened for other foghorns. The crew heard a foghorn from another ship and responded by sounding a steam whistle. It was the convention of that time that, when ships exchanged whistles, both ships would turn right and thereby avoid the collision. There is some evidence that the Italian passenger ship "Florida" turned left instead. The Florida suddenly appeared out of the fog and crashed into the Republic amidships. Seven people were killed outright by the collision. The Florida struck the bulkhead between the two engine rooms on the Republic, thereby flooding the two largest compartments below the waterline. The engines had to be shut down which also terminated the electricity needed to run the pumps and the radio.

Jack Binns saves the day

The Republic's radio shack was a wooden cabin that had been tacked onto the upper deck. It was located where it was easy to connect to the antennas that were strung up in the ship's rigging. As luck would have it, the bow of the Florida sliced part way through the radio "shack" pushing equipment aside and disabling the radio. The operator John (Jack) R. Binns was sleeping on a bunk next to his operating station. He said later that if he had been still working at his radio he would have been gravely injured. Binns managed to piece his transmitter back together, but his little cabin was now open to the cold and fog. Because the ship's electricity was off, Binns had to rummage around in the dark below decks to find batteries to run his radio. Without the ship's electricity, Binn's transmitter range was limited to about 75 miles. His best hope was to reach a station on Cape Cod, 65 miles away. Even Binn's telegraph key was broken. He had to hold it together with one hand while he used his other hand to send out history's first emergency SOS.

Actually, the official distress call at that time was not SOS but "CQD." "CQ" meant calling any station, just as it still does today on the ham bands. CQ was supposed to be short for "Seeking You." "D" of course meant danger or distress. Binns managed to contact the station on

Cape Cod. Through them, he continued to call for help and talked to rescue ships for 12 hours while the Republic slowly settled into the sea.

Since the Florida was in no danger of sinking, the Republic crew transferred the Republic passengers to the Florida by lifeboat. Meanwhile rescue ships criss-crossed the fog trying to find them. In addition of foghorns, ships of that era were equipped with "submarine bells" which had a greater range than sound from horns was able to travel through air. The submarine bell of the Republic was heard by the liner Baltic and used its sound to guide it the final few miles to the Republic.

In another account of the rescue there was no submarine bell and the contact was made when the Baltic shot off "its very last aerial rocket bomb." The crew of the Republic heard the explosion and gave them the correct bearing by radio. When the Baltic arrived, the remaining crew on the Republic were rescued, then all 2,494 passengers from both the Republic and Florida were transferred by lifeboat to the Baltic. 39 hours after the collision the Republic sank. Meanwhile rescue ships managed to tow the Florida to New York City.

The success of the Republic rescue was a huge news story. Overnight radiotelegraph operators were transformed from curiosities into heroes. It's bizarre and even criminal that the White Star Line didn't seem to learn anything from the sinking of the RMS Republic. However, in 1912 the Titanic sinking and the partial success of the Titantic's SOS emergency call further elevated the status of radio communications. The steamship Carpathian sailed 300 miles to rescue the Titanic survivors the morning after the sinking. Another freighter, the Californian, lay at sea anchor just 10 miles away. The captain of the Californian didn't want to risk steaming at night through the icebergs - smart man! The Californian radio operator sent an iceberg warning to Titanic, but the Titanic radio operator told the Californian to get off the frequency because he was handling telegrams for the passengers. The Californian radio operator shut down his radio and went to bed. The night crew on the Californian could plainly see the Titanic but didn't realize the Titanic was in trouble. When the Titanic shot red emergency rockets into the air, the Californian crew thought the rockets were fireworks to amuse the wealthy passengers.

The dawn of amateur radio

In the early days of radio anyone who wanted to get on the air could build his own transmitter and just do it. Frequency assignments were based on whoever was on the air first with the biggest transmitter and the best antenna. Basement inventors began building their own radio equipment and amateur radio was born. In those days, there were no licenses, so amateurs at first just gave themselves call letters. All radio communications in the beginning were low frequency, 200 meters wavelength and longer. This meant that all communications were happening at what is today AM radio (1,700,000 Hz to 550,000 Hz) and below. Higher frequencies were inefficient to generate and it was believed that higher frequencies were only good for local communication.

When a modern amateur radio operator reads descriptions of early radio transmitters and antennas, he is impressed by the industrial scale of the commercial equipment. For example, the rotary spark gap transmitter on the Titanic was rated at 5000 watts. It was so huge and made so much noise, it was installed in a separate room from the receiver. With all that power and size, its reliable range during the day was only 250 miles. At night the range could be as far as a thousand miles. From the modern viewpoint, it's apparent that the biggest weakness of early day

equipment was the insensitivity of their receivers. Back then amateur receivers were just as bad and probably worse. Moreover, amateurs were unable to compete with the power used by commercial stations. Consequently, hams were lucky to talk to the next county, let alone any significant distance.

Because early ham radios were limited to short range, radio amateurs banded together to form "relay nets" so that messages could be relayed to destinations many hundreds of miles away. This organization became formalized as the American Radio Relay League in 1914. During World War I the US government banned amateur radio as a national security measure. After the war in 1919 the American Radio Relay League under the leadership of Maxim Percy lobbied the government to allow hams back on the air. The government, especially the military, was unsympathetic. To placate them, eventually the government gave the hams all the "worthless" frequencies above 200 meters. That was roughly everything above present day AM radio.

Flemming develops the vacuum tube diode detector

The vacuum tube diode had actually first been built by Edison. During Edison's work on the electric light, he perfected the technology to put electrodes and filaments in evacuated glass bulbs. Edison was also the first to notice that electrons can flow from a hot filament across empty vacuum toward a positively charged electrode called a "plate." However, the electrons could not flow from the plate back to the filament. As a result, the diode behaved as a one-way check valve. Edison experimented with this and wrote about it. This effect became known as the "Edison effect."

Flemming was a British inventor who was intrigued with Edison's discovery and applied it to the detection of radio signals. He worked with Edison who shared his data on the Edison effect. A radio signal received on an antenna consists of a high frequency sinewave voltage that switches from positive to negative and back again hundreds of thousands (or millions) of times per second. These rapid alternating (AC) currents can't power a headphone until they are converted to lower frequency bursts of DC. By passing radio signals through a vacuum diode, one polarity of the signal is "sheared off" leaving just the polarity of the flowing negative electrons. When Morse code signals are received, this results in bursts of DC current that can be used to power a sounder, headphones or other kind of transducer.

Flemming's detectors became known as the "Flemming Valve." In England thereafter, all vacuum tubes became known as "valves." In terms of sensitivity, the vacuum tube detector was _not_ more sensitive than a crystal detector, but it was far more rugged, reliable and versatile. Later on, when it was combined with the vacuum tube amplifier, its sensitivity was vastly improved.

Lee DeForest launches modern electronics

Tesla was not the only radio pioneer with an ego problem. In many ways DeForest had a personality similar to Tesla's. DeForest was industrious and gifted. While he was a young man he developed several important inventions. One of his cleverest was a telegraph multiplex system that allowed one wire to carry up to six telegraph messages simultaneously. It's hard to imagine how it could have worked, considering that all he had to work with were switches, relays, transformers and motors. De Forest's most important invention was the triode vacuum

tube, which he called an "audion." The audion was the functional equivalent of the modern transistor. DeForest's triode vacuum tube was essentially a "Fleming valve" with a grid placed between the filament and the plate. DeForest used the audion to make receivers more sensitive by amplifying weak audio and radio signals.

Actually Edison built the first triode while he was studying "the Edison Effect." Edison added a grid-like electrode between the filament and the plate of his diode to learn more about the flow of electrons across a vacuum. Although Edison made his measurements, he didn't notice that the grid was like a sensitive "gate" that could control the current flow to the plate.

The grid can be compared to a matador's one-pound red cape steering a 2000 pound bull. When big currents are controlled by little currents, the device is said to "amplify." Little signals coming into the grid can modulate the big current into a larger, "amplified" version of the original signal. Notice that the original signal is not "inflated" in some way, but rather, the amplifier just directs the generation of a larger copy of the original signal. Notice that the copy may or may not be good likeness of the original.

DeForest successfully applied his triode vacuum tube to radio receivers. The triode meant that weak signals could be amplified to a level high enough so that after detection they could drive a loudspeaker. Once amplifiers became available, nearly every kind electronic device known today became at least theoretically possible. Eventually even television was implemented with the descendents of the audion vacuum tube. During World War II the first computers were built using vacuum tubes.

The vacuum tube oscillator cleans up radio transmissions

A few early, high power systems used alternators to generate low frequency radio signals. However, the frequency of an alternator is limited by the speed of a mechanical, rotating magnet. In practice, alternators couldn't get much higher than audio frequencies, 20 to 50 KHz. An advantage of an alternator was that it generated a pure sinewave signal. Unfortunately it could only cover the very bottom of the radio spectrum.

In contrast, the vacuum tube amplifier could amplify its own output, causing a self-sustained oscillation at any frequency up to hundreds of megaHertz. Like an alternator, a vacuum tube oscillator could generate clean sinewave signals that were confined to a single frequency. Up until that time, radio transmissions from all high frequency transmitters were generated by discharging electric sparks, then letting radio frequency signal components ring in a tuned circuit. "Spark gap" transmitters made a noisy, hissing, signal that splattered energy all over the band.

Have you ever heard static in an AM radio from a passing automobile ignition? Similarly, lightning causes a pop or crash of static that can be heard over the entire radio spectrum. Other than having a filter to limit the noise to one band, early radio transmitters were like little lightning radio noise generators. These early sparkgap transmitters wasted power and frequency space. Because of the availability of vacuum tube oscillators, spark gaps became unusual in the early 1920's and were totally banned in the United States in 1927.

If an inventor is persistent, it's sometimes possible to invent wonderful things without really understanding why they work. This was the case with DeForest's audion. In the short run, ignorance can be OK, but in the long run the inventor had better figure out exactly what he has

developed. Specifically, he must be able to explain how it works in his patent application.

Unfortunately, DeForest blew it. His patents failed to give valid explanations of how his vacuum tube devices worked. A dozen years after the invention of the audion, DeForest's patents came into conflict with later patents that were accurately explained. In court DeForest was literally unable to explain how a triode amplified. It is completely understandable how he might have been naive at the time of his inventions. But considering that the vacuum triode was his crowning achievement, it isn't flattering that he never bothered to keep in touch with the field of electronics well enough to find out how his own invention worked. Forty-five years after his invention of the audion, De Forest was still strutting around in formal clothes grandly referring to himself as "The Father of Television."

Reginald Fessenden transmits speech

Professor Reginald Fessenden is an almost unknown hero of radio development. He is truly one of the most amazing radio pioneers. Although Marconi first demonstrated transatlantic communication, Fessenden was the first to offer it as a regular service in 1906. Fessenden's most amazing accomplishment was the transmission of speech. He is not remarkable so much for what he did, but rather when he did it. In December 1900 he transmitted a voice signal to his assistent Alfred Thiessen over a distance of one mile from his laboratory on Cobb Island in the Potomac River. "One-two-three-four..... Is it snowing where you are, Mr. Thiessen? Telegraph back if it is."

"Yes, it is!" tapped out Thiessen over a telegraph. From a modern perspective Fessenden's invention came at least 15 years before the parts were available to do it gracefully. What Fessenden needed was high power audion tubes. However, he didn't know that. So he transmitted AM modulated voice transmission using spark gap transmitters. That sounds impossible. And perhaps because spark gaps were "dead end technology," it isn't totally surprising that Fessenden has been largely forgotten. The only articles on Fessenden that I have ever read don't describe his apparatus clearly. However, he seems to have succeeded by means of three major breakthroughs and many minor ones.

Fessenden smooths out the sparks

A smooth, pure carrier wave is needed to produce clear AM modulation, but there is nothing smooth about static from a spark gap. Fessenden reasoned that, if the static crashes occurred often enough, the frequency of the buzzing racket would be too high frequency for human ears to hear. So instead of sparking a few dozen or a hundred times a second, Fessenden's generator sparked 10,000 times per second. Then (apparently) he filtered the heck out of the signal using inductor/ capacitor resonant circuits. The transmitter had its own steam engine power plant and was probably quite powerful. The steam engine had to be running at full speed before the speech became intelligible.

Using high frequency noise to get rid of low frequency noise is reminiscent of the modern "Dolby sound" noise canceling principle. Rather than fight the noise inherent in any analog recording system, the Dolby system deliberately modulates the music with a high frequency sinewave at about 25,000 Hz to obliterate the noise.

I read another account of Fessenden's work in which his voice transmitter was described as a high-speed alternator. Oh, well, transmitting speech with a high-speed alternator sounds

pretty tough too. Garbled technical descriptions are a serious problem when studying the history of radio. It is hard to figure out exactly what they did.

Fessenden invents the barretter

Fessenden also invented a sensitive new detector that he called a "barretter." Barretter means "exchanger" in French and is still used as the "barretter" microwave detector. Modern barretters consist of a microscopic platinum wire that heats and cools rapidly when bursts of tiny radio frequency currents pass through the wire. As the wire changes temperature, its resistance changes rapidly and this can be used to modulate a DC current passing through a sensitive telephone earphone.

What I don't understand is how the professor got enough signal strength out of a 1900-era telephone microphone to modulate a powerful transmitter. In my opinion that would have been his third amazing breakthrough. In a commercial amplitude modulated (plate modulated) transmitter from the 1930's and later, the audio sound from the microphone had to be amplified up to half the power output of radio transmitter. For example, for a 1000 watt transmitter, a 500 watt audio amplifier was needed. There was no way to build such a thing in 1900.

Perhaps he invented the "magnetic modulator." In the 1920's some phone transmitters used a transformer to impress amplitude modulation directly on the RF signal. The microphone modulated a DC current on the transformer primary while the transmitter ground for the antenna went through the transformer secondary. By saturating the iron in the transformer, the current flowing through the secondary can be radically changed with a small signal, thereby providing the needed amplification. Fessenden must have been an obsessed genius to broadcast speech successfully with steam engines, iron bars, copper wire and spark gaps.

At the time Fessenden's achievement didn't go unnoticed and he was able to raise money to start a broadcast company. His first public demonstration consisted of speaking and playing "Oh Holy Night" on the violin on Christmas Eve in 1906. However, his commercial progress was slow and by the time AM broadcast was beginning to work well, nearly everyone was stealing his ideas. The Marconi Company eventually licensed his patents in 1914. From a modern perspective, Fessenden's biggest problem was his lack of viable business plans. He invented neat stuff, but had difficulty getting paid for his work.

Edwin Howard Armstrong

Another engineer who understood his own inventions was Edwin Armstrong. He studied electrical engineering during World War One, then, right after graduation, he produced the first of his three great inventions, *the super-regenerative receiver*. In the early days of radio, it was too expensive to design receivers with large numbers of large, expensive, power-hungry vacuum tubes. Armstrong invented a way to use feedback on a vacuum tube amplifier to increase the sensitivity of the receiver by an order of magnitude. Super-regenerative receivers were crude and had to be adjusted just right to avoid an unpleasant squealing noise on top of the stations you were trying to hear. However, when super-regenerative receivers began to be used, the range of radio broadcasts soared to a thousand miles and more.

In spite of their severe limitations, ham radio operators commonly made homemade super-regenerative receivers as late as 1960. "Super-regens" were primitive, but they were a stepping-stone to the next generation of receivers. In the 1920s Armstrong developed *the super-*

hetrodyne receiver. This is the basic design used today in most modern receivers, from television to cell phones. When I was a young ham, I built a Knight "Ocean Hopper" super-regenerative receiver from a kit. I only bought it because it was cheap. The high-pitched noise the super-regen made was so obnoxious, I couldn't wait to replace it with a high quality super-hetrodyne communications receiver.

The TRF receiver didn't cut it

To achieve the required amplification without super-regeneration, the obvious solution was to put several radio frequency tube amplifiers in series. These radios were called "tuned radio frequency" (TRF) receivers but they were never very popular. Each amplifier in the string had to be tuned separately to the desired station. This meant that the first TRF radios literally had three or four station tuning knobs, which all had to be tweaked independently. Alternatively, in the best TRF radios the tuning capacitors were ganged together so that they always tuned to the same station simultaneously. This method was extremely hard to synchronize and calibrate so that each tuned coil would track precisely over the entire frequency band. Another problem was that they were inherently "low Q" and tended to receive more than one station at once. The only practical TRF receivers were either extremely expensive or were designed to receive just one frequency.

The super-hetrodyne receiver

Armstrong's solution to the gain problem was to convert the incoming radio signals to a constant "intermediate frequency," an "IF." The IF frequency remains the same no matter what station the radio was tuned to. In other words, *a superhetrodyne is a single-frequency TRF receiver with a frequency converter on the front end.* The IF strip is tuned up just once at the factory. It never needs to be tweaked again. Another important advantage was that the signal on the IF strip could be filtered so that it would only admit a bandpass equal to the actual width of the signal. For example, an AM radio receiver might have an IF bandpass of 20,000 cycles per second (one cps = one Hertz). However, a Morse code signal only needs 100 Hz of bandwidth or less. So when a narrow bandwidth filter is used in the IF, the receiver can select just one signal out of many that may be crowding the band. In contrast, a TRF receiver or even a super-regenerative receiver or may force you to listen to 50,000 Hz of bandwidth at once.

The super-hetrodyne generates the IF by means of a "local RF oscillator." The principle can be illustrated with audible sound. When two different frequencies of sound are mixed together, the sound waves cancel and reinforce each other generating frequency components that are the sum and difference of the two signals. For example, if you hit two adjacent keys on a piano simultaneously, the sound is discordant. That's because you're hearing those sum and difference frequencies. In another example, twin-engine, propeller-driven airplanes are equipped with engine speed synchronizers so that the engines don't make an obnoxious "WAH -WAH-WAH" beat frequency sound. This sound is the difference in frequency between the two speeds of the engines. The same principle works with electrical sinewaves at radio frequencies. Unlike the annoying audible examples, in radio, the beat frequency is usually the desired product and that was Armstrong's invention.

A super-hetrodyne is tuned, not by tuning a sharp filter on the antenna, but rather by tuning an oscillator sinewave oscillator that is offset from the signal you wish to hear. The amount of offset frequency is equal to the IF frequency. For example, in a household FM radio,

if you wish to tune to a station broadcasting on 100 MHz, then the local tuning oscillator is tuned to 110.7 MHz. The difference between the two frequencies is 10.7 MHz which is the IF commonly used in FM radios. Because the tuning oscillator generates only one precise frequency, and because the IF filtering can be quite narrow, the tuning of a superhetrodyne receiver can be extremely selective. The superhetrodyne is made sensitive by putting several IF amplifiers in series. Or, as explained earlier, you can look at the IF amplifiers as a single frequency TRF receiver.

By the late 1920's spark gap transmitters were banned and replaced by vacuum tube sinewave oscillators. The sinewave oscillators generate just one, discrete frequency. After this improvement, hundreds of Morse code signals could share a band without interfering with each other. And using Armstrong's superhetrodyne, the receiver could select just one of these Morse codes signals.

Beat Frequency Oscillators – where the musical Morse code tone comes from

Although a simple superhetrodyne receives AM broadcasts beautifully, Morse code is essentially inaudible because a pure sinewave signal is unmodulated. During the 1920's Morse code transmitters were often modulated with a mechanical motor driven switch device that made the Morse sound like a buzz and more like an old spark gap.

To hear Morse code with a superhetrodyne, another oscillator called a Beat Frequency Oscillator (BFO) is needed to produce the musical sound. For example, my first short wave receiver was one of those ancient all-band radios often found in living rooms in the 1940's. The receiver worked fine for receiving foreign AM radio stations like Radio Moscow. However, when I tuned to the ham bands, the Morse code signals were inaudible or just thumping noises. To receive Morse code I had to place a small table radio on top of the big shortwave radio. I used to tune the little radio until I could hear the table radio's tuning oscillator (local oscillator) in the big receiver. This signal beat with Morse code signals and made them audible. This was extremely tweaky and barely practical. A communications receiver of course has a built-in BFO and is easy to use.

Getting rid of the atmospheric static

Radio communication was essentially 100% Morse code until after World War 1. Suddenly it became common to hear voices over the radio. In 1921 the first commercially successful Amplitude Modulated voice broadcasts began. With AM broadcasts, the transmitter was not turned on and off like Morse code, but rather the transmitter was left on continuously. The transmitter power was raised and lowered in time with the music or voice audio frequency. This process impressed or "modulated" voice and music onto the signal. In other words, with AM modulation the information content is proportional to the momentary strength of the signal.

So long as the strength of the signal is high and there is no interference from lightning storms, big DC motors or nearby automobile ignitions, amplitude modulation (AM) radio works quite well. By 1930 AM radio was a standard appliance in American households. But with all that crackling and popping noise on weak signals, AM radio is never really high fidelity except when tuned to strong, local stations.

Atmospheric static is a natural noise signal that has the same amplitude modulated form as man-made AM signals. Therefore it is impossible to get rid of the static without changing the

method of modulation. Edwin Armstrong secluded himself in his laboratory in the Empire State building in New York City and worked to find a way to eliminate the static in voice broadcasts. Armstrong needed to create an audio modulation that could be impressed on a transmitter signal without imitating the natural noises from lightning and static discharge.

Armstrong eventually hit upon the idea of modulating the frequency of the signal rather than the intensity of the signal. In other words, as the announcer talks, the frequency of the transmitter moves up and down in time with the audio frequency of the sound*. **Frequency Modulation** solved most of the noise problem and was the origin of the FM broadcasts we listen to today. Armstrong had been working for the Radio Corporation of American that manufactured superhetrodynes. Because of the superhetrodyne, RCA with its subsidiary, the National Broadcast Company, dominated AM radio for as long as that patent lasted. RCA was run by David Sarnoff who failed to reward Armstrong's contribution to the company. Armstrong left RCA and started his own FM radio broadcast network.

Sarnoff needed FM radio to transmit the audio signal with television so he simply stole the invention from Armstrong. Sarnoff, being able to hire more lawyers, was able to play the patent war both ways in his favor. His lawyers even convinced the court that RCA had invented FM, not Armstrong. Sarnoff also persuaded the FCC to force FM stations to broadcast on VHF frequencies at low power that restricted them to local broadcast. This prevented FM from ever being used by long-range stations like the 50,000 watt "clear channel" AM stations that are still scattered around the U.S. Ultimately Sarnoff won all the battles and ruined Armstrong. Armstrong, who loved to climb on high radio towers, ended his life by jumping out a 13 story window in 1954.

The transistor miniaturizes electronics

The bipolar transistor was invented in 1947 by Shockley and Bardeen while working at Bell Laboratories. In function, the transistor can be thought of as a "miniature triode vacuum tube." Unlike a tube, a transistor consists of a grain of semiconductor crystal with three wires attached. Like a triode, a control gate called the "base" allows a small current to control a much larger current that flows from the "emitter" wire to the "collector" wire. Unlike tubes, there is no vacuum chamber, no heated filament, no relatively high voltage, and no separate power supply needed to light the filament.

In vacuum tubes, the control grid of a vacuum tube must always be referenced to the negative pole of the circuit. That is, the grid is always operated at just a few volts different from the voltage on the filament (cathode). The vacuum tube plate potential is usually quite high, usually hundreds of volts, and is always positive polarity. In contrast, transistors can run on as little as one or two volts and can be built in two polarities. The control base can be referenced to either the negative pole, (NPN transistors) or the positive pole, (PNP transistors.) Because they are available in complementary designs, the two types can be used together to form compact, high gain circuits with fewer additional components such as resistors and transformers.

The first transistors were fragile devices called "***point contact transistors***" that never appeared in consumer products. (An attempt to build point contact transistors is described in chapter 4.) The first widely used transistors were made from germanium and not silicon. Early germanium transistors could only tolerate tiny power levels. For example, the 2N35 transistor would burn out if it dissipated more than 35 thousandths of a watt. In the 1950s they were sold

to amateurs for experimentation, but it was difficult to get them to work before they burned up. I bought one for $5 and promptly ruined it. Today that amount of money would be like $50 each. Then in 1960 the Texas Instruments Company perfected silicon transistors and the dominance of the vacuum tube was doomed.

Radio covers the globe

The Sony Company in Japan realized that silicon transistors presented a unique opportunity. They jumped on it and revolutionized AM radio. They made tiny battery powered "transistor radios" that cost a few dollars and fit in a shirt pocket. Because they didn't need power from the wall and the batteries were small and cheap, suddenly even the poorest people on Earth could afford transistor radios.

In the 1960s another type of silicon transistor, the Field Effect Transistor (FET) appeared. FETs are also three wire devices. The control gate of an FET is actually called the "gate" and the gate uses use tiny voltages, rather than tiny currents, to control the big current flowing from the "source" lead to the "drain" lead. Like bipolar transistors, FETs come in two polarities called "N-channel" and "P-channel." Today FETs are the basis of most integrated circuits used in computers, and as we'll see later, they are also valuable in radio circuits.

Becoming a ham radio operator

My serious shortwave listening began during the cold war. My big "all band radio" allowed me to tune the shortwave bands. This radio was three feet high, two feet wide and packaged in a beautiful wooden cabinet. But compared with a real communications receiver, this living room radio was extremely limited. It had poor selectivity and only covered a few ham bands. It had no "band spread" so the ham bands were about 1/8 inch wide on 4 inches of dial. On the other hand, it wasn't worthless. I was able to hear occasional AM phone conversations between hams. Later I bought a World War II surplus "morale radio." These were shortwave receivers that were issued to the troops so they could listen to broadcasts from home, Tokyo Rose or other AM modulated stations. Morale radios also had no "beat frequency oscillator" and could not receive Morse code without resorting to the second-radio-trick described earlier.

I learned Morse code in the Boy Scouts. One requirement for our Boy Scout First Class badge was to send and receive Morse Code using a signal flag. The flag was waved over one's head to the left for "dash" and to the right for "dot." Our Boy Scout manual admonished us to remember what the Dutchman said, "Dots right!" Today Boy Scouts don't have the Morse code requirement. That's a shame. In an emergency, the ability to communicate by tapping through a wall or waving across a canyon might not be a trivial skill. Prisoners throughout the world often communicate by tapping messages through walls using a universal code. The prisoners' code translates the alphabet into tapping where the letter "A" equals one tap, "B" equals two taps and of course "Z" equals 26 taps. Good Grief! I guess prisoners have lots of time on their hands.

Several of my friends were also interested in shortwave and we started a shortwave listening (SWL) club. For code practice my buddy Eric Raimy rigged up a telegraph system of buzzers that communicated between his bedroom, the downstairs hall closet and the basement. We three junior high students sat at our posts and talked with our slow Morse code until we got our speed up to 5 words a minute and could pass the Novice class ham radio test. We got our ham licenses with the help of a local school principal, Glenn Johnson, WØFQK.

If you wish to get a ham license, you need to find a local ham radio club in your area. Ham clubs generally conduct classes for new hams and give the license exams. Check the Internet for local clubs. Failing that, go to the American Radio Relay League website, www.arrl.org or (888) 277-5289. The ARRL will help you in many ways. They can provide you with study materials, magazines, books and people to contact in your area.

Ham radio in the last 80 years

Like electronics in general, amateur radio has exploded into many different facets since World War II. From a hobby that was originally Morse code, it has expanded into a long list of capabilities and activities. Each decade has added more and more variations in the ways and methods for amateurs to use radio technology. As a rule, new technologies were first demonstrated ten years before they became commonplace. Of all the ham modalities that have ever been used, only spark gap transmitters are completely extinct. However, AM phone is rarely used today.

1920's Continuous wave Morse code and early AM radio.

(Vacuum tubes and the end of the spark gap transmitter.)

1930's AM phone, Very High Frequency (VHF) 54 MHz and above.

1940's Radio Teletype (RTTY), VHF FM communication, mobile rigs in cars.

1950's Single Side Band Phone (SSB), amateur television, slow scan television (a kind of radio Fax). UHF communication, 220 MHz and above. Directional Beam Antennas.

1960's Amateur microwave communication. Easy to use SSB HF transceivers. Moon bounce and meteor bounce communication.

1970's Amateur Satellite communication, VHF/ UHF relay stations.

1980's hand-held transceivers. Computer station log keeping. AMTOR packet message handling (radio e-mail)

1990's Spread Spectrum communication, radio control and amateur rocket telemetry, robot stations, PSK-31 messages (computer instant e-mail), IRLP (Internet-connected VHF relay stations), QRP (low power) stations, and amateur radio radio-controlled models, TV on small rockets.

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From the point of view of variety of new equipment, amateur radio is booming. On the other hand, thanks to the Internet, fax machines and cellphones, much of this technology can now be used by people who have no license and no interest in how it works. However, some aspects of ham radio remain unique to this hobby and haven't changed. These are:

1. Morse code.

2. Exchanging QSL (contact confirmation) cards,

3. Homebuilding equipment.

4. Mastering new or exotic modes of communication, such as satellite relay or unusual signal propagation modes like moon bounce.

The future of ham radio frequency bands

The existence is ham radio as a hobby is totally dependent on our government allowing us to transmit. For this we need allocations of the frequency spectrum. But every day more and more commercial uses for wireless communication are being found. These applications are in two categories. Short-range communications, so called "Part 15 applications," transmit less than 100 feet. They link printers to computers, support cordless phones, open garage doors and unlock automobiles. Suitable frequencies can be low, say 1 Megahertz and below. Or they can use very high frequencies, 40 MHz and above. The high frequency (HF) range in between 1 and 40 MHz is not desirable for these applications because, when atmospheric conditions are right, signals from great distances, even the other side of the world, can trigger a local device.

For example, when the first Soviet Sputnik satellite was launched in 1957, it broadcast on 20 MHz. Every time the satellite went over the United States, many homeowners discovered their garage doors mysteriously cycling up and down. Through the use of selective receivers and digital coding, most of this kind of radio interference has been eliminated. But when the frequency bands become crowded with signals, even a sophisticated receiver will eventually be paralyzed by the interference and won't respond to the correct code.

Cell phones, global positioning and Internet links transmit over distances of a few miles or up to satellites to provide reliable communications. The best frequencies for these applications are above 40 MHz because random signals from the rest of the world usually won't interfere. At 500 MHz and above, signals from over the horizon will almost never interfere. These frequencies can be relied upon day and night for dependable communication. In the modern era it's these UHF and microwave frequencies that have the most commercial value. Hams have a few frequency bands in this high-value part of the spectrum. So far we have been allowed to keep them by sharing them with the military.

Thank goodness for the erratic nature of HF

Since 1930 the most important ham bands have been the HF frequencies between 1.8 and 29.7 MHz. The good news for amateurs is that it is the unreliability of these bands that makes them attractive to us and unappealing for commercial users. When we hams turn on our receivers, we really don't know what we're going to hear. There may be just static or there may be two local guys discussing their golf game. Or we might hear a ham in Mongolia looking for a chat. It's like going fishing. No telling whom you might catch! That's the fun of it.

Bad signs for the future

As ham radio equipment becomes more complex, fewer and fewer hams understand how it works. It's fair to say that the majority of hams today are overawed by the complexity of the equipment they use and no longer make a serious attempt to understand it. As a result only a tiny minority attempt to build their own. FCC licensing for hams reflects this trend. As fewer hams build their own equipment, ham radios have become just another form of consumer electronics. The FCC has become more concerned about manufacturers building fool-proof equipment than it is about hams understanding their equipment.

Forty years ago, the radio license exams were administered directly by the Federal Communications Commission. The tests were devoted to the technical details needed to be sure hams knew how to keep their homemade transmitters operating within assigned bands. The

privilege of using all the ham frequencies was only granted to the best-trained hams. They had to demonstrate 20 words per minute Morse code speed and take a complex test that included drawing circuit diagrams of various kinds of transmitters and calculating design parameters. Today code speed for the highest class of license, Extra Class, has been reduced to just 5 words per minute. The tests are now multiple-choice exams given by ham volunteers. In preparation for the exams, modern hams study the tests, rather than the material covered by the tests. In terms of engineering knowledge, the modern ham is a lightweight compared with hams 50 years ago.

Another alarming sign is that the number of ham radio operators is relatively fixed and the average age of hams continues to rise. It's a logical conclusion that eventually our frequencies will be taken away for lack of interest. Ham radio will have become another historical pastime in the same category with quilting-bees and buffalo hunting.

The latest threat to ham radio is the broadband power line initiative. Power companies wish to make money by using power lines as Internet connection conduits into every house that receives electricity. Unfortunately the power lines would leak this radio noise into the sky and produce a strong buzz of noise that would obliterate all weak to moderate radio signals between 2.0 and 80 MHz. This radio noise would be an end to nearly all ham radio and shortwave broadcasts.

Mastering the technology

As civilization's technology becomes more sophisticated, the knowledge base among our population becomes more and more fractured. Although the amount of knowledge that individual educated people have in their heads may be the same, each citizen knows more and more about less and less. Operating modern ham radio transceivers resembles operating a complex VCR. Yes, the equipment can handle all the modern modes and frequencies. But first you must read the manual and push 48 buttons to select all the right menus and options. It's not easy to operate one of these do-everything wonders. But when you've succeeded, you really haven't learned much about electronics.

Modern transceivers remind me of integrated circuits. Transceivers are packed with dozens (or hundreds) of integrated circuits containing perhaps several million transistors. Like the transceiver as a whole, an integrated circuit cannot be fixed, its contents are mystery and it is usually a black, rectangular solid with "feet" or leads. Even with the service manual of a modern radio transceiver in front of you, it's hard to get more than a general idea of its block diagram and how it works.

But surely the engineers who designed these wondrous modern radios know how they work! No, not really. Yes, maybe there are a handful of engineers in the world who have a good grasp of all the technologies in a modern transceiver. But I wouldn't bet on it! Each engineer specializes in assembling or programming modules that are bought from other factories. The modules are sealed and can't be repaired. Exactly what's inside those modules is probably as much a mystery to them as it is to the rest of us.

Over the last century, a radio operator's span of knowledge has continued to shrink. A hundred years ago, the early radio pioneers were not only on the air testing radios, they were also working on the materials to build the components for their radios.

Cell phones, Citizens band ———→ ◄— How to operate radio

Ham Radio Year 2000.

Ham license

20 wpm to 5 wpm in 2000.

learn code

Ham kit building. Routine for major kits as late as 1985.

Align & test

Solder in parts

Make circuit board

Ham homebrewing skills. Routine as late as 1950 .

Chassis construction

Circuit prototype & test

Circuit and software design

Radio pioneer skills. 1870+

Manufacture of radio components.

Manufacture of raw materials, wire, magnets, etc.

Extraction of useful mineals from rocks.

Transportation of ores to smelter at reasonable cost.

Mining engineering - How to extract ores.

Geology - Identify useful minerals.

Knowledge of geography - Locate the mineral deposits.

This trend can be illustrated by a "technology pyramid" for ham radio technology. At the very top of the pyramid is the knowledge of how to operate a two-way radio. At the bottom of the pyramid is the prospector who explores the wilderness and first finds the raw materials needed to make a radio and every other modern technology. In middle are the skills needed to build your own radio equipment.

One way to look at the change is that ham radio has slowly retreated up the pyramid to become just another consumer product like TVs and cellphones. Most hams argue that ham radio can do more things than ever and is therefore more interesting. We can transmit live amateur television, e-mail message nets, and faxes. Fortunately or unfortunately, the same technologies are becoming available to ordinary folks without licenses. Why bother with ham radio?

Homebuilt ham radio and the "QRP"

Building your own radios is commonly known as "homebrewing." Up until World War II, ham radio was homebrewing. In the early days decent radio equipment was barely available and during the depression it was unaffordable to average people. If you couldn't build your equipment yourself, you probably couldn't afford to get on the air. In this respect a little poverty isn't always a bad thing. When life is too easy, it becomes boring.

Up until 1950, homemade ham equipment was routine. After that time, building transmitters at home remained common only among the young and impoverished. Good communications receivers were the hardest to build, so homemade receivers were the first to go. In the 1950's and 1960s pre-fabricated, well-designed kits from companies like Heath and Allied Radio replaced the homebuilt equipment. To have good, usable equipment, all you had to do was solder it together. Finally in the 1980s the kits became so complex, the kit companies wouldn't

let us do more than solder prefabricated assemblies together. When that happened, the kits became so boring that they disappeared altogether.

Today there is a growing interest in building low power "QRP" transmitters. The majority of QRP hams are once again building kits. A few modern pioneers are building them from discrete parts. One branch of this hobby builds transmitters in sardine cans to emphasize the small size of the transmitter. Another group uses metal "Altoid" candy boxes that are even smaller. In any case, QRP is the brightest hope our hobby has in remaining technically competent and attractive to young people.

CRYSTAL SETS TO SIDEBAND

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CHAPTER 2

HOME-BUILDING AMATEUR RADIO EQUIPMENT

What qualifies as "homebuilding?"

The ultimate homebrewer would be a guy that walks off into the wilderness stark naked. Then, using rocks and sticks, he builds a high tech communications system. Hey, don't laugh! Our ancestors did it. Of course, they had to stay out in the woods for thousands of years to finish the job. Our ancestors were smart, hard working folks. From our lofty position today it's easy to look down on them as some sort of blue-collar, country bumpkins. Ironically, country bumpkins are often more than they appear. In my opinion, today's family farmers are masters of a wider range of technology than any other group of people in our society. Farmers today can't afford to hire others to repair their old equipment, so they have mastered skills from electrician to biologist. Most farmers today have talents and knowledge that make the rest of us look like specialized robots on an assembly line.

Building your own radio equipment is fun and gives you the satisfaction that comes from mastering knowledge. Homebuilding doesn't need a precise definition. If you're having fun and learning something, just do it! You should feel free to invent your own definition. However, the more levels of the technology pyramid you master, the bigger your achievement. Besides, buying ham equipment is like skipping school and buying a diploma. You get the same privileges, but the result will be empty in many ways. My personal definition of "homebuilding" is that I build my own equipment starting from simple components that (I believe) I understand.

I try never to buy equipment or subassemblies specifically designed for amateur radio. I am proud to be the bane of most of the advertisers in ham radio magazines. I still buy individual electrical components, of course. I just pretend that the electronics industry never got around to inventing radio communications.

One of the ironies of our hobby is that, when the few remaining homebrewers retire from their day jobs, they often build and sell ham radio equipment. These industrious guys manufacture and sell every imaginable ham gizmo. I doubt any of them have noticed that, by making everything readily available, they have discouraged homebuilding.

When is homebrewing NOT appropriate?

Homebuilding should not be done as a way to save money or procure modern equipment. Modern multiband, HF ham transceivers are amazingly cheap. You should be able to buy a good used high frequency SSB transceiver for as little as $500 - $1000. The good news is that our society is so prosperous that parents can often afford to give kids toys costing hundreds or even thousands of dollars. The bad news is that the economic incentive for young hams to build their own has almost vanished. Also, if you do build your own, even the most skilled homebuilder will not have enough years to build a truly equivalent, modern amateur radio station. The commercial units contain custom integrated circuits, custom cabinets and are the end result of multiple prototypes and exhaustive testing.

Homebuilding with vacuum tubes

40 years ago hams built reasonably good transmitters and receivers in their basements. A well-built homebrew could cover all the high frequency (HF) bands (1.8 to 30 MHz). Best of all, its signal didn't embarrass you on the air. Homebrew CW and AM phone were routine. On the other hand, homebrew single sideband phone (SSB voice transmission) has always been rare because SSB is complex to generate.

Circumstances have changed. If you could examine the complete schematic of a modern ICOM, Kenwood or Yaesu transceiver, you will need a microscope to read it. Of course if it's an "F" size drawing, you might be able can read it OK, but the schematic wouldn't fit on your living room floor. In contrast, the schematic for a 1970 all-band, CW/ AM phone ham transmitter, complete with parts list, fits comfortably on one page of a ham radio magazine. In short, modern stuff is complicated. If they were just made of "little vacuum tubes," it would still take hundreds of times longer to build them. But there are more differences.

Frequency stability

Nearly all hams today are using transceivers designed around precise, digital frequency synthesizers. The frequency is digitally displayed on a little screen to precision as close as 0.1 Hz. The numbers on the readouts may not be that accurate, but the average guy believes his dial is accurate because he hasn't actually read the specifications. For example, stability might typically be specified to 1 part in a million. So on the 10 meter band, 28 Megahertz, the precision of the display might be 0.1 Hz, but the guaranteed accuracy might be +/- 28 Hz. However, if the commercial equipment is reading an error of 28 Hz, it is still probably much more stable than a typical homebuilt oscillator. Consequently, when a homebuilt transmitter goes on the air and drifts more than about 20 Hz, it isn't long before the criticism begins.

Today if a homemade transmitter frequency drifts like *typical* rigs of 40 years ago, the complaints will probably drive that ham off the air. In my limited experience, typical vintage ham transmitters from 30 or 40 years ago are likely to transmit poor quality signals that will provoke lots of complaints. On the other hand, if you are using top-of-the-line, best-quality, 40 year old equipment, then the signal quality is likely to be acceptable. Chapter 14 illustrates the effort needed to build old-fashioned equipment suitable for use on the air today. Yes, it can be done, but with such high standards, it's a challenge to make those old parts perform like modern equipment.

Lead Inductance

Another barrier to homebuilding transmitters today is "***lead inductance***." The problem is that simple wires act like coils. They resist AC currents when the frequency becomes high. When the currents are tiny, like those used in 1960-era ham transmitters, this problem isn't severe. However, most modern transistorized transmitters run on 12 volts. Since 12 volts eliminates most of the power supply complexity, this sounds safe and easy. For operation in a vehicle, you don't even need a power supply, you just run it directly off the battery using the cigarette lighter outlet. In an old vacuum tube transmitter, the plate voltage ranged from 500 to 2000 volts or even more. 12 volts DC supplies are safer and sound like good news.

Unfortunately, if your power supply is only 12 volts, the currents in your transmitter will be 50 times higher for the same amount of power. Therefore the voltage drop across lead

inductances will be 50 times higher. Suddenly each component in your circuit acts as if it has an inductor (high resistance to radio frequency current) in series with it. These unwanted inductors cause the transistor stages to self-oscillate, or simply to produce no power gain. The bottom line is that it's much harder to build transistorized transmitters.

The solution to the inductance problem is ***printed circuit boards*** and very short leads between the components. This means that the craftsmanship needed to build a transistorized transmitter is higher than we needed with vacuum tubes. Without carefully limiting your goals, and without working within your knowledge and time constraints, the decision to homebrew, can lead down a long road of frustration.

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BASIC ELECTRICAL KNOWLEDGE

The first challenge in building radio equipment is acquiring the technical know-how. There are many ways to learn basic electronics. The American Radio Relay League (ARRL) Amateur Radio Handbook is published every year and has (nearly) everything you need to know. This large volume covers all aspects of the hobby. Unfortunately, its size is overwhelming for many readers. Also, so few hams build their own equipment today that serious homebuilding has been de-emphasized in the Handbook. In fact, if all you had were the handbook, you would probably conclude that building your own equipment is totally impractical. A goal of my book is to help restore homebuilding to the role it once held in Amateur Radio. This chapter introduces the minimum knowledge you need to get started. If you have trouble grasping the perhaps overly simplified explanations in this book, read about the same topics in the ARRL manual and other texts.

Much of the following is written in a "Dick and Jane" fashion that ignores many of the fine points. For example, if I say, "***all circuits are complete loops***," a purist might bring up unusual situations in which this doesn't appear to be true. However, it's important to have some simple, bedrock concepts to fall back on which will usually serve you well. "Rules of thumb" are essential to keep your reasoning organized. However, keep your mind open to exceptions, because you'll encounter lots of them. When you do find exceptions, don't throw out the basic rules of thumb. They usually work well and will keep you sane.

I only use math when it is essential to do the job. A serious problem with engineering schools is that engineering professors are selected from the 2% of the students who naturally think in terms of math. So after graduation, the math geeks are the guys who hang around to educate the next generation. The students who think like "normal people," go out in the real world to build things that work. Actually, the majority of engineers are so disenchanted by the obsessive/compulsive, math-mumbo-jumbo, they go into management or sales.

Learn a qualitative understanding first

By concentrating on math, professors often fail to teach the basic concepts of how electricity works. A friend of mine, John Anderson, taught third year electronics engineering. He was discouraged to discover that most of his students could cover a blackboard with equations, but couldn't bias a light emitting diode or predict the voltage on the collector of a saturated transistor. Any good technician or experienced ham can do these tasks with hardly a

4. Chapter 2, Harris

thought.

As John said, "Engineering is like learning to paint a picture. First you need the skill to paint a horse so it looks like a horse and not like a house. It's not important for most painters to be able to calculate the physical chemistry of paint pigments. Those skills are only important to a few specialized members of the art community."

Personally, I worked for decades as a real engineer, but my methods are primarily qualitative. I only use simple math that I completely trust. One day I was working on a project with John Anderson when he turned to me and said, "You spent four years in engineering school and all you learned was that math doesn't work and shouldn't be trusted." I am ashamed to admit he's right. Once I got into the real world, I spent too many months calculating random, useless numbers on paper. Eventually I learned to work primarily from experience and intuition. In other words, I work like a radio ham! I'm making this confession to emphasize that when I use formulas and math, it is important stuff and you won't be able to avoid using it.

In case you believe that building radios in your basement is just idle entertainment, consider this: During my four years in the Air Force my job title was "electronics engineer." I did my technical work entirely with my ham skills. No one ever asked me to write equations. All they wanted from me was a working power supply by Thursday, a working radio control link, a static electricity protection circuit, or whatever. If I had not been a ham, I suppose the Air Force could have found some kind of paperwork for me to do, but I would not have been able to complete the tasks I was originally assigned.

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MAGNETIC AND ELECTRIC FIELDS

Magnets - an everyday physical force generator

I never get tired of playing with magnets. Other than Earth's gravity, magnets are the most common devices in our everyday world that allow us to experiment with a physical field. An invisible force from the magnet reaches out and grabs paper clips or thumbtacks from a quarter inch away or more. Playing with two magnets is even more interesting. One magnet can attract another, the same way a magnet attracts steel. But when you reverse the direction of one of the magnets, the magnetic force acts as a "repeller" pushing the other magnet away or causing it to spin 180 degrees to the opposite polarity. After it has been reoriented, the second magnet jumps toward the first magnet.

Playing with magnets gets us accustomed to the idea that a magnetic field may be generated by a physical device. We also observe that ***a magnet field is a short-range phenomenon.*** With small magnets the field only seems to be effective for a quarter of an inch or less. With such short range, refrigerator magnets don't seem promising as a starting point for long-range communication.

The magnetic field from a permanent magnet arises from the individual atoms that make up the magnet. Each atom has electrons that orbit around the nucleus. These electrons resemble electrons passing around the coils of an inductor. Unlike the electrons in ordinary atoms, the electrons of iron and other magnetic atoms orbit the atoms aligned to at least a small degree. In contrast, ordinary atoms have electron orbits that race around the entire atom in perfectly

spherical shells. Ordinary atoms generate magnetic fields too, but there is no alignment and the fields cancel.

Electric fields are also common in our everyday world, but the effects are usually subtle. During the winter at northern latitudes the humidity in our houses drops and static electricity discharge often startles us when we grab a metal doorknob. Like the magnet, static electricity can move lightweight objects a short distance. It can make non-conductors stick together, or even repel them. Unlike magnets, the objects affected by household electric fields must be featherweight items, like lint or hairs. Static cling in our clothes is an example of oppositely charged materials attracting each other, just like the magnets. In contrast, petting the cat may make the cat's hair stand on end. When hair stands on end, each hair is repelling the hairs around it. Moreover, a bit of humidity makes the phenomenon vanish. Because the effected objects are so lightweight, static electricity seems pretty minor. For both magnetic and electric fields these everyday phenomena seem to be strictly short range.

WHAT IS ELECTRICITY?

Electricity consists of electrons flowing through conductive materials. Some physicists might jump in now and start lecturing about holes flowing through P-type semiconductor or chemical ions migrating through electrolytic solutions. But let's forget about exceptions for now. It's easier to visualize current flow as electrons.

Electrons are a form of "charge." "Charge" just means an excess or lack of electrons that gives rise to an electric field. When charge is gathered together in one place, it establishes an electric field with respect to nearby objects that have an opposite charge, or just have less of the same charge. If a conduction path is established between the two objects, the electric field becomes a ***voltage. Voltage is the force that pushes a current flow*** from one object to the other until the charges are equal.

Electrons have a negative charge. The word "negative" is arbitrary. It is just a word and could just as well have been called "George" or "Napolean." The opposite of negative charge occurs when an object has lost electrons and needs to replace them. An object with a dearth of electrons is said to have a "positive charge." When the electrons are given the opportunity to travel, they will flow from a negatively charged region to a positively charged region at (nearly) the speed of light. "Positive current flow" is usually taken to mean current flow from positive to negative. In other words, positive current flow is the direction opposite to the flow of electrons.

One outer
Electron

Four outer
Electrons

Six outer
ELectrons

copper
Metal conductor

silicon
Semiconductor

Sulfur
Insulator
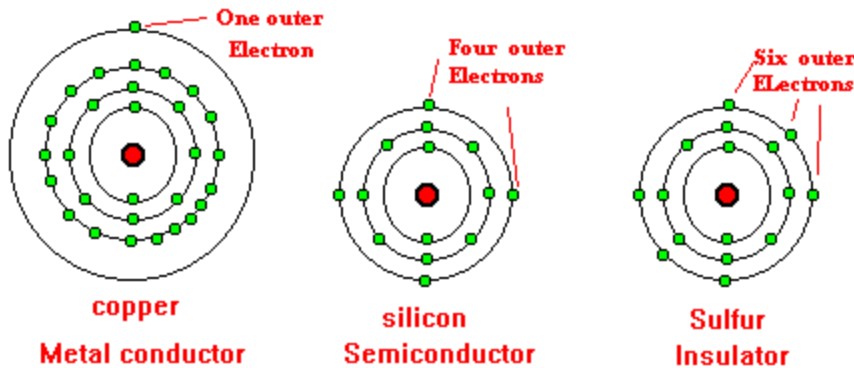
Metal Conductors

Materials that allow electrons to travel are called "electrical conductors." Electrical conductors are usually metals. If you remember your chemistry, metals are on the left side of the periodic table. Metals have an outer electron shell with 1, 2,3 or 4 electrons. As you may recall, 8 electrons are needed to complete a stable outer electron shell in most elements. The outer electrons orbiting metals are not tightly bound to their atom and these electrons can be easily lured away. In a piece of metal the outer electrons wander away from their home atoms and move over to neighboring metal atoms. These roaming electrons form an electric current. For example, copper has just one outer electron. When one considers price, weight, conductivity, ductility and corrosion characteristics, copper is the best available metal for making wires.

Insulators

The atoms on the right side of the periodic table the electron shells are filled with 8 electrons or are nearly filled with 5, 6 or 7 electrons. These atoms do not have loose electrons, but they easily accept loose electrons to complete their shells. In this way, insulators take free electrons out of circulation and prevent current flow. These elements are inert gases and materials like sulfur and phosphorous which are poor conductors. Non-conductors are called *insulators* and are vital in electronic circuits to confine the electric currents in the intended pathways. For example, sulfur has six electrons in the outer shell and is a crystalline electric insulator. All the lighter elements with 7 and 8 outer electrons are gases. In practice insulators are usually compounds made from two or more atoms with four or more outer electrons. For example, ordinary silicon-dioxide glass is made from silicon with 4 outer electrons and oxygen with 6 outer electrons.

Semiconductors

Just to the right of center in the periodic table are the *semiconductors*. Semiconductors, such as silicon, germanium and carbon have a valence of 4. That is, they have half-stable outer electron shells. If enough voltage is applied, electrons can be forced to leave a semiconductor atom and the semiconductors can act like conductors. Or, if the missing 4 electrons are supplied to the atom, it can become a temporary insulator. This ambivalent nature is exploited in semiconductors to make electronic switches and diodes that can be turned on or off. In addition, combinations of semiconductor elements have other surprising properties. Silicon solar cells turn sunlight into electricity. Light emitting diodes turn electricity into light. Other types of

simple semiconductor devices detect magnetic fields, detect gamma radiation, regulate voltage and serve as reset-able circuit breakers. Needless to say, complex matrix arrays of semiconductors are also manufactured into entire computers on a chip or visual displays.

Ordinary, amorphous carbon like charcoal is a poor conductor, not a semiconductor. But when carbon is crystallized into graphite it becomes a semiconductor. Unfortunately, graphite is too heat sensitive be used for transistors. Mixtures of silicon and carbon are used successfully in blue LEDs. In theory, carbon in the form of diamonds might make superb high performance semiconductors. In practice, this has been difficult and hasn't happened yet.

Some semiconductors are made from mixtures of lightweight elements with valences of 3 and 5 that give an average valence of about 4. For example, all light emitting diodes are made of mixtures like this and use a wide variety of elements. As examples, LEDs are made from silicon carbide, indium phosphide, and gallium-aluminum-arsenide, and aluminum-indium-gallium-phosphide. These produce red, green, yellow, blue and even infra-red "colors."

High atomic weight elements make poor semiconductors and insulators

The neat relationship for properties of elements breaks down at the bottom of the periodic table. Heavy elements like lead and tin have 4 electrons in the outer shells. Their location in the table suggests that they should be semiconductors. However, when they react chemically, they usually just lose 2 electrons, not 4. They are good electrical conductors and their physical properties resemble zinc or copper, rather than carbon or silicon.

Arsenic, antimony and bismuth should be insulators since they have 5 electrons in their outer shell. But as the atomic weight rises, they look and act less and less like crystalline insulators and more and more like heavy metals. Bismuth is a good electrical conductor that closely resembles lead. It wasn't fully recognized as being different from lead until 1735. All the elements heavier than the inert gas radon are conductive metals, regardless of their outer shells.

Circuit Loops
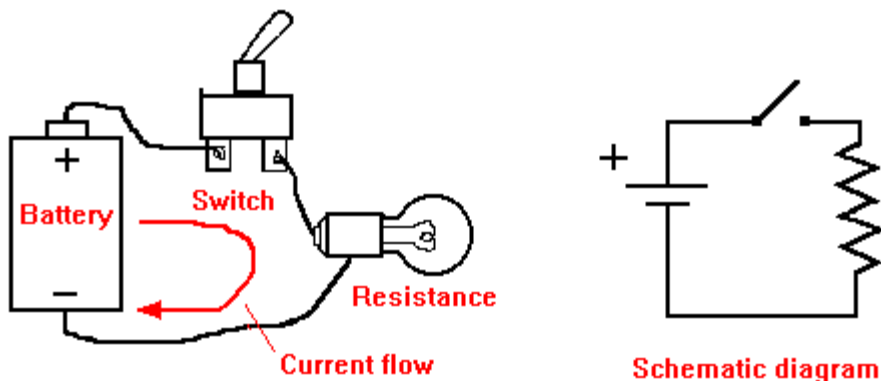
All circuits are in complete loops. Electrons must flow in complete circles or no work is accomplished. ***Voltage is the force that pushes electrons around a circuit.*** Voltage by itself does nothing. Only when voltage is able to push electrons through a complete circuit, does anything happen. For example, unscrew a light bulb while it's glowing. The light is extinguished because the current no longer passes through the bulb. That was obvious, but notice that current doesn't jump across the terminals inside the bulb socket and it doesn't leak

out into the room. There's still plenty of voltage across the light socket terminals. You could put your finger in the socket to test it, but current would flow through your finger and, with household voltage, that is a very poor idea.

Voltage = Electrical Pressure

Voltage, electrical pressure, is measured in **VOLTS**. As you know, an ordinary flashlight battery has about 1.5 volts of electrical pressure. Household power has about 120 volts pressure. You already know that handling 1.5 volts is harmless to people, while handling a hundred times that much is dangerous. Sticking your fingers in light sockets can be fatal. If there is enough voltage present, voltage can push an electric arc right through thin air. This feat requires about 30,000 volts per inch of air. If you're interested, you may calculate the voltage needed to generate a typical thunderbolt during a thunderstorm. Hint: This will be a really big number.

Current = The Flow of Electric Charge

Current could be measured in terms of electrons flowing through a circuit per second but that would be unwieldy. Instead, current is measured in **AMPERES.** An ampere is defined as a coulomb of electrons flowing through a wire in one second. One coulomb equals 6.242 billion-billion electrons. Enough. Let's use amperes! In ham radio, currents larger than an ampere are only common in transmitters. The currents delivered by 12 volt power supplies usually get up into the amperes. However, most ham circuits found in receivers or signal processing deal with currents measured in milliamperes and microamperes.

One milliampere = 1/ 1000 of one ampere.

One microampere = 1/ 1,000,000 of one ampere (one millionth of an ampere.)

Faucet provides water
AND water pressure

Flowers need
water to grow.
Pressure does nothing
for the flowers directly.
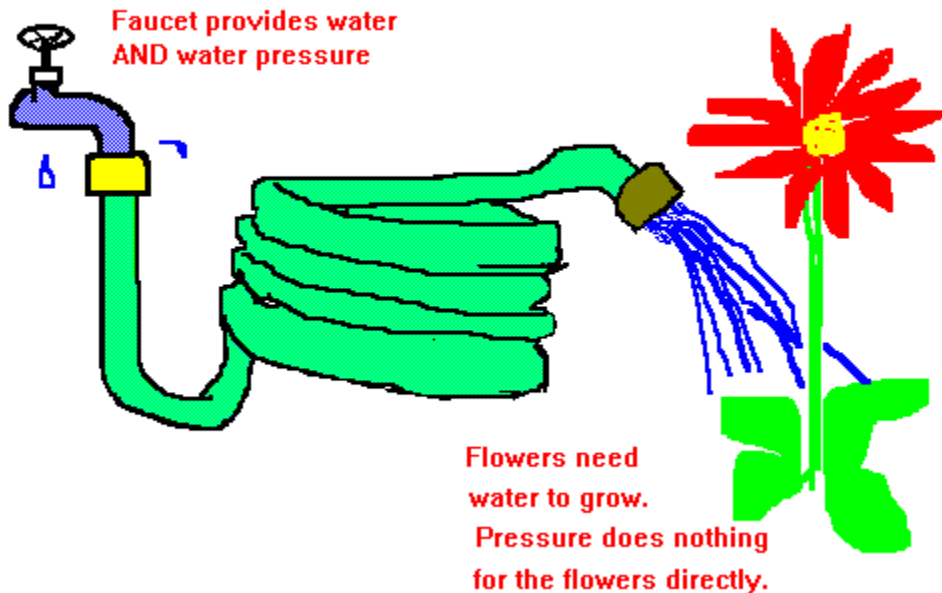
Many people have trouble keeping voltage and current straight in their minds. To the average guy electricity is zappy-shocking stuff. Maybe the following will help. Voltage is

analogous to water pressure while electric current is analogous to water. A simple way to remember this is that you can't water flowers with water pressure. Alternatively, there can be lots of water in the reservoir, but pressure is needed to push it through the hose to the flowers.
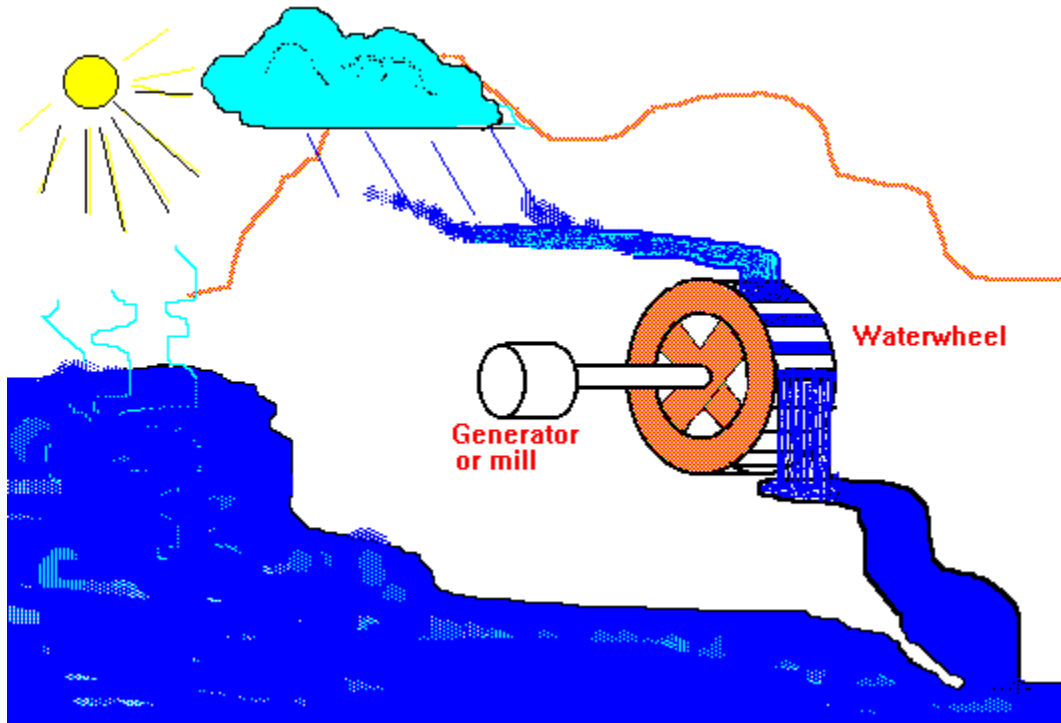
Water falling as rain and flowing from the mountains down the rivers produces a cycle that is reminiscent of a complete electrical circuit loop. Sun shining on the ocean causes evaporation that raises the water up above the mountains where it again falls as rain. In other words, the sun's energy is the "battery" that keeps the cycle going. Lifting the water into the air literally raises the potential energy of the water. Rain gathers as mountain streams and rivers that can flow through dams on the way back to the ocean. The falling water imparts its gravitational energy to the water wheel in the dam, thereby doing useful work. In other words gravity provides the water pressure.
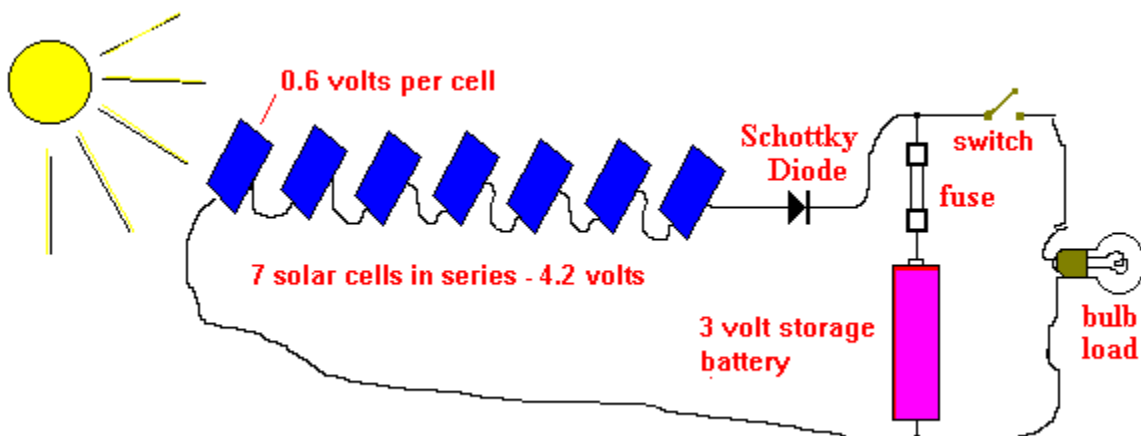
Solar cells are devices that are the electrical equivalent of sunshine raising water vapor to high potential energy through evaporation. In a solar cell, sunshine provides the energy to "boost" electrons up to a higher energy level. In practice, each solar cell generates just 0.6 volt of potential. So, in order to charge a 12 volt car battery, at least 20 solar cells must be placed in series so that the electrons can be boosted up to 12 volts.

Power = the rate of doing work

The rate at which the water wheel does work is its "power." ***Power is defined as energy produced or expended per second.*** In ham applications power is usually measured in watts. Watts are defined as joules of energy per second. ***Joules*** are occasionally used in ham work when designing coils or figuring out how big a capacitor should be. However, you won't need them very often and they aren't needed to get through this book.

The amount of energy that can be extracted from falling water equals the volume of water times the height it falls. Notice in the water wheel above, the water is only pushing the wheel around for the upper half of the diameter of the wheel. The rest of the descent is wasted. Not very efficient as drawn.

Power = Height of fall (water pressure) x   amount of water falling (current)

In electricity the relationship is the same:

Power = Voltage (electrical pressure) x Current (electrons doing work)

$$P = V \ x \ I$$

Where "I" is electrical current. "I" is the letter used by engineers to represent current. No, I don't know why. Maybe it's because "C" usually stands for electrical capacitance or the speed of light.
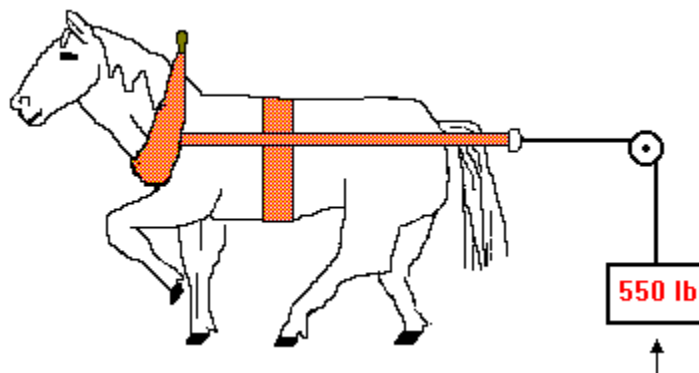
To put watts in familiar terms, power was probably first described in terms of equivalent working horses. When expending energy, objects such as ore are often lifted from a mineshaft. Pulling on pulley mine hoist, a typical horse might lift 550 pounds each second. This was defined as one horsepower. It turns out that:

746 watts = 1 horsepower = 550 pounds lifted each second.

Resistance

In the water cycle analogy above, the rain falls in the mountains then makes a long

journey of days back to the sea. This long journey is analogous to a high electrical resistance. In contrast, if the rain fell directly into the sea, the journey would take only a minute or two. This "short circuit" journey would be analogous to a LOW electrical resistance.
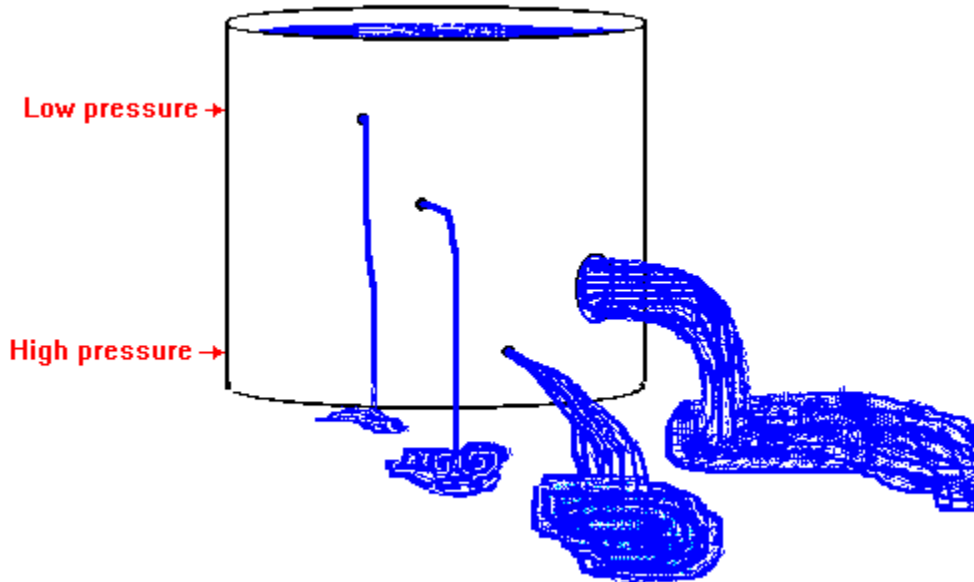
Good water analogies for electrical resistances are narrow water pipes and wide water pipes. For example, suppose a large water tank is suddenly punctured by small bullet holes and large holes the size of a melon. Obviously the water rapidly flows out of the tank, especially the water coming out of the big holes. The speed at which the water leaves depends on the size of the hole and the water pressure. The water pressure is much higher at the bottom of the tank than it is at the top. Therefore, water leaving from a hole at the bottom of the tank squirts out at considerable pressure, while at the top of the tank it just dribbles out slowly.

Ohm's law

Voltage is analogous to water pressure and current is analogous to water flow. Resistance is measured in ohms. The ohm is named after the Georg Simon Ohm. The relationship between these parameters is described by Mr. Ohm's law, which says that one volt will drive one ampere through one ohm resistance.

Voltage = (current) x (resistance)

In electrical formulas V = voltage and R = resistance. Ohm's law is written as

$$V \;=\; I \; x \; R$$

If you know any two of these three parameters, you can find the missing value with algebra. Rearranging the letters we can have:

V = IR or **I = V/ R** or **R = V/ I**

Sorry about the math, but this relationship is unavoidable for anyone who wants to succeed with electricity.

For example: You know that household electric current operates at 120 volts. Suppose that you measure the current through a light bulb and measure it as 0.833 amperes. What is the resistance of the light bulb?

120 volts = (0.833 amperes) X Resistance

Resistance =   Voltage / Current.

Resistance =   120 volts / 0.833 amperes = 144 ohms

The symbol for ohms is usually the capital Greek letter Omega, Ω.   For example, 144 ohms might be written as "144 Ω."

Resistors in series

When current must pass through two or more resistors in series, the total resistance is equal to sum of the resistors.   For example, two 100 watt light bulbs in series will present twice as much resistance as a single bulb:

Voltage = 120 volts = 0.417 ampere x (144 ohms + 144 ohms)

Because the current must pass through twice as many obstacles, the current flow is half and the bulbs will only burn dimly, if they light at all.

A voltage divider made from resistors

A common use for resistors is to reduce DC or AC voltages. Two resistors in series make a voltage divider. This is analogous to the remaining potential energy of the rainwater after it has returned halfway back to the ocean. In the light bulb example above, the voltage across one of the two light bulbs in series will be 50% of the total. In other words, the voltage will be reduced to 60 volts AC. In the DC electronic circuitry is it common to reduce a voltage to bias a transistor or to control the voltage across a light or other application. The more current required at the lower voltage tap point, the lower the resistances must be to support the extra load at the reduced voltage.

In the example below 10 volts AC is divided to produce 5 volts AC. This same resisitive divider could just as well divide 10 volts DC down to 5 volts DC. You'll see shortly that there are other ways to make AC voltage dividers and that is why the odd value of "530 ohms" was used in this drawing.

10 volts RMS
60 Hz sinewave
input

530 ohms

5 volts RMS
60 Hz sinewave
output

530 ohms
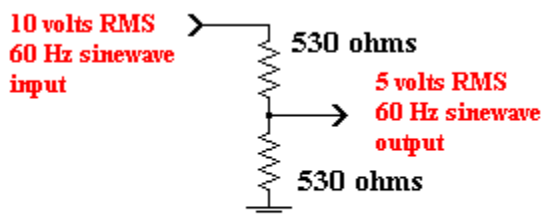
A Voltage Divider Made from Resistors

Resistors in parallel

When two equal resistors are placed in parallel, the resistance seen by the voltage source

will be half as much as if there were one resistor. This causes twice as much current to flow. In the case of light bulbs, when you turn on twice as many lights, the current flow doubles, all bulbs burn equally brightly and your electricity bill doubles.

When the parallel resistors are equal in size, the current they will draw is intuitively obvious. That is, each resistor receives the same current. But when the resistors in parallel are all different, then you will need to calculate the equivalent resistance using the formula:

Resistance equivalent = $1/(1/R_1 + 1/R_2 + 1/R_3 + …..etc.)$

The equivalent resistance is the inverse of the sum of the inverses of the resistances.

If there are just two resistors, then the formula is slightly less ungainly, but perhaps harder to remember:

Resistance equivalent = $R_1 x R_2 / (R_1 + R_2)$

For example, suppose a 50 watt light bulb with a resistance of 288 ohms is in parallel with a 100 watt light bulb with 144 ohms resistance. The equivalent resistance would be:

Resistance equivalent =   (288 ohms x 144 ohms)/ (288 ohms + 144 ohms)

Resistance = 96 ohms

Batteries

Batteries are analogous to water tanks.   A really large battery, like a single battery cell used in a submarine, can have a huge capacity and may be able to supply hundreds of amperes for hours. But in spite of its great size, it might only be able to supply two volts of electrical pressure. In a submarine there might be a hundred or more of these huge cells in series to supply 200 volts to the electric motors. In terms of analogous water tanks, a low voltage battery might be equivalent to a large cattle watering tank, perhaps twenty feet wide but only one foot deep.

A car battery is the biggest battery most people ever see. Notice that, in order to start the car on cold mornings, the battery must delivers hundreds of amperes for a few seconds. It does this through LARGE copper wire cables. These are the thickest electrical wires under the hood. If you tried to use thin wires for this load, the wires would melt in seconds. How much power does it take to start your car in January?

Power = 12 volts x 200 amperes = 2400 watts

or,   Power = 2400 watts / 746 watts/ hp = 3.2 Horsepower.

In contrast, an ordinary 9 volt alkaline transistor battery has six 1.5 volt tiny cells in series for a total of 9 volts. Each cell is only rated at delivering about 1/2 ampere (550 milliamperes) for one hour. In terms of power, this is about 4.5 watts.

Power = 9 volts x .55 amperes = 4.5 watts

Notice that a little battery with several cells in series would be analogous to a tall water tank with low volume. For example, suppose a pump is located at the bottom of well one hundred feet down. The pipe might be only an inch in diameter. Therefore a hundred feet of this pipe will only contain a few gallons. But the pressure at the bottom of the pipe will be huge, 123 pounds per square inch. In municipal water systems the water is stored in big tanks up on towers to provide both water pressure and a large reserve of potential water flow.

Electrical conductors are comparable to holes punched in the water tank. Fine wires have higher resistance than fat wires made of the same material. Metals like copper and silver have such inherently low resistance that this difference isn't so obvious. But in a conductor like carbon, a fat stick of carbon will have far less resistance than a thin fiber of carbon like the fibers Edison used in his first commercial light bulbs.

Electrical Power

What is the power consumed by the light bulb? Or more familiarly, what is the light bulb "wattage?"

$$Power = Volts \ X \ Current$$

$$Power = (120 \ volts) \ X \ (0.8333 \ amperes \ ) = 100 \ watts.$$

Another way to calculate power is often useful when the voltage isn't known:

$$Power = Resistance \ X \ (Current)^2$$

$$P = I^2 \ x \ R$$

Substituting for voltage from above,

$$Power = (Current \ x \ Resistance \ ) \ X \ Current$$

$$Power = Resistance \ x \ (Current)^2$$

Or, if you only have voltage and resistance,

$$Power = (Voltage)^2 / (Resistance)$$

$$P = V^2 \ / \ R$$

For example, $100 \ watts = (120 \ volts)^2 / 144 \ ohms$

Capacitors

Capacitors are devices that store electric charge, much like a battery. Capacitors are usually made from two parallel plates of conductive metal separated from each other by a thin layer of insulation. The insulation can be air, paper, plastic, mica or even vacuum. When the two plates are connected to the poles of a battery, charge rushes into the capacitor by means of wires. Since positive charge is attractive to negative charge, the charge gathers on the plates as if it were "trying" to jump across the gap. Because the voltage from the battery has established the same uniformly voltage across the plates, the charge gathered on the plates of the capacitor will maintain that voltage, even after the battery is disconnected from the battery. The charge is held on the plates by the force of attraction from the opposite plate.

If a charged capacitor has high quality insulation that doesn't leak charge across the gap, the capacitor will store energy in the form of trapped charge indefinitely. For example, large, low voltage capacitors are sometimes used to maintain computer RAM memory when the rest of the computer is turned off. However, with present technology capacitors rarely seriously rival electrochemical batteries as a long-term energy source.

Positive charge
(lack of electrons)
gathers on postive
plate.

Battery

Switch

+ + + + + + + + + + + +
= = = = = = = = = = = =

Electrons gather on negative plate.
When switch opens, attraction across the
gap holds charge in place.

Schematic diagram
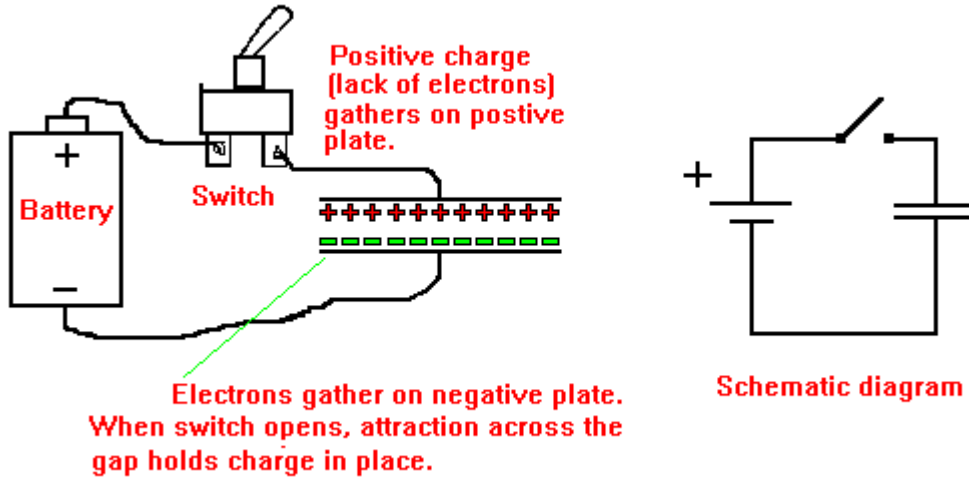
In a capacitor the electrons gathered on the plates establish an electric field across the gap. Another way to look at a charged capacitor is that the electric field across the insulation stores energy, just as a magnet stores energy in the magnetic field in and around the body of the magnet.

The Voltage Across a Capacitor Can't Change Instantly.

In electronics, the single most important property of capacitors is that **the voltage across a capacitor can't change instantly**. The current flowing into or out of a capacitor can change immediately, but the voltage can't change until more charge has been stored or charge has been removed. In other words, current must flow into or out of a capacitor before its voltage can change. In contrast with a capacitor, the voltage across a resistor and the current flowing through it are proportional and change instantly. With resistors, voltage and current are always strictly related by Ohm's law. Ohm's law works with capacitors only when the driving voltage is a continuous sinewave operating at a constant frequency.

Capacitors are commonly used in circuits in four different ways:

1. They store energy for short periods of time.

2. Because capacitor voltage can't change instantly, capacitors are used to smooth out or regulate voltages and hold them constant. For example, direct current (DC) power supplies use large capacitors to hold the direct current at a constant voltage.

3. Capacitors are used to separate AC signals from DC. Capacitors conduct alternating current much like resistors, but because of the insulation layer, capacitors block the flow of direct current.

4. Capacitors are used with inductors to form resonant circuits. Capacitor/ inductor resonant circuits are the core of radio technology and will be discussed in detail later.

Farads

The storage capacity of capacitors is called "*capacitance*" and is measured in **FARADS**. One farad of capacitance is a huge capacitor. Although you can buy such a thing, the insulation

between the plates is generally very thin and will only tolerate low voltage, usually just a few volts. In low frequency audio electronics and power supplies the capacitors used are usually measure in MICROFARADS, one millionth of a farad.

Microfarads are sometimes written as " µ Farads" where the Greek letter µ is short for "micro." For example a large 10,000 microfarad capacitor might be labeled "10,000 µF."

Capacitors store electrical charge, which is measured in **COULOMBS.** A coulomb of electrons is 6.242 billion-billion electrons. A common electronics laboratory practical joke involves charging up a large capacitor say, 10,000 microfarads, to greater than 20 volts. The capacitor is then tossed to a "friend." "Hey, Joe, catch!" Joe catches it and receives a big jolt as it discharges through his fingers.

A defibrillator for restoring normal heart rhythm works on this principle. A large capacitor is charged to about 400 joules of energy - that is, 400 watts for one second. The capacitor is then discharged through large paddles placed across the victim's chest. Being defibrillated is a horrific jolt and can be fatal if misapplied.

Notice that any conductive object isolated from a second conductor by an insulator comprises a capacitor. For example, your body is a conductive object. If you're wearing insulating rubber soled shoes and standing on a metal floor, you are now a capacitor with respect to the floor. Your body capacitance might typically be, say 50 picofarads. A picofarad is one thousandth of a billionth of a Farad. This sounds trivial, but it is not.

If the humidity is low and your body becomes charged as you scuff your feet on the wool carpet, your body can be charged up to thousands of volts potential. Fortunately only a tiny amount of charge gathers on your body, typically far less than 1 microcoulomb. Otherwise you might be electrocuted instead of just jolted when you touch a metal object. This phenomenon becomes important when handling integrated circuits and transistors. Discharging your body capacitance into a chip can instantly ruin it. Always ground your body before touching chips and transistors, especially chips made from field effect transistors.

Capacitors in parallel are calculated like resistors in series

If two capacitors are placed in parallel, the storage capacity of the pair is the sum of the two. This is easy to visualize. If the capacitors are equal, then the size of the parallel plates double while everything else remains the same.

Total capacitance = C1 + C2 + C3 + …..etc.

When capacitors are in series, the calculation resembles resistors in parallel. Capacitors in series have less ability to store charge, but they gain extra insulation and can withstand higher voltage. The voltage rating of a capacitor is called its **working voltage** or "**WV.**"

Equivalent Capacitance = 1/ (1/C₁ + 1/C₂ + 1/ C₃ + …..etc.)

If you have just two capacitors in series they may be calculated like resistors in parallel

Equivalent Capacitance = C₁ x C₂ / (C₁ + C₂)

The current that flows into a capacitor moment to moment while the capacitor is charging can be calculated using relationships that are based on Ohm's law. Unfortunately, to express a formula that will work in all cases of changing voltages requires a differential equation. In

general,

$I = (dV/dt) / C$

Where t stands for time and C = the capacitance in farads. "dV" means "the differential of voltage and dt means the differential of time.

Life is too short for hams to get too far into calculus unless it happens to fascinate you. Fortunately we rarely need it. There are special cases in which we can do simpler calculations to get what we need. For example, from the point of view of an AC sinewave current, capacitors look like resistors. That is, the capacitor takes a finite amount of time to charge and discharge. Therefore, when a sinewave voltage is applied to a capacitor, the current flowing in and out of the capacitor will be limited by how much voltage is already charged across the capacitor.

At one extreme, when the frequency is infinitely high, the capacitor has an equivalent resistance of zero – a short circuit. At the opposite end of the spectrum, to a DC current, the capacitor just looks like an open circuit. That is, it will have infinite resistance. After all, the capacitor is just an insulator separating two conductors. And if the charging voltage hasn't changed in ages, no current will be flowing into or out of the capacitor.

Capacitive reactance

At frequencies between zero and infinity a capacitor resists sinewave current flow as if it were a resistor. You can calculate the equivalent resistance or *capacitive reactance* as follows:

Reactance in ohms   = 1/ [2 π (Frequency) (Capacitance in Farads)]

$$X_C = 1/(2\pi f C)$$

Where π is "pi" or 3.1416

For example, the reactance of a 5 μ Farad capacitor at 60 Hz is:

X_C = 1/ [2 π (60 Hz) (5 μ F)] =   530 ohms

We can use this resistance-like property to attenuate sinewave signals or make voltage dividers. For example, two 5-microfarad capacitors in series can divide the voltage of a sinewave in half.

10 volts RMS
60 Hz sinewave
input

5 μF

Reactance of each capacitor at 60 Hz is
530 ohms

5 volts RMS
60 Hz sinewave
output

5 μF
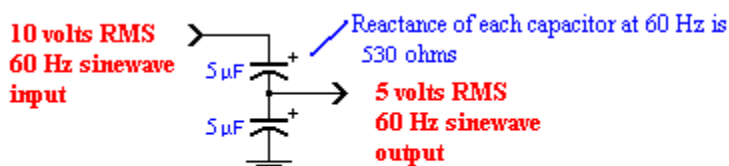
A Voltage Divider Made from Capacitors

Unlike a comparable divider made from 530 ohm resistors, no energy would be dissipated in the capacitors, so they don't get hot and they don't waste energy.

Electrolytic capacitors

Capacitors larger than roughly 1 microfarad are nearly always *electrolytic capacitors*. In the divider above, the little + signs over the capacitor symbols mean they are electrolytic

capacitors. It also means that, when you wire them into a circuit, you must wire them so that the + mark is oriented to line up with the polarity of any average <u>DC</u> <u>voltage</u> that might be applied to the capacitor. In the example above, the polarity would not matter because the capacitors are only exposed to AC voltage.

An electrolytic capacitor achieves high capacitance by means of two tricks: First, the insulator is an oxide layer electrochemically plated onto a sheet of aluminum or tantalum metal. The oxide layer serves as the insulator and can be extremely thin. Capacitance is inversely proportional to the distance between the plates, so the thinner the insulator, the higher the capacitance. Because the insulation is chemically bonded to the metal, there are no gaps between the metal and insulation and the contact is as intimate as possible.

The second trick is that, although one pole of the capacitor is the metal sheet, the other pole is an electrolytic solution, a salt bath. The fluid is in extremely intimate contact with the insulation, so that the effective gap between the two conductive bodies is truly tiny, just a few molecules thick.

Electrolytic capacitors must be wired with the correct polarity

Now the bad news: ***Electrolytic capacitors are polarized***. In other words, they must be oriented in the circuit so that on pole is always positive and the other is always negative. If the electrolytic is wired backwards, the insulating layer of oxide will be corroded by the DC current and the capacitor will short out. When the short occurs, the capacitor usually vents a cloud of foul smelling steam, or in the case of tantalum capacitors, they may even catch fire. ***It is extremely exciting to have one go off in your face.*** Therefore always make an extra effort to be sure the polarity is correct. This is especially vital in DC power supplies where the capacitor is always subjected to the same polarity.

Fortunately, in low frequency circuits it's OK if the polarity is briefly reversed. For example, if an electrolytic capacitor is used to drive a high power HI-FI speaker, the audio signal voltage is both positive and negative as the music signal goes through it. But when there is no sound present, the capacitor must be oriented, so the local DC voltage has the correct polarity across the capacitor. There are also special capacitors called "***non-polar electrolytics***." They are made from two electrolytic capacitors back to back. They are generally more than twice as large as a polarized electrolytic capacitor of the same capacitance.

INDUCTORS

Inductors are the functional opposite of capacitors. Remember that the <u>voltage</u> across a capacitor cannot change instantly. Similarly, ***the <u>current</u> through an inductor cannot change instantly.*** Whenever electrons flow through a wire, a magnetic field appears in the space surrounding the wire. This energy floats in the space surrounding the wire. Since the energy is real, it doesn't appear without a cost. The price paid for establishing the field is that energy must be expended in the wire to "charge up" the magnetic field before the electrons can pass through. When the current first begins to flow, the wire appears as a "resistance" for a moment. Then, after the field has been established, this pseudo-resistance drops to zero and the direct current flows through unimpeded.

This property of wires is called "***inductance***." The longer the wire, the more inductance it has. Inductance is measured in **Henries**. It is named after Joseph Henry, an English Physicist

who first described this phenomenon. In equations, inductance is usually represented by "**L,**" which doesn't make much sense.

Inductor Design

The picture below shows several turns of wire wound into an "***inductor***." A coil of wire like this has more inductance than would be expected from a straight length of the same wire. The magnetic fields from each turn overlap and gather in the center of the coil.
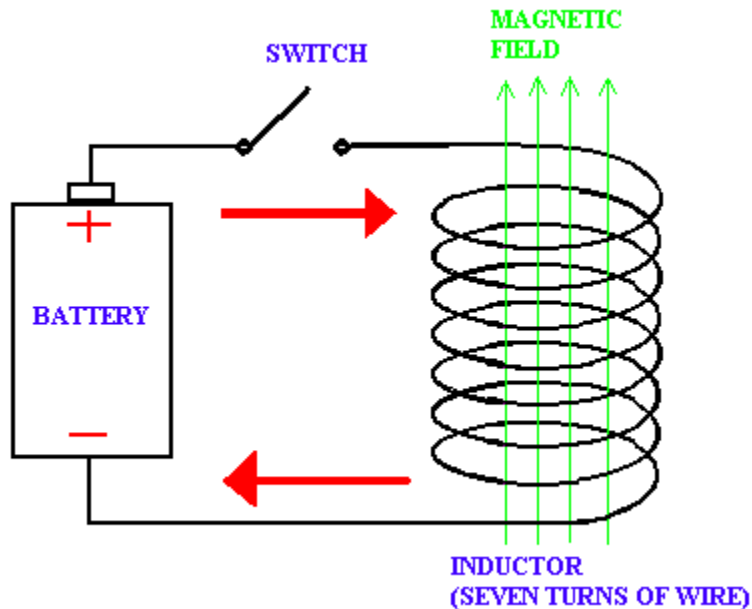
The more turns in a coil, the more inductance it generates. In fact, the inductance is proportional to the square of the number of turns. Therefore a seven-turn coil like the one above has 7^2 or 49 times more inductance than a single turn coil would have. Notice that the magnetic field produced by this coil is a genuine magnet. In fact, it will lift iron filings. Heck, big electromagnets like this are used in junkyards to lift cars!   Unlike a refrigerator magnet, this magnet can be turned on and off using the switch.

If you wanted to build a big electromagnet of the junkyard variety, an air-core coil like the one above would be impractical. By the time you had wound enough turns to generate a field strong enough to lift a car, you would need miles of wire. Miles of fine wire would have a huge electrical resistance. This is not the kind of resistance called "impedance" or "reactance", but just the resistance of the copper metal that makes up ordinary wires. To push big currents through a high resistance takes a high voltage, high current power source. If you actually did that, all those turns of fine wire packed together in a coil would get hotter than blazes. As we saw above, power = current times voltage. A high resistance coil would be in danger of melting because the energy dissipated in it would be so high.

As permanent magnets demonstrate, magnet fields require no power consumption at all once the field has been established. Only a current is needed to generate a magnet field. In a permanent magnet, the electrons orbiting around the iron or other magnetic atoms provide the current. No outside power is needed to keep those electrons orbiting, so a permanent magnet can

generate the field forever. In theory, superconducting wire can be wound in a closed loop to produce a permanant magnet by having a current circulating through the loop endlessly without loss to form a permanent magnet. In practice, the unavailability of high current, high temperature superconducting wire makes this dream impractical.

Instead, ordinary iron can be "recruited" to form a magnet even when it is not already crystallized with all the magnetic atoms lined up in the same direction. ***Electro-magnets are constructed by winding a coil around a piece iron.***

The Current Through An Inductor Cannot Change Instantly

In electronics, the single most important property of inductors is that **the current through an inductor can't change instantly**. The <u>voltage</u> across an inductor <u>can </u>change immediately, but the current can't change until the magnetic field surrounding the inductor has been augmented or decreased. In other words, voltage must change across the inductor to force a change in the current and its corresponding magnetic field. In summary, inductors are the opposite of capacitors. As with capacitors, Ohm's law works with inductors only when the driving voltage is a continuous sinewave operating at a constant frequency.

Inductors are used commonly in electronic circuits in four ways:

1. Inductors are used to prolong the flow of current into a resistance and hold the current constant. This prevents surges of currents that might otherwise damage other components. They are used in filters of various kinds to regulate voltage and currents.

2. Inductors generate magnetic fields that attract iron and produce motion. Consequently, inductors are a component of relays, solenoids and loudspeakers.

3. Inductors, as part of transformers or acting alone, are used to change voltage levels up or down.

4. Inductors are used with capacitors to form resonant circuits. Capacitor/ inductor resonant circuits are the core of radio technology and will be discussed in detail later.

Inductance in measured in Henries

The unit of inductance is the ***Henry.*** A Henry is a relatively large inductor. An inductor that large nearly always has an iron core and is often used in low frequency applications like power supplies. At radio frequencies a microhenry is a significant inductance. As you will see, most radio circuits use inductors in the range of 1 to 100 microhenries. The energy handling ability of inductor is rated in ***amperes***. For example, a small inductor might be rated at 1 millihenry at 100 milliamperes. If you put more than 100 mA through it, the wire might burn up or, if it has an iron core, the iron might saturate and the inductance will drop dramatically to much less than its 1 mH rating. Iron cores and saturation will be discussed in more detail shortly.

Inductors in series

When current must pass through two or more inductors in series, the total inductance will be equal to the sum of the inductors. When two equal inductors are place in series, the current must pass through twice as many obstacles, the current flow will charge up the inductors half as rapidly, but twice as much magnetic field energy will be stored.

To calculate the equivalent inductance of several inductors in series, just add up the separate inductances.

Inductance equivalent = L₁ + L₂ + L₃ + L₄ +...... etc.

Inductors in parallel

When two equal inductors are placed in parallel, the inductance seen by the voltage source will be half as much as if there were one inductor. This causes twice as much AC current to flow and the magnetic field energy will charge twice as fast and be half as large.

When the inductors are equal in size, the AC current they will draw when in parallel is intuitively obvious. But when the inductors in parallel have different inductances, then you will need to calculate the equivalent inductance using the formula:

Inductance equivalent = 1/ (1/L₁ + 1/L₂ + 1/ L₃ + …..etc.)

That is, the equivalent resistance is the inverse of the sum of the inverses of the resistances. If there are just two resistors, then the formula is slightly less ungainly, but perhaps harder to remember:

Inductance equivalent = L₁ x L₂ / (L₁ + L₂)

Calculating sinewave current flow through inductors and the voltage across them can be done using Ohm's law. Unfortunately, just like capacitors, when the current is not a constant sinewave, the calculations are tricky because the current flow is time dependent. To do it correctly in a way that works under all circumstances requires a differential equation. Specifically,

Voltage (t) = L dI/dt

Where t is for time and L = inductance in Henries. Why "L"? Inductance could have been "I," but that stands for current. Fortunately, hams rarely need to make these calculations. However, when the changing current is a sinewave, the voltage or equivalent resistance **_(inductive reactance)_** of an inductor is easy to calculate.

Inductive reactance

From the point of view of a constant AC sinewave current, inductors look like resistors. At one extreme, if the frequency is infinitely high, the equivalent AC resistance is infinite. At the opposite end of the spectrum, to a DC current, the inductor just looks like a long piece of copper wire. In other words, at DC, a perfect inductor would have zero resistance.

At frequencies between zero and infinity an inductor resists sinewave current flow as if it were a resistor. You can calculate the equivalent resistance or **_inductive reactance_** as follows:

Reactance in ohms   = 2 π (frequency) (Inductance in Henries)

$$X_L \;\; = \;\; 2\,\pi\,f\,L$$

For example, the reactance of a 5 Henry inductor at 60 Hz is:

X_L = 2 π (60 Hz) (5 H) = 1885 ohms

Like capacitors, inductors can be used like resistors to attenuate currents or divide

voltages. For example, two 5-Henry inductors in series can divide the voltage of a sinewave in half. Unlike a comparable divider made from 1885 ohm resistors, virtually no energy would be dissipated in the inductors.
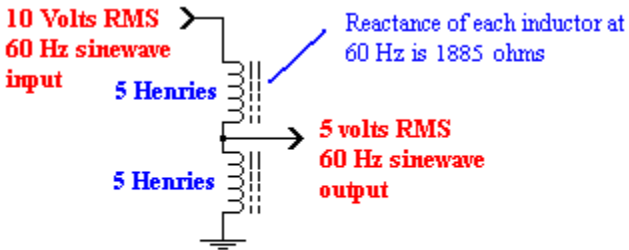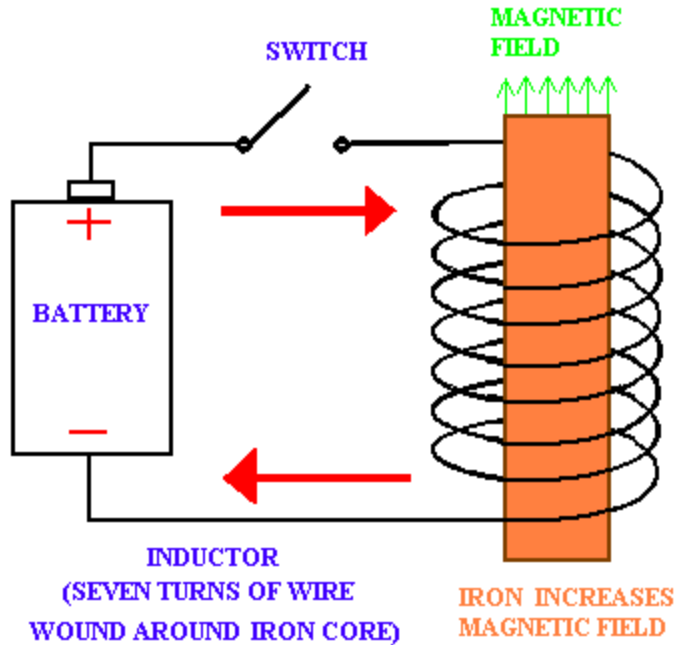

Voltage Divider Made From Inductors

If you wanted 530 ohms reactance like the previous voltage dividers then you can solve for the inductance starting with 530 ohms. As you can see, smaller reactance means a smaller inductance.

530 ohms $=$ 2 π (60 Hz)(L) , L $=$ 1.4 Henries.

Iron core inductors

An iron bar placed inside a coil of wire greatly increases the inductance and the magnetic field energy by orders of magnitude. This is how high-force electromagnets are made. In the divider circuit above the dashed lines next to the inductor symbols means that the inductor has an iron core. In practice, any inductor larger than about 0.5 Henry will nearly always have an iron core to achieve such high inductance. Maybe if room temperature superconductors ever become practical, this may change. But for now, large inductance means iron core.

SWITCH

MAGNETIC FIELD

BATTERY

+

−

**INDUCTOR
(SEVEN TURNS OF WIRE
WOUND AROUND IRON CORE)**

**IRON INCREASES
MAGNETIC FIELD**

Transformers

Transformers are devices consisting of two or more inductors that share the same magnetic field. Suppose the two coils are placed next to each other so that the magnetic field from one coil will pass through the other:

A __changing magnetic field couples energy from one coil to another.__ If we put a voltmeter or oscilloscope across the resistor on the secondary coil, we will see a voltage jump up from zero, then immediately fade back down to zero as the magnetic field in the coils is being established. Once a static magnetic field is established in both coils, there will be no voltage across the secondary winding and resistor.

MAGNETIC
FIELD

TURN
SWITCH ON

SWITCH

RESISTOR
LOAD ON
SECONDARY
WINDING

BATTERY
15
VOLTS DC
+
—

TRANSFORMERS WORK
WITH *CHANGING* CURRENT.

VOLTAGE ACROSS
RESISTOR JUMPS UP,
THEN DROPS TO ZERO.
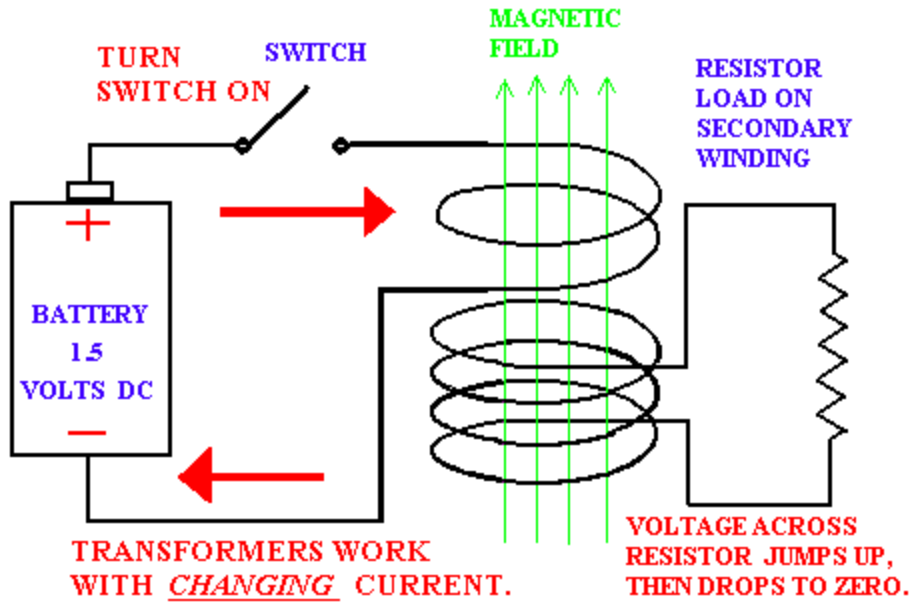
Iron core transformers

Putting an iron core inside a transformer vastly increases the inductance of the windings. This vastly prolongs the voltage spike observed across the secondary coil.

MAGNETIC
FIELD

TURN
SWITCH ON

SWITCH

RESISTOR
LOAD ON
SECONDARY
WINDING

BATTERY
15
VOLTS DC
+
—

IRON
CORE
INCREASES
INDUCTANCE

TRANSFORMERS WORK
WITH *CHANGING* CURRENT.

VOLTAGE ACROSS
RESISTOR JUMPS UP,
THEN *SLOWLY* DROPS.
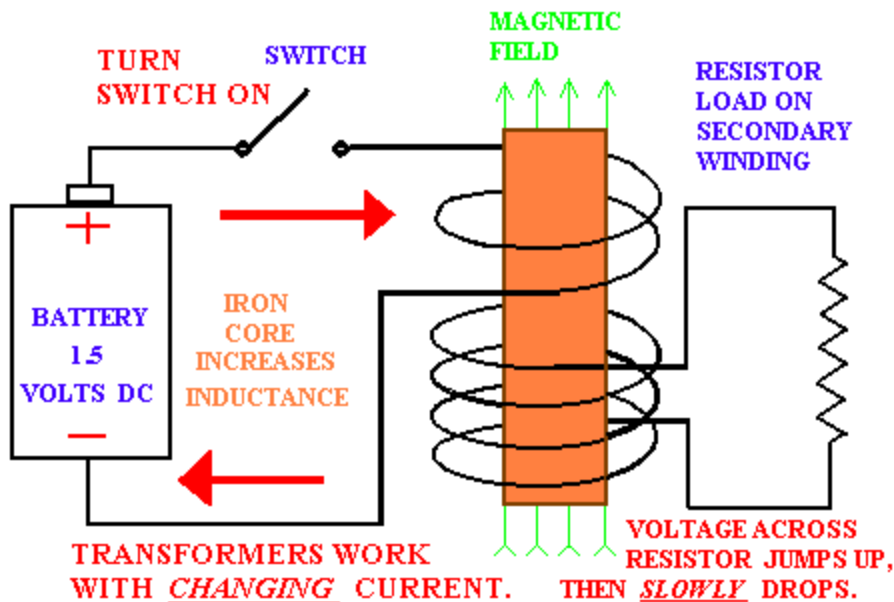
Unfortunately, ordinary iron not only generates magnetic fields, it is also a conductor of electricity. As you know, the copper windings are loops of conductive metal. Whereas the iron core is a solid mass of conductive metal. Consequently, the iron acts like a bunch of shorted loops competing with the copper windings for current flow. As a result a simple iron transformer like the one above works poorly unless the changes in the current are very slow. That is, so long as the changes take place slowly, like manually turning an electro-magnet on and off, then it

works OK. But as the switch is thrown faster and faster, more and more energy is wasted in circulating currents inside the iron.

An automobile spark coil

Subdividing the iron core into vertical slats of iron ameliorates the problem of circulating currents. This forces the currents to circulate into little tiny loops that don't waste so much energy. The figure directly below shows a simplified ignition system for an automobile. The switch in this case is the breaker points in the distributor. In modern cars, the switch is actually a transistor, but the function is the same as the old-fashioned mechanical breaker points. Since the engine can fire many thousands of times per second, the rates of change of the currents in the primary are fairly high.

AUTOMOTIVE IGNITION TRANSFORMER.
12 Volt primary winding, 10,000 Volt secondary winding.
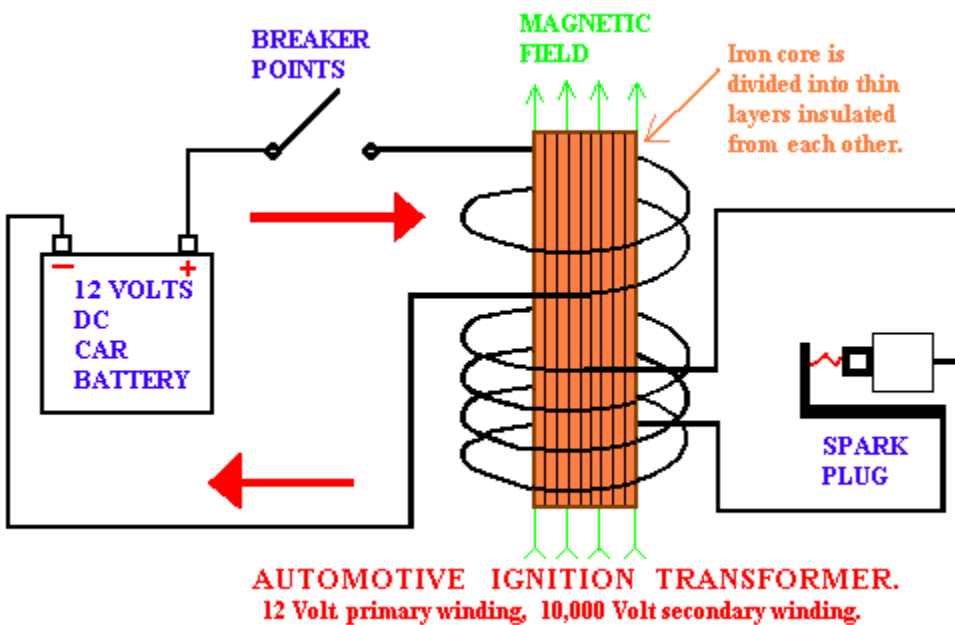
Voltage step up and current step down

A vital characteristic of an automobile ignition transformer is that the voltage across the secondary must be extremely high. Without the high voltage, the spark would not jump across the spark plug gap. ***Voltage is raised by having far more winding turns on the secondary than there are on the primary***. An important use for transformers is to change varying (AC) voltage up or down by increasing or decreasing the number of turns on the secondary.

Power out of the secondary (nearly) equals the power into the primary winding

A transformer "transforms" the ratio of current to voltage. In other words, if the voltage is stepped up, the current in the secondary will be proportionately stepped down. The power into and out of the transformer remains the same.

Power in = (Voltage in) X (Current in) = Power out = (Voltage out) X (Current out)

Generation of sinewave currents

An *alternator* is a device that generates low frequency AC current. How it works will be discussed in detail shortly. But for now let's just use it to deliver an AC voltage to the primary of a transformer. In contrast to a simple switch and battery, the alternator generates alternating sinewave current. When the sinewave from the alternator is fed into the primary winding of a transformer, the secondary winding will have a continuous sinewave on it, just like the primary. The voltage that appears across the secondary will be proportional to the ratio of the numbers of turns on the primary and secondary. For example, as drawn below, there are twice as many turns on the secondary as on the primary. Therefore the secondary voltage will be twice as high as the primary voltage. Similarly, the secondary current will be half as great as the primary current.
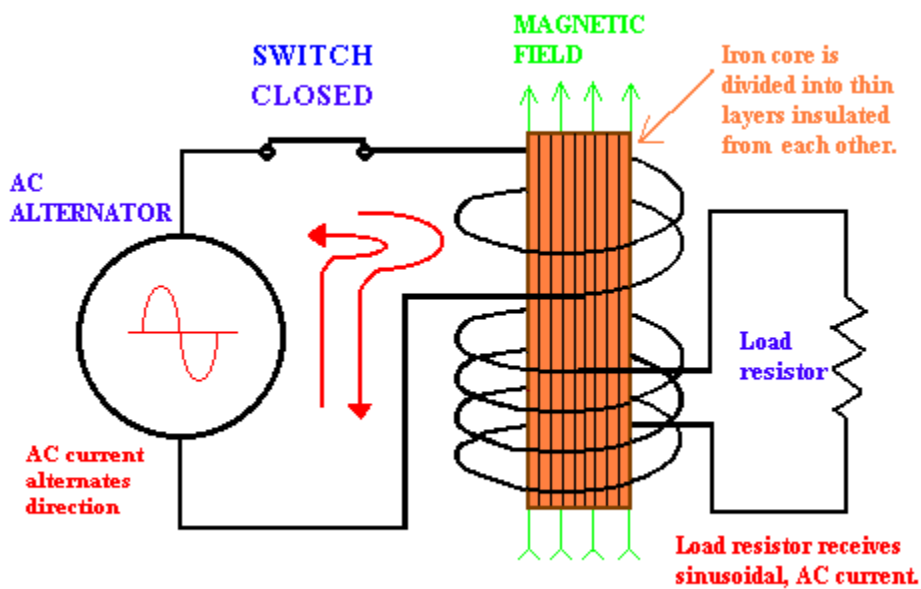
Toroidal or closed loop transformer cores

The best coupling efficiency is achieved when the magnetic field is confined to the iron core and is not allowed to fill the space around the transformer. Also, the amount of inductance per turn of wire that can be achieved is the highest when the iron core is a closed loop. In the drawing below, the thin donut-like, iron plates making up the core are stacked going away from the observer and so they are not shown.

MAGNETIC FIELD
IS CONFINED TO IRON
DONUT

AC
ALTERNATOR

Load
resistor
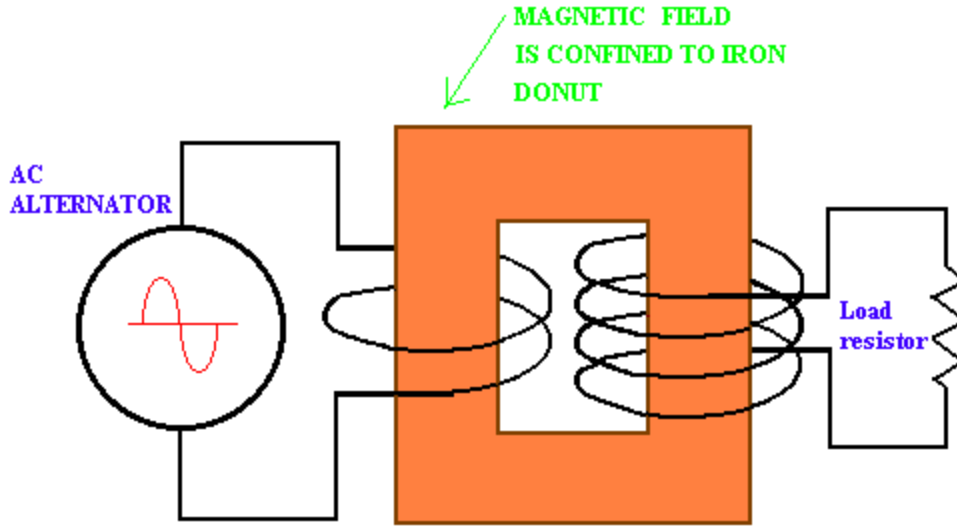
TYPICAL 60 HZ IRON TRANSFORMER
Iron core made from laminated sheets of silicon steel.

Household power distribution

Electric power comes into our homes in the form of 240 volts alternating current on THREE wires. This power source is referenced to ground. The reference point is not on one of the two hot wires, but is ground located halfway in voltage between the two live wires. We use the two 240 volt AC wires for our 240 volt stoves and clothes driers.

HOUSEHOLD POWER DISTRIBUTION

Circuit
breakers

4400
Volts
AC

120 volts AC

120 volts AC

240
Volts AC

Neighborhood
distribution
transformer.

Power
line into
house.

Household
line outlets

Third plug pins and
the white "neutral"
wire are tied to Earth
ground.
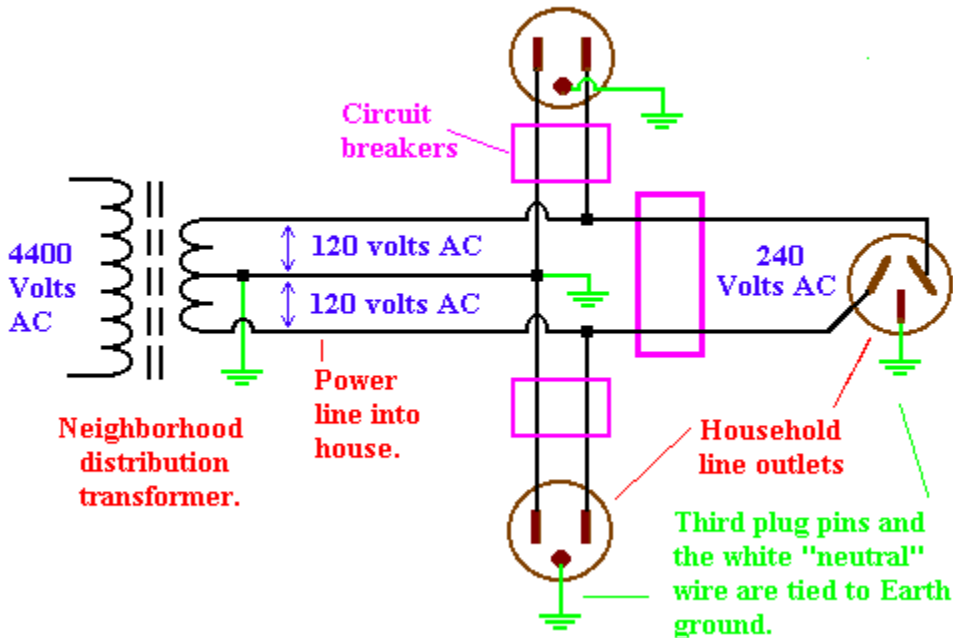
However, most of our lights and appliances are powered with 120 volts AC. This voltage

is obtained by tapping between one of the "hot" 240 volt wires and ground. In your circuit breaker box you will find two "**buss bars**" which are the 240 volt terminals. Another buss in the middle is the ground terminal. The big 240 volt breakers snap onto the outer terminals. The smaller 120 volt breakers clamp onto the center ground and either one of the two 240 volt side rails. Clever, huh? Now you can get two different voltages from the two 240 volt AC wires.

Electric power comes into our neighborhoods at very high voltages, 4400 volts AC or more. Large transformers out in the alley convert this power down to 240 volts for several houses in the neighborhood. These step down transformers are those large, black "pole pigs" up at the top of power poles. Why not just generate electricity at the power plant at 240 volts AC and be done with it? Because copper wire has a significant resistance. If high currents travel through miles of wire, the energy will be dissipated in the copper instead of being delivered to the customers. By using very high AC voltages, high power can be delivered with small currents and low loses. For long cross-country power lines the AC voltage is usually hundreds of thousands of volts.

Low frequency transformers at home

120 volt 60 Hz power line transformers are common around the house. Most appliances that contain electronics have a transformer to drop the voltage level down to 12 volts or less. The closed loop iron transformer above is the basic design. Usually, the windings are placed on top of each other rather than on opposite sides of the donut. Also, there are usually two holes in the "donut" with the coils wound on the center post between the two holes.

Safety is an important advantage of transformers. Transformers are often used to isolate AC voltages from ground. For example, if the input current on the primary is referenced to ground, the two secondary wires will only be referenced to each other. Well, OK. Depending on transformer design, there may be as much as one milliampere of leakage current if one of the wires were touched to ground. In a well-designed transformer, the leakage can be just a few microamperes. But for all practical purposes, the AC voltage on the secondary has no relationship to ground.

As you are probably aware, our household AC line voltage is referenced to "ground." Ground is literally the wet dirt in your yard. This means that if you grasp a grounded water pipe with one hand and stick a finger in a light socket with the other, a large current will pass through your body and you will experience *electrocution*. This should be avoided unless you are tired of living. We ham radio operators have many opportunities to be shocked, burned or killed by high voltage. But in practice, probably the most common serious accident for hams is falling from roofs and high towers. We need to be far more concerned about safety than ordinary citizens. Isolation transformers are one way we hams make accidents less likely.

Compared to capacitors, inductors are relatively "imperfect"

In electronics capacitors are used far more often than inductors. One reason is that inductors are more expensive than capacitors. It's hard for a machine to wind wire around tiny cores, especially a closed loop core. Another problem with inductors is that significant lengths of copper wire must be used to build them. This wire inevitably has a significant resistance. This means that every inductor is actually two components; an inductor and an unintentional resistor. In contrast, capacitors, especially small capacitors, can approach perfection. Capacitors have

essentially no resistance and no inductance and their properties are constant over their operating range.

The other limitations of inductors are the limitations of the iron cores. As pointed out earlier, circulating currents in the iron dissipate energy. This loss appears as a warm iron core and wastes energy as if they were yet another resistor in series with the inductor.

Inductor saturation

As current flows through the windings, the magnetic field "recruits" the magnetic fields of the iron atoms to generate a much larger magnetic field than the coil would otherwise generate. This works fine until all the iron has been recruited. At this point the iron "saturates" and the coil abruptly returns to being able to generate no more magnet field than its copper windings can produce. As a result, iron core inductors have a limited operating range.

Little bitty inductors made from extremely fine wire wound on iron cores the size of a raisin can have impressive inductances. The catch is that these tiny coils saturate almost immediately and the inductance is only valid at essentially zero current. Needless to say, components like this have limited usefulness! Small, low inductance coils with heavy wire and with no iron core are closer to perfect inductors, but without the iron, the magnet fields surround the coils. These stray fields induce currents in nearby components. Again, if an inductor couples unwanted signals into neighboring circuits it is not an ideal component.

Inductor core hysteresis

Another problem with iron is *hysteresis.*   When the current in the coil shuts off, some of the magnetism in the iron remains. Then when the iron is magnetized in the opposite polarity, energy must be wasted to first restore the magnetism to zero before it is magnetized in the new direction. Again, this is a big departure from an ideal component.

Inductors at radio frequencies

Inductors and transformers are vital to radio circuits. In radio circuits AC currents alternate not at 60 Hz or a thousand Hz, but at millions of Hz. The principles are identical to those explained above, but there are differences that may surprise you. First, in general, the more power an inductor or transformer must handle, the bigger it must be. However, the size of a required inductor varies with the frequency. At low frequencies, like 60 Hz, a transformer is comparable to bailing water with a really big bucket. Since it only delivers "water" 60 times a second, the bucket must be large to deliver a lot of water. Now suppose the same water is delivered with thimbles instead of buckets. If the thimbles are filled and emptied millions of times per second, the same amount of water could be delivered as the bucket. So *at high frequencies high power can be handled by tiny transformers.*

Powdered iron cores

Unfortunately, many transformer problems are accentuated with high frequencies. For example, it is no longer sufficient to build iron core transformers with sheets of steel. For high radio frequencies the iron must be ground into a fine powder and dispersed in ceramic. There are two kinds of powdered iron cores used at high frequencies. Ordinary *powdered iron cores* have a high percentage of ceramic and relatively little iron. This insures low loss in the cores and prevents abrupt saturation at high peak current level. *Ferrites* are a sophisticated type of

powdered iron core that looks more like black glass but has more iron and much less ceramic content. In spite of having little ceramic in the mixture, ferrites manage to insulate neighboring granules of iron from each other. With ferrites much higher inductances can be used at radio frequencies than would otherwise be practical.

Ferrites and powdered iron cores are usually in the form of toroids – donut shaped rings. This is the modern way to build radio frequency inductors and transformers. At lower frequencies ferrites are often formed into "pot cores" which totally enclose and shield an inductor with ferrite. This almost totally confines the magnetic fields so they cannot interfere with neighboring circuits.

Sinewaves – "Pure alternating current"

The origin of household AC sinewave current is a giant alternator out at your local power plant. Alternators are a kind of AC generator that can be thought of as a modified transformer in which one of the windings is mechanically rotated by an engine or other mechanical power source. An alternator produces a pure sinewave output simply from the natural rotation of its input shaft. The "stator," is the stationary part of the alternator. It consists of the iron frame that surrounds the rotation shaft. The stator has a pair of coils mounted on it on opposite sides of the chamber. These coils are hooked up in series so that the voltages generated at any moment are added together.

ALTERNATOR

Generator has iron frame.

Output from alternator is an AC sinewave voltage.

+V

- V

Rotor is a permanent magnet that rotates past the pair of coils.

A pair of stator coils surrounds spinning rotor.

Power to spin rotor is supplied by an engine, fan belt, etc.
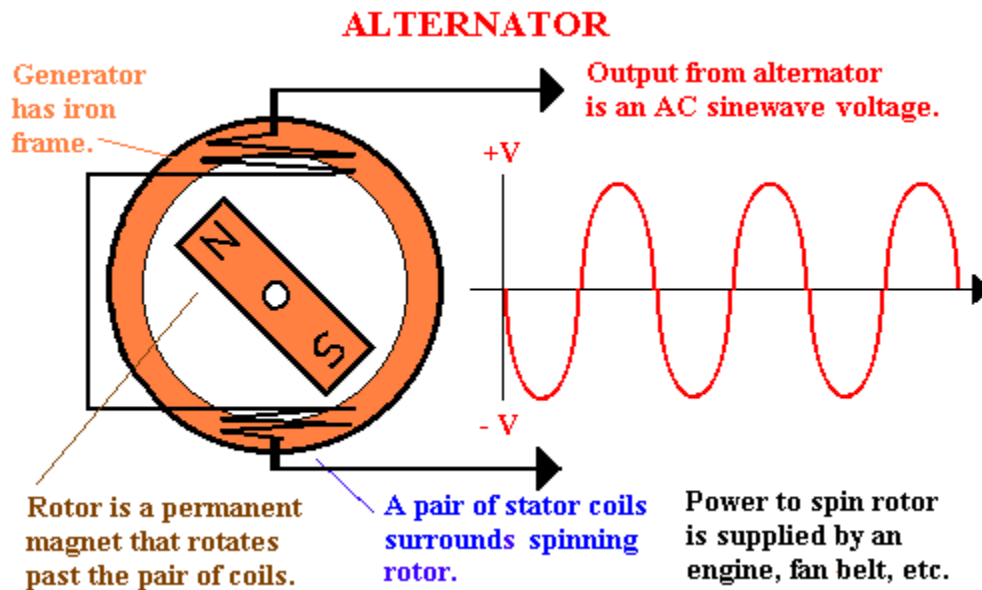
The rotor is the central part that rotates. As drawn here, the rotor consists of a simple bar magnet. Actually, the rotor is usually an electro-magnet, but I'm trying to keep it simple.   As the north and south poles of the magnet sweep past the coils, they generate voltages of opposite polarity. That is, the negative voltage appears on the bottom terminal while the positive voltage appears on the top terminal. When the rotor spins around to the opposite alignment, the voltage polarity reverses. The sinewave comes about from changing angle of the magnet with respect to the stator coils. To express it in terms of math, the voltage output equals the sine of the angle

plus ninety degrees.

Voltage at any given moment = (Peak voltage) Sine (Angle + 90°)

Because of the 90 degree offset, this waveform is actually a cosine wave, but nobody calls it that.

When viewed abstractly, alternators closely resemble AC transformers as described above. Although there is a small air gap between the rotor and stator iron, the magnetic field travels in essentially a closed loop. The rotor is analogous to the primary winding. Instead of the energy coming in on wires, the energy enters the system mechanically. The moving magnetic field then creates the sinewave as it zooms past the stator coils.

Automobile alternators

Most alternators, such as the one in your car, are more complicated. They have three sets of stator windings crammed into the same frame. These three windings generate three separate, out-of-phase sinewaves. In your car these three outputs are rectified (converted to DC) by semiconductor diodes to produce 12 volts DC. (We'll describe diodes in chapter 4.) The DC is then used to charge the car battery. Alternator rotors are nearly always made from electro-magnets. They are powered by "slip rings" that bring DC current in from outside to the moving rotor. Using an electro-magnet for a rotor allows the output voltage from the generator to be controlled by varying the strength of the current that maintains the magnetic field. This is how the voltage regulator in your car keeps the battery charged, but not over-charged.

 A sinewave voltage from an alternator obviously has only one frequency because the input shaft can turn at only one speed. And because of the direct way the waveform is generated, the sinewave is as natural as the mathematical formula that expresses it.   In contrast, modern digital electronics often generate "artificial" sinewaves by reproducing voltages dictated by a series of numbers that represent a sinewave. The end product is a complex "stair step" waveform that resembles a sinewave.

RF sinewaves

In radio technology natural sinewaves are universal in every circuit. For example, the voltages on transmitting or receiving antennas are sinewaves. Radio Frequency AC voltages are called "***RF voltages.***" They are generated by transistor oscillators as pure sinewaves. But unlike the output from an alternator, in radio circuits there are often multiple sinewaves riding on the same wire. For example, a receiving antenna carries sinewaves from ALL of the different radio waves impinging on it. Much of radio technology concerns ways to select and filter one sine wave from among a crowd of sinewaves.

So far we have introduced low frequency electrical theory. Radio frequencies are the same thing, but as we have seen, different aspects of the theory become more important as the frequency goes up. In the next chapter we'll put together a basement radio lab and get ready to build radios.

CRYSTAL SETS TO SIDEBAND

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CHAPTER 3

SETTING UP AN ELECTRONICS WORKSHOP

Research and Development as recreation

Building an amateur radio transmitter and receiver from the component level up is true research and development. That's why it's fun. Sure, it's much easier than developing products that have never existed before, but conquering the details will be hard and you'll find it plenty satisfying. When you're done, you can brag about your rig to your ham buddies. These days, if you have a 100% homebuilt station, you'll find you are almost unique among other hams.

We can learn how to do R & D by studying the methods of the master inventors. We Americans would probably nominate Edison as the single most famous inventor in history. Edison is not credited with the invention of radio, but he did develop many of the components used in 20th century radios. Also many of the techniques to build those components were first developed in Edison's laboratory. Edison fabricated the first vacuum tube diode detectors, the loudspeaker and the triode vacuum tube, but he never applied them to radio. Edison is best known for a handful of his most important inventions. However, *Edison's greatest contribution may have been his <u>methods</u> of inventing.*

Persistence

A reporter asked Edison why he had often succeeded in perfecting inventions, while other experimenters who started down the same path were never able to build a practical device. Edison replied, "Most inventors will have a good idea and try out one or two versions of their concept. When it doesn't work, they declare it hopeless and give up. The difference is, I never give up."

Try everything and keep careful notes

The most well-known story about Edison's persistence was his legendary search for the ideal material to make lightbulb filaments. Edison was asked if he was discouraged by his failure to find a suitable material after trying hundreds of substances. He replied that it hadn't been a failure. He now knew hundreds of materials that didn't work.

The corollary to Edison's method is that it's essential to write everything down in detail. It's not fun writing the details of experiments that failed. But a year later, any researcher can tell you they have had that "deja vu" sensation halfway through an experiment only to find in their notes that they had tried this before. At the moment when you discover "a pearl of wisdom," it seems so profound to you that you believe you will never forget it. Wrong. Unless your memory is much better than mine, months later an old laboratory notebook can be re-read almost as if someone else had written it.

Lots of junk

Edison was asked what a fellow needed to become an inventor. He said, " First you need a large pile of junk. You can't afford the time and money to run down to the store every time you

need something. Often the junk pile will supply the parts to try out an idea right away. If you order parts from hundreds of miles away, you may waste weeks just to find out that your idea didn't work."

Subdivide the problem and build for modification

A complex invention like the light bulb, consists of many parts. Light bulbs only look simple. What kind of glass can stand the heat of the filament? What kind of wire has the same coefficient of thermal expansion as that of glass? What kind of filament material is optimum? What should the resistance of the filament be in order to be compatible with the electric power source? How does the resistance change with temperature? What is the trade off between operating life and brightness? How good a vacuum is needed and how can it be produced? Once the air is pumped out of the glass, how can the bulb be sealed? Answers to all of these questions had to be found and tested one at a time before Edison could make a practical light bulb.

Have you seen the movie Gizmo? Gizmo is a collection of film clips of early 20th century inventors showing off their inventions for the first time. The movie is hilarious because again and again, the inventors make the same mistake. They take ideas that are often fundamentally sound, and then they build an entire, polished, handsome prototype without ever testing the pieces. They make the first test run of their airplane, jet boat, etc. in front of a movie camera. In some cases they apparently even called in the press just to be sure the test would be as humiliating as possible.

My favorite relatively recent invention was McCready's human-powered airplane. In 1965 an English sponsor named Cramer offered a $100,000 prize to the first fellow who could fly over a 20 foot obstacle, fly over a half mile course, fly over a second 20 foot obstacle, then turn around and return to fly over the first obstacle again. The plane had to be 100% powered by muscle power. For 20 years many smart people tried to build a pedal-powered plane. Again and again they made the same mistake. They worked for months building beautiful, handcrafted balsa wood airplanes. Then on the first flight the plane would crash and be smashed beyond repair. After two or three attempted flights, the inventors had spent months or years and were out of money and enthusiasm. In contrast, McCready designed his aircraft out of aluminum poles, wire, tape and mylar. He designed his plane to be flown, crashed, repaired and modified. McCready was able to crash and redesign his plane once or twice a day until he got it right. And he made sure there were no cameras around until it was tested and working.

Build for function, not beauty

First and foremost, your equipment should work well. It is natural to feel embarrassed by its crude, homemade appearance. Don't be! Commercial ham equipment has been designed and redesigned several times before you ever see it. Moreover, commercial equipment is packed with custom displays, custom heat sinks, custom cabinets and even unique integrated circuits. You can't compete with that, so don't try. Instead take pride in your crude prototype.

When you see designs for homebuilt equipment in the ARRL handbook or in ham magazines, the equipment is usually quite attractive. But if you read carefully, you will find that the unit in the picture is prototype number five or even number one hundred. You probably don't have time to rebuild your station 5 times just to achieve beauty. Also, if you attempt to duplicate one of those units, you'll find you must use exactly the same parts and circuit board the author

did. This means buying a custom circuit board and perhaps a parts kit from some manufacturer. If you try to substitute parts, I can almost guarantee it won't work.

Get smart guys to help you

This piece of wisdom from Edison may be limited in usefulness to the basement ham, but it's still interesting. Edison was the first fellow to industrialize the process of research and development. Once he acquired financial backing, he hired a whole team to work on his projects. He didn't try to do everything himself. The quantity of Edison's inventions can be partly explained by the number of competent guys he had working for him. Edison and his lab were credited with inventions that represent the work of dozens of lifetimes. Even for a guy who works day and night, there are limits on what one fellow can do. If you're a one-man show, it's important to limit yourself to projects you can complete. Be sure to use the library to find previous work in your area. Although real ham homebuilders are rare, homebuilding is the most fun if you can find someone in your area to share your triumphs and problems.

Assume as little as possible

Edison looked for guys who had the right attitude about R & D. Many job applicants have a knack for sounding good in an interview, but turn out to be more glib than useful. One of Edison's tricks was to take potential employees out to lunch. If they put salt and pepper on their food without tasting it first, they were in big trouble with Edison. Edison's selection method is probably extreme, but it does illustrate a cardinal rule of research. ***Never assume anything about the project without good data to back up your starting assumption.***

For example, I had known for twenty years that resistance in series with a transistor emitter was important for the thermal stability of an RF amplifier. However, I believed that any emitter resistance would inevitably reduce the signal output from that stage. In other words, I thought stability and gain were a tradeoff. Recently I took the time to try different values of emitter resistance over the entire range of possibilities. I was amazed to find that maximum output occurred not at zero ohms, but at a certain significant value, 300 ohms in my specific amplifier. When you do experiments like this, write down the details! You'll want them later.

Many inventions are frustrated by assumptions that turn out to be limiting. For example, weapons inventors were limited for centuries by the concept that firearms had to be ignited by flintlocks. When you consider the practical difficulties of inventing a waterproof, rapid-firing, breech-loading flintlock rifle, it's no wonder that firearms were essentially unchanged for 250 years. Millions of lives were probably saved by this fixation on flintlocks! Narrow-mindedness in inventors isn't always bad for society, but it sure restricts innovation.

The genius of trying

Magic happens when you actually sit down at your workbench and try to do something. You may have thought about the problem in spare moments for weeks, but when you actually have the work in front of your face, ideas pop into your head as if by magic. For this reason, many people, like Edison for example, were well known for working non-stop all night. Once you get the momentum going, it can be wasteful to stop. Otherwise you may not remember all the details when you get back to work hours or days later.

I used to work with a patent attorney, Robert E. Harris, who always put everything off

until the last minute. I kidded him about his procrastination. He answered me seriously with an explanation that went something like this: "I do it deliberately," Bob said. "I find that in order to write a patent application, I need complete concentration and nothing gives me that intensity like an approaching deadline. In order to write a good patent, I must have all of the prior inventions in my head at the same time. If I just put in just a few hours, by the next day I will have forgotten important details.

"For example, suppose that Jones' claim 14 partially eclipses our proposed claim 12. But the essence of Jones' work was already in place by Smith whose patent has recently expired. Therefore, Jones claim was already invalid and should never have been allowed. And the novel part of our claim 12 now becomes valid because it has no precedent and the old part doesn't interfere with Jones. For that reason, the day before the deadline I go into seclusion and work all night if necessary."

When you get stuck, do something else for a while

Unfortunately non-stop work often slows to a crawl when you run out of significantly new ideas to try. As long as you keep sitting in front of the problem, you will keep finding little variations to try, but as the hours go by, you will become more and more tired and your ideas will become less and less creative. To escape from this trap, get up from the workbench and do something else. Take a walk, take a shower, go home. When you're not in front of the work, you can't do anything with your hands. Since you've been concentrating so long on the problem, your brain will continue to work on the problem long after you leave the workbench. Because you can no longer try out little, uninspired ideas, your mind must wander farther and you'll find you are thinking seriously about radically new concepts.

For example, when Edison was searching for his light bulb filament material, he was stuck on the idea of using an inert metal filament. An inert metal would not react with oxygen or with residual gasses that might remain in the light bulb. If Edison had been able to use his "try everything" philosophy, he would have eventually tried every known metal. Therefore, he would have eventually tried tungsten and that's what filaments are made of today. But perhaps tungsten wasn't available 120 years ago.

Edison was particularly stuck on platinum as a filament material. Yes, it was expensive, but it seemed to work beautifully and gave a bright yellow-white light for a few hours. Unfortunately, eventually a segment of the platinum wire would become thin and abruptly melt, thereby ruining the bulb. A related problem was that the resistance of platinum was too low. This meant that a long, very thin platinum wire had to be used to make the filament compatible with his 100 volt power source.

Edison and his team realized that, if they could detect the sudden resistance rise of the filament as it started to fail, they could turn down the current and keep the filament intact. In theory, a temperature/ current regulator could allow the bulb to last indefinitely and would make it almost immune to power surges. The team expended a great deal of effort to invent the regulator, but it never worked well enough. Finally while away from work, Edison thought that the whole idea of a metal filament should be reconsidered. From metals he turned to carbon filaments. Carbon was cheap, had an inherently high resistance and it didn't melt. Carbon turned out to be a practical answer he could use and in the end carbonized cotton thread became the filaments in his first commercial bulbs.

Developing your own basement electronics laboratory

Before you can begin building ham equipment you will need some basic tools and materials. Notice that, in addition to books, you will need both heavy-duty tools and light-duty ones. If you use tools that are too fragile, you may ruin the tool. If you use tools that are too heavy, you may ruin your project. The following list is incomplete, but it will get you started.

1. Buy an ARRL Amateur Radio Handbook

An R&D hobbiest can't hire a staff of underlings and consultants, but he can get advice from guys who have done it all before. ***The first investment a new ham should make is <u>The ARRL Handbook for the Radio Amateur.</u>*** These handbooks are as big as a phone book. It is published every year and the latest edition has all you need to understand the breadth of our hobby. It will also give you a good background in basic electrical principles and some detailed descriptions of do-it-yourself construction projects.

The ARRL Handbook , 1986 edition

Yes, the above handbook is way out of date. However, I have two criticisms of modern ARRL handbooks. First, they are so huge, they discourage most people from sitting down and reading them. The second limitation is that modern hams no longer build complex receivers and transmitters. So projects like this are no longer described in detail. In fact, reading my up-to-date handbook I got the impression that building complex transmitters and receivers is impossible for amateurs. That's not true and that's why I'm writing this book.

Other than that, the latest edition handbook is a great reference to own. It covers all the latest exotic technology and you can use in like an encyclopedia. For actual homebuilding I recommend a handbook from the 1980's. During that decade hams were still building good equipment from discrete transistors. Handbooks from the 1970's and earlier usually describe projects that are unnecessarily primitive. The projects in the Handbooks from the 1990's and later usually contain integrated circuits which don't teach you anything about how your project works. The authors of the present day handbook don't seriously expect anyone to build complete stations. You should be able to find a handbook from the 1980's at a ham radio swap fest. Or maybe you can buy one from a ham in your neighborhood who has no interest in homebuilding.

2. A heavy duty, 100 watt soldering gun and a fine pointed small 25 watt pencil or gun

You need both. The big soldering iron is important for soldering antenna wires and heavy work. A fine pencil is essential to solder the leads on fragile components like transistors and integrated circuits.

3. 60/40 Rosin core solder, fine and coarse sizes

Rosin core solder (60% tin/ 40% lead) is used for joining wires whenever reliable electrical conduction is the primary goal. The rosin flux is built into the wire-like solder, so you never have to apply solder flux. Acid core solder is used for structural purposes. It is not usually recommended for electrical use because the acid continues to corrode the metal for years afterwards. Eventually residual acid may result in a poor electrical connection. However, *a roll of plumber's acid core solder is nice to have around.* Sooner or later you will be building an antenna or some other project that forces you to solder copper wires to steel. Since nothing else works, a bit of acid core solder can be a lifesaver.

4. Fine needle nose pliers and diagonal cutters for bending and clipping tiny leads

These should be high quality and your best pairs should be almost small enough to fix watches. In fact, if you use modern "surface mount" electronic components, you will also need fine pointed tweezers to manipulate the parts*. A cardinal rule about fine tools is NEVER use them on large wires and parts.* These delicate tools will be ruined instantly if you try to cut steel wire with the small diagonal cutters or use the needle nose pliers as a wrench. A hemostat can be useful for holding small parts in place while you solder. A non-conductive plastic screwdriver is helpful for adjusting trimmer capacitors in situations where the adjustment screw is floating above ground.

The yellow-handled tool in the collection below is a wire stripper for removing plastic insulation from wires. A pocket knife is also nice to have for stripping insulation off the ends of enameled and Teflon insulated wire. These kinds of insulation cannot be removed gracefully with a wire stripper and must be scraped and carved off with a knife blade. A set of tiny jewelers' screwdrivers is also useful.

5. Microscopes & reading glasses

Even if your eyes are much better than mine, you'll need a strong magnifying glass to inspect your solder connections. Often tiny whiskers of solder or bits of thin wire short out connections. Other times a solder joint looks OK from a distance, but under extreme magnification, the piece is not actually making contact with the desired terminal. These problems usually can't be seen with the naked eye and you might spend hours looking for a problem you could have noticed immediately with a glass. I routinely examine each solder connection with my lens before moving on to solder the next component. I use pocket microscopes, a strong magnifying lens and over-the-counter, strong (+3.50) reading glasses for this purpose.

6. Heavy needle nose pliers, heavy-duty diagonal cutters and small wrenches

You will often need large versions of the delicate tools. Use them when appropriate. You will also need a vise, assorted files, a hacksaw, and hole reams for shortening and mounting PC boards and heat sinks.

7. A set of wood carving gouges

"A set of what?" you ask. Wood carving gouges are a kind of delicate wood chisel with a cupped end. I use them for cutting traces on blank printed circuit boards. You will find they work well for making one-of-a-kind prototype printed circuit boards. In my opinion, carving a circuit board is superior to any other method I have seen for homebuilt radio frequency circuit boards. (Other folks prefer the Superglue and disk method described in chapter 6.)

8. An electric drill

An electric drill is used make holes in PC boards and heat sinks.

9. Male Thread taps

Rather than assemble your entire project with machine screws and nuts, you'll find it's often simpler and more professional to tap threads into the aluminum heat sinks and brackets. I find 4-40 and 6-32 threads to be the most useful sizes.

10. A high quality multimeter

Modern digital "multimeters" measure voltage, current and resistance. Fancy ones may also measure frequency, conductance, capacitance, decibels, temperature and other parameters. All multimeters are based on a high input impedance voltmeter. A quality modern meter has an input resistance (impedance) of 10 million ohms. High impedance is needed so that the measurement doesn't load down the circuit and alter what you are trying to measure. Old-fashioned electro-mechanical meters have impedances as low as a few thousand ohms. A quality meter is also extremely accurate. Measurements of a certain voltage or resistance will be correct to several decimal points. ***Don't be cheap with this item.*** It is the core of your electronic measurement capability. If you expect to take the meter outdoors to work on the car or up onto the roof to do antenna work, then maybe you should also buy a cheap multimeter you can afford to break.

11. A high quality oscilloscope

The oscilloscope is another foundation of your laboratory. The traces on the screen tell whether your device is working and how well. Without a scope, you are almost blind. Perhaps the most amazing achievement of people like Edwin Armstrong is that they were able to do their work by inferring the function of circuits from secondary measurements. For example, the plate current of an RF amplifier tube dips when resonance is achieved. However, it's so much easier to just look at the signal with a scope and WATCH the actual sinewave while the circuit is tuned.

A first rate oscilloscope might cost $10,000 brand new. But there are advantages to living in the 21st century. One of them is that 20 year old $10,000 oscilloscopes are all transistorized, still first-rate quality and you can buy a used one for $300 or $400 dollars. The prime consideration is that the scope must have a frequency rating higher than the frequencies you will be working with. For HF ham radio, 50 MHz is enough, but you can find used scopes that will go as high as 1000 MHz.

The oscilloscope is connected to your project by a "*probe*." A probe is a 3 to 6 foot long coaxial cable with a ground wire clip and a little "grabber" at the end that hooks onto the wires carrying the voltage waveforms you want to look at. Probes usually have a 10:1 voltage divider that protects the oscilloscope from high voltages you may be measuring. Not all probes are created equal. ***For high frequency radio work you need a short probe with minimum capacitance***. If you buy a probe, look at the specifications to see what kind of capacitive load you are putting on your circuit.

For example, if your circuit is tuned by a variable capacitor that ranges from 5 to 60 pF capacitance and your probe has 50 pF of capacitance, the probe will totally dominate the circuit tuning. In general, a good RF probe has a short cable and a short ground lead. Of course even 5 pF is a significant load. So when I'm tuning a circuit, I try to tune one stage of an amplifier, while I use the scope to monitor the signal in the <u>following</u> stage. That way, the tuning of the first stage will not be affected by the probe.

12. A frequency counter

As soon as you as you build your first ham transmitter, you will need to prove that your transmitter is operating inside the ham band. Also, we hams are supposed to limit our transmissions to one frequency, not splatter all over the band. By definition, a pure sinewave is a single frequency. My solution is to routinely monitor the frequency and shape of my RF sinewave right at the base of the antenna. If it looks like a good sinewave on the scope, the signal is almost certainly clean.

You can estimate the frequency of the sine wave by using the horizontal marks on the oscilloscope screen to measure how long it takes to complete a complete sine wave. If you count grid squares on the screen, you can measure the frequency of a sinewave to about 10 or 20%. Unfortunately, that isn't nearly good enough. For example, if your transmitter frequency is 7.05 MHz, one complete sine wave will take 0.142 microseconds. You won't be able to read it closely enough be sure it isn't really 0.143 microseconds and just outside the 40 meter band. You really need a frequency counter.

Some sophisticated oscilloscopes have built-in frequency counters to measure the exact frequency of a signal. Almost certainly, you will have to buy a separate frequency counter to tell you exactly where you are to the nearest Hz. You can buy a new, quality counter for $2,000 or more. Or you can get a new, cheap frequency counter for $200. The best bargains are first-rate used frequency counters. You may be able to buy one for under $100.

13. A quality short wave receiver

Aside from using it to hear other hams, a good quality, commercially manufactured shortwave receiver can serve as a laboratory instrument. A modern receiver is so well calibrated that it may be used as a substitute for a frequency counter. Also, it's important to be able to listen to your own signal in a receiver to be sure that it doesn't have subtle defects that may be hard to see on an oscilloscope. Ideally, you should have both a counter and a calibrated receiver.

14. A laboratory power supply

A laboratory power supply allows you to apply voltage to a circuit cautiously. This will usually prevent component damage due to wiring errors or other problems. Meters tell you how much current is being drawn and the voltage applied. This particular old power supply is actually three separate supplies. For example, you might use the 5 volt supply to power a microprocessor, while the other two variable supplies could be set up to deliver + 12 volts and – 12 volts for operational amplifier circuits.

15. An RF frequency generator

This is a tool you will eventually want.   But if you have everything above, it isn't essential. The RF frequency generator allows you to inject a sinewave of known amplitude and frequency into an amplifier so that you can align it. When aligning a homebuilt receiver, it is nice to have a known test signal you can listen to any time you want.

16. A capacitance meter

While not essential, you can use a battery-powered capacitance meter to sort out your junk drawer and give a reliable indication of capacitor size. I find it extremely useful for determining the maximum and minimum set points on trimmer capacitors.

17. Catalogs of electronics parts suppliers

You will need at least 3 or 4 catalogs. I like RF Parts Company, Jameco, Digi-Key, Newark, Mouser and Radio Shack. Hopefully you have a Radio Shack store in your area in case you need some routine part in a hurry.

18. Your very own junk collection

As Edison said, it is important to collect junk parts so that you aren't continually waiting for parts to arrive in the mail. Considering that a capacitor or potentiometer costs a few dollars new, it is easy to spend hundreds of dollars on a project. If you are **not** getting most of your parts from old TVs and ham swap-fests, your project will cost a fortune and will proceed slowly. Never throw away an old radio or computer without first cannibalizing it for useful parts. Organize your parts in bins, parts drawers and labeled boxes so you can find them when you need them. If you can't find a part when you need it, junk is just junk.

19. A laboratory notebook

Your memory isn't half as good as you may think. Write down all your experiments, triumphs and especially your failures. The experiment that doesn't work is just as important as the experiment that did.

20. A simple calculator

You probably already have a calculator that will be adequate for the simple component value calculations you must do. Square roots may be the most complex calculation you'll perform on your way to your first two-way ham radio contact.

When I was in engineering school, the calculator age had not yet arrived. We young engineers swaggered about carrying big sliderules that hung from our belts like swords. We were

very cool. When I sat down in class to take a test, I would ceremoniously draw my sliderule from its sheath and check to see that the upper scale was perfectly aligned with the lower scale. If it wasn't lined up perfectly, I used the blade of my pocketknife as a screwdriver to adjust it. For me this ritual was something like a US marine checking out his rifle one more time before hitting the beach.

For you whippersnappers who haven't used sliderules, these antiques do logarithms, calculate trigonometric functions, take squares and square roots and do almost everything you can do on a simple "scientific" calculator. The point of this archaic story is that sliderules don't do decimal points. Therefore, to get the right answer, we had to have a FEEL for the math. We had to be able to estimate the answer so that we would know what order of magnitude it would be and where to put the decimal point. In other words, we had to know what we were doing. The sliderule expanded our skills. It did not replace them.

When calculators came out, engineering students suddenly began to fill their test papers with random numbers. Beginners think that, if they push the buttons, the calculator is doing the thinking for them. Wrong. It turns out that calculators really aren't different from sliderules. The students must estimate the work in their heads so that they will know if they have pushed the right buttons. After the students mastered the ability to estimate, calculators became a boon to engineering.

Software for experimenters

I hesitate to mention circuit simulation software. I am a rebel against the modern age of smug engineers who have never soldered a wire. I don't like the trend of increasing specialization and generalized ignorance that is spreading through the technical industry. Spice programs are very much like calculators. They're wonderful if you can estimate what the circuit should do before you activate the simulation. Once you get very far into building ham gear, you will probably get tired to doing everything the hard old way. There are many different simulation programs available that allow you to emulate a circuit on your PC computer before you build a real circuit. Like most modern conveniences, this one is truly marvelous. However, Spice should complement actual circuit testing, not replace it.
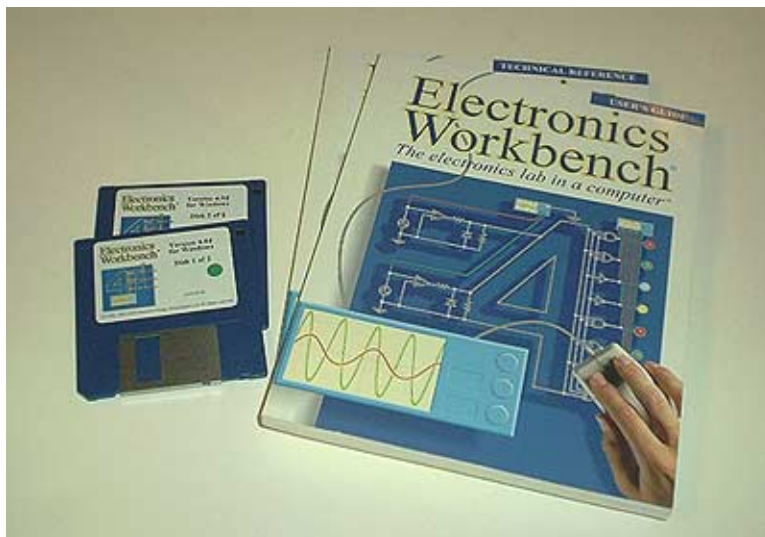
I use an old **Electronics** **Workbench** "Spice" program, but there are probably many newer ones that work as well or better. Mine is a simple program that will not simulate some components, such as crystals or some kinds of circuits like oscillators. I really like it for simulating filters. If I need to build a filter with a certain cut-off frequency, but I don't have the right parts, I can simulate substituting parts and see how critical the values are. Actually, it's so much fun trying out circuits with so little work, that it's almost addictive. Also, other problems in my design become obvious that I had never thought of.

For example, I built a filter for a ham transmitter that was designed to eliminate interference to the neighbors' TV reception. (See chapter 9.) Any transmitter signal has minor "impurities" in its frequency spectrum. This means that it can easily be radiating weak signals on the TV channels. A filter will reduce these harmonics. Before I built my filter, I took the time to model it on the Spice and found that, as I had planned, it severely reduced interference on channels 2, 3 and 4. Above those channels, the attenuation of possible harmonics was not nearly as great. For the upper UHF channels, there was hardly any attenuation. Once I saw the problem, it was easy to add a couple more stages of filtering to insure that *all* TV channels were protected.

Test leads and experimental "socket" circuit boards
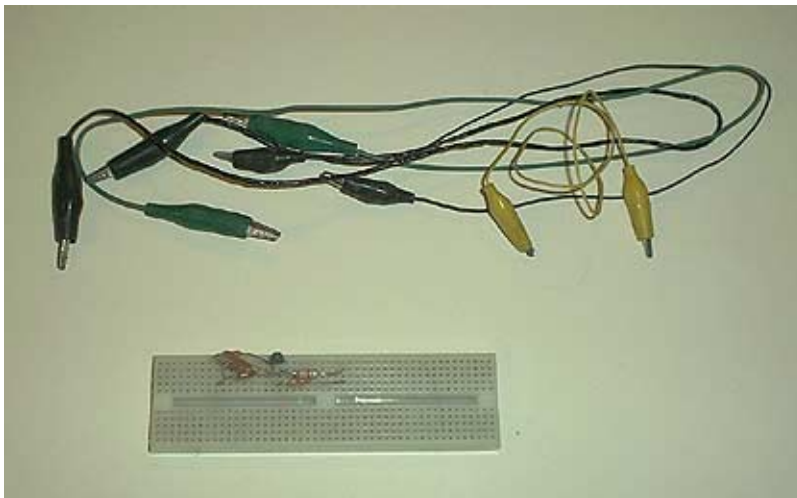
Every electronics lab has handfuls of test leads and a few temporary circuit boards. Although I routinely use these, I am hesitant to recommend them. *ANY ELECTRICAL CONNECTION THAT ISN'T SOLDERED CAN'T BE TRUSTED!* Yes, it's true that these gizmos often work, but many times I have been led to believe that parts were bad or that circuits didn't work when they actually worked fine.

Let me illustrate: Once when I was in the Air Force I had to wire some explosive squibs on a 1500 pound cargo parachute load. The squibs were supposed to explode and deploy the parachute. I passed the bare, scraped copper wires into two tinned metal eyelets, then wound the wire through the eyelets again and again until the eyelet holes were stuffed with clean, bare wire. Then I wrapped the remainder of the bare copper wires tightly around the outside of the metal eyelets and wrapped the whole thing securely in tape. I thought there is no way that the copper wire wasn't in good contact with eyelets! The huge box fell 3000 feet and crashed into the dirt at a couple hundred miles an hour. The squibs never fired. I checked the firing circuit with my

meter and found the proper 3 volts across the squibs. I unwrapped the tape from the eyelets. The squibs exploded as soon as I tugged on the bare wire. After that day I soldered my squib wires and never had another failure.

Pliers for crimping connectors and eyelets

What about the special pliers used to crimp connectors and eyelets? Some metal eyelets and lugs are designed to be installed onto wires using special crimping pliers. Yes, crimped connections can be fairly reliable in the short run. However, in my experience crimped wires pull out easily and, after several years, they often become open circuit. I have seen dozens of failures on old equipment. Personally, when I use eyelets on leads, I always solder them. Eyelets that are screwed down to sheet metal are fairly reliable. However, I always solder the wire onto the eyelet (rather than crimp it) before I screw it down.

In conclusion,

The equipment described above should get you started. Everyone has different ideas about what works best and what is essential. For what it's worth, the above list pretty well describes my workshop.

CRYSTAL SETS TO SIDEBAND
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Chapter 4
HERTZIAN WAVES IN THE BASEMENT

Crystal set radios and ancient spark gap transmitters from the 19th century may seem too simple and too far removed from ham radio to be worth building. If you're already familiar with basic electronics and early radio history, you may not learn anything from this exercise. If you're dying to build a real ham rig, please skip ahead to the next chapter. On the other hand, if you have little electronics experience, there are worlds of lessons to be learned from old technology. And if you've never built simple radios before, you should find it fun.

The nature of radio waves

Before we build transmitters and receivers, let's review radio waves. When we understand what radio waves are, the technology to generate and receive them becomes more obvious. An electromagnetic wave is an oscillation in free space that radiates out away from its source at the speed of light. It is called "*electromagnetic*" because it is both electric field energy and magnetic field energy. The wave "oscillates" or changes back and forth between these two forms of energy as it travels.

Propagating across vacuum

From our experiences with magnets and static electricity, it's hard to visualize how a magnetic or electric field can travel millions of miles across the vacuum of space. In our experience these fields are tightly localized around the device that generated them. How can a magnetic field exist isolated in a vacuum, perhaps even light years away from the nearest atom? Suppose we could somehow magically generate a magnetic or an electric field in space, miles from the nearest object. Would the field just sit in space forever waiting for an object to pass by and be influenced by the field?

Let's suppose there is a refrigerator magnet floating in the void of space. Its magnet field will be at rest in the space surrounding the magnet, just as it does on your refrigerator. As always, the magnetic field will reach out its usual distance of a quarter inch or so. However, if the magnet were to suddenly vanish, the energy in the field would lose its "container" or "anchor" and be loose in the void.

The same scenario can be proposed for an electric field: If a flashlight battery were floating in space, the electric force would extend perhaps an inch out into the space in a halo around the two battery terminals. Again, if the battery suddenly vanished, the electric field energy would lose its generator and be stranded in the void. Without its anchor, it would spill out in all directions.

Oscillation occurs when two form of energy rhythmically change back and forth

When magnetic and electric fields are turned loose in space, what becomes of them? As James Maxwell first explained over a century ago, electric fields and magnetic fields are intimately related. It turns out that *a changing or moving electric field generates a changing*

magnetic field and vice-versa. As the energy continues to "spill" out in all directions, the energy oscillates back and forth between these two kinds of fields. This connection is not "obvious" or intuitive. If it were, the Greeks, Chinese or Egyptians would have described and exploited it long ago.

Mechanical oscillators

Many physical devices in our world "oscillate," so oscillation between electric and magnetic fields should not be a surprise. An oscillation in nature can be described as energy spontaneously transforming from one form of energy into another then back again. For example, as a clock pendulum swings back and forth, the pendulum acquires the kinetic energy of motion as it swings through the bottom of its arc. Then, when the pendulum swings back uphill, the energy contained in the kinetic energy is returned to gravitational potential energy. When the pendulum reaches the top of its swing, it momentarily comes to a complete halt, turns around and races back downhill. When it is at the top, the energy is all "potential." A boulder sitting on the lip of a cliff doesn't seem to have any energy until it is nudged off the cliff. The fellow standing at the bottom of cliff can testify that the rock had plenty of energy when it slams into the foot of the cliff. (That assumes, of course, that he survives.)

Boulder on edge of cliff. It has zero kinetic energy, high potential energy.
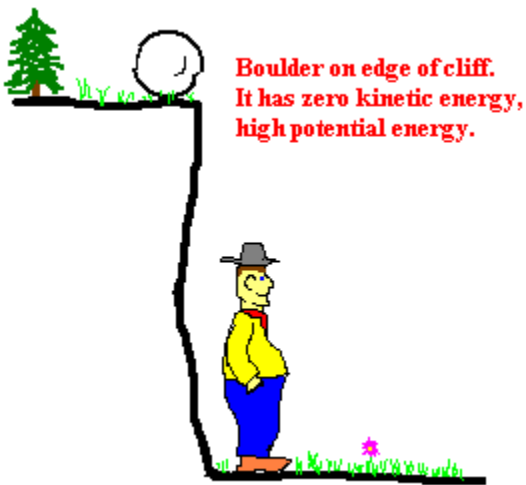
To reiterate, an oscillating pendulum switches its energy back and forth between kinetic energy and potential energy. Notice that the length of the pendulum establishes the frequency of the oscillation of a pendulum. This is because gravity is constant and lightweight things fall just as fast as heavy things. If you ignore air resistance, the frequency of the pendulum swing is determined solely by the length of the pendulum arm. This makes a pendulum good for keeping a mechanical clock running uniformly and accurately. Similarly, once the frequency of a radio wave is established, it doesn't change frequency as it races through space and becomes weaker.

Maximum potential energy at top of arc

Maximum kinetic energy at bottom of arc.

In summary, free space (which is literally "nothing"), can support magnetic or electric field energy, but only temporarily. To be maintained, a magnetic field needs to be generated by a device. ***Or it can be generated by a nearby collapsing electric field.*** Similarly, as the magnetic field collapses, it produces a temporary electric field in the adjacent space. The result of this seesaw is a radio wave traveling outward across the void at the speed of light.

To generate radio waves, we need to build a device that will produce a decreasing electric field that will in turn generate a rising magnetic field adjacent to the generator. Once we've done that, the magnetic field should generate an electric field in the space beyond and a radio wave will be launched. Alternatively, we can build a device to generate a changing magnetic field which will in turn generates a changing electric field and so on.

Transmitter antennas are designed to generate either a rapidly changing electric field, or alternatively, a rapidly changing magnetic field. The antenna is placed out in the open with free access to the sky. The electric or magnetic fields around the antenna create the opposite kind field and the result is a free-flying radio wave. The same antennas work well for receivers. As radio waves flash past the metal antenna elements, electric currents are induced into the structure just as if it were temporarily a capacitor or a secondary loop of a transformer.

The LC circuit, the fundamental electronic oscillator
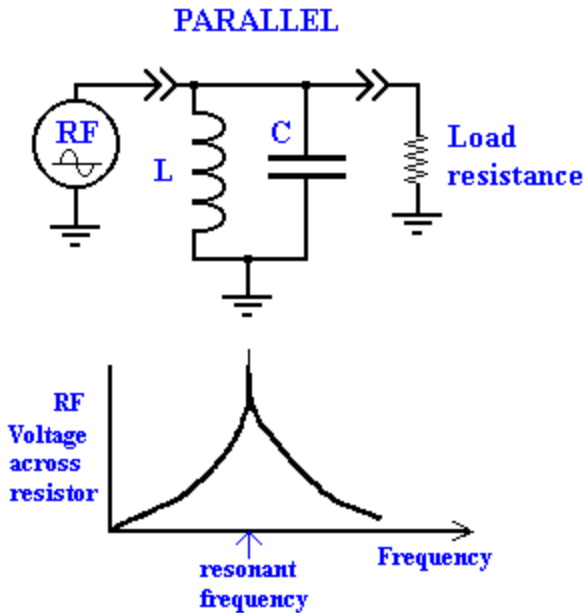
PARALLEL

The most fundamental component of all radio transmitters and receivers is the ***capacitor/ inductor parallel resonant circuit***. This basic circuit consists of an inductor wired in parallel with a capacitor. These are called "LC circuits" where "L" is the letter used when calculating inductance and "C" of course stands for capacitor. If a high frequency sinewave voltage is applied across the parallel LC circuit, there is a specific frequency at which the LC circuit resonates and appears to be an open circuit. At all the other frequencies the LC appears as a load or short circuit. The LC circuit attenuates or eliminates the sinewave at every frequency except one. In this way one radio signal can be "tuned in" preferentially over another.
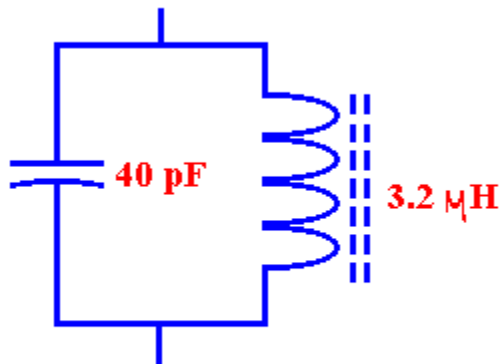
20 Meter   RESONANT CIRCUIT

For example, the circuit above resonates at 14 MHz, the 20 meter ham band. The tiny inductor is just 3.2 microHenries. The capacitor is only 40 picoFarads which means 40 millionths-of-a-millionth of a Farad.

The LC circuit is a kind of electric oscillator. It is analogous to a swinging pendulum or a weight bouncing up and down on a mechanical spring. The LC oscillator goes through the same

energy cycle as radio waves. First the energy is stored in the magnetic field inside and around the inductor. During the next half cycle, the energy is stored in electric field between the plates of the capacitor. The energy alternates back and forth between these components until it is dissipated by the resistance in the wires.

A parallel resonant LC circuit with dual antennas forms a simple transmitter

Significant energy can also be leaked off into the space around the LC circuit as radio waves. Therefore, once we get an LC circuit to oscillate, we are already on our way to generating radio waves. *If we simply add wires to the ends of the parallel LC circuit, these wires form an antenna to couple the electric field to the free space around it.* In other words, the simple circuit shown below is a crude radio transmitter.
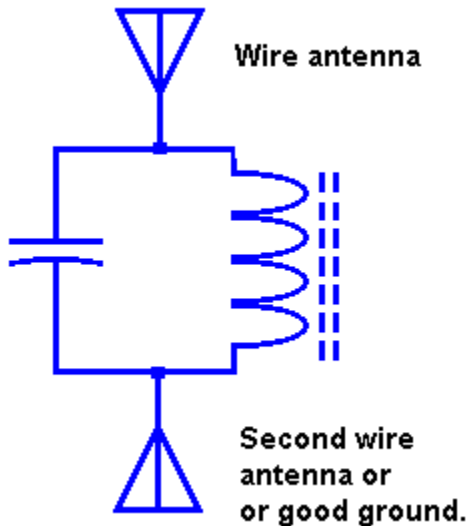
A receiver of radio waves can be built in the same way. Imagine that an identical parallel LC circuit with antennas is tuned to resonate at the same frequency. Now imagine that this second circuit is floating in the void, perhaps miles from the transmitting circuit. When the radio waves radiate past the receiving LC circuit, the electric field component in the radio wave will produce a tiny surge of current in the wires that charge the capacitor. Alternatively, and depending on the orientation of the coil with respect to the radio waves, the magnetic component of the radio wave will induce a tiny voltage to appear across the coil. This is the same as if the inductor were the secondary of a transformer. Once the radio wave has zoomed past, a tiny, miniscule oscillation will remain in the receiving LC circuit, ringing back and forth between the inductor and capacitor.

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CRYSTAL SET RADIOS

A crystal set radio is an excellent first radio project. They have few parts and are easy to understand and build. Crystal sets were a common toy when I was a kid and my first electronic project was building one. Although we kids played with crystal sets, we didn't really understand them. When they didn't work, we had only the haziest notion of how to fix them. If you bought

a commercial toy crystal set, I never saw one that had explanations even remotely as complete as what you are now reading. Starting with the crystal set, later on we can build on what we learn to build transmitters and more elaborate receivers.
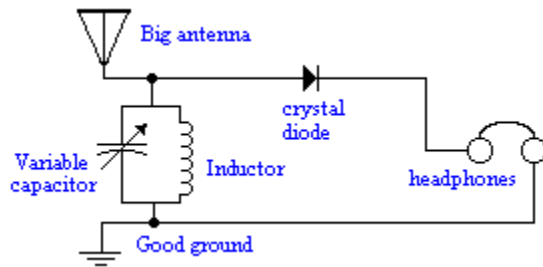
Crystal sets have six basic parts. The antenna of course picks up the signal from the air. The combination of inductor and capacitor tune in the desired station. That is, the inductor and capacitor oscillate at the frequency of the desired station. The crystal diode rectifies the sinewaves oscillating across the LC circuit. This converts the high frequency sinewaves into low frequency sound frequencies that can be heard in the headphones.

The antenna

For crystal sets it is easiest to build an "electric field" antenna. It is usually just a long piece of wire strung out a window or up in a tree. A limitation of a single wire antenna like this is that, when the radio wave generates a voltage on the wire, the current it might produce has no where to go. A simple wire antenna is like one terminal of battery. Yes, the battery has a voltage, but without a connection to the other terminal of the LC circuit, the current has no circuit to flow through. To provide a destination for the current we can add a second antenna. Alternatively we can connect the crystal set to "ground."

The ground

Electrical "ground" is a word that we learn as youngsters, but most people go through their whole lives without ever understanding it. I suspect that the term arose during the early days of telegraph communication in the 1840's. It turns out that wet earth is a fairly good conductor. If you drive two metal stakes into the ground in your backyard and connect a battery to the two stakes, current will flow from one stake to the other. For two stakes about 100 feet apart, the ground has a resistance of about 100 ohms. It turns out that most of the electrical resistance to current flow occurs right around the stakes. Once the current gets launched, the electrical resistance only increases slightly as you increase the distance apart. A metal stake in a backyard in China and the one in your backyard in the US might only have 300 ohms resistance between them. This was a boon for early telegraphers because it meant they only had to string one wire between cities instead of two wires to complete the circuit loop. In practice, using ground as an intercity "wire" is not as reliable as stringing a second wire, but it illustrates the concept of ground.

Metal stake
driven into
ground.

The entire
Earth

Metal stake driven
into ground on far
side of world.

Ohm
meter
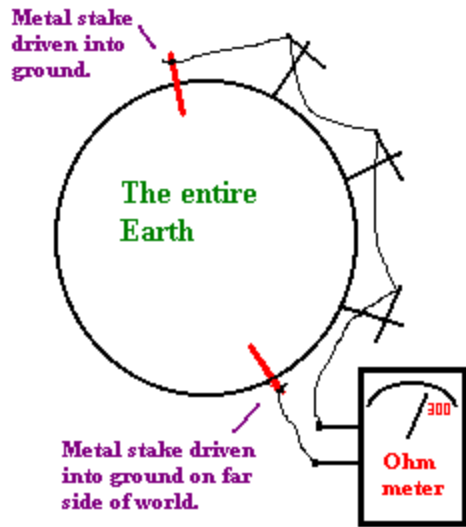
A good electrical connection with ground is an essential component of the crystal set. The most accessible ground for a crystal set or a ham radio station is usually a copper water pipe or a hot water heating pipe. At low frequencies, like standard broadcast AM, ideal electric antennas are very large. Needless to say, being able to use the entire Earth as half of the antenna is often quite convenient.

Dipoles

Unlike low frequencies, at high frequencies, like VHF television or FM radio, the ideal length for an electric antenna is just a meter or so. So although you could use a stake driven into your lawn for the "ground" path on your TV, it is much simpler to just use a second short antenna oriented 180° away from the "real" antenna. This dual antenna is called a "*dipole*" and is the most common basic antenna design used in ham radio and TV antennas. Although it isn't obvious, the arrays of thin metal tubes on roof tops are just refinements of the basic "dipole antenna." A common and versatile ham antenna is the dipole shown below. In general, the lower the frequency, the larger the dipole must be to work well. A typical ham radio dipole is shown below.

$$\text{Length} = \frac{468}{\text{MHz}}$$

Copper wire

Solder joints

Plastic strain
relief

Plastic insulator

Guy wire or rope

50 ohm coax, RG-58U or equiv.

Center conductor goes
to transmitter, outer
braid goes to ground.
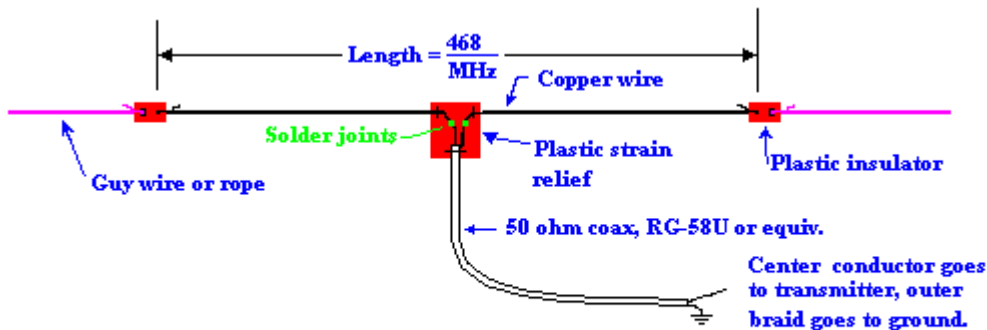
For 40 meters the length is 66 feet. The coax feed line
can be any length, but shorter is better.

Transmission lines

In the ham radio dipole antenna above, the "arms" stick out in space in opposite directions and snag the passing electrical field. In general, the higher the dipole is above the local terrain, the better the dipole will receive signals. Unfortunately, you and your radio are down on the ground. Climbing up on the roof to listen to the radio is inconvenient, to say the least. The problem of how to move radio frequency signals down to the radio is solved with a "*transmission line.*"

A transmission line is a pair of parallel wires separated by insulation. It works very much like a speaking tube in a ship or even the string in a tin can telephone. In all these devices, vibrations are transmitted down a narrow pathway with surprisingly little loss of energy. A terrific example of a mechanical transmission line can be a farmer's ditch filled with water. Provided the water is flowing slowly, when you throw a big rock into the ditch, the wave from the splash will travel hundreds of yards before it dissipates. A wave in the ditch propagates unchanged for many minutes and travels great distances. In contrast, if you throw a rock into an open pond, the wave spreads out in all directions and quickly vanishes.

Each conductor acts like a series of inductors

Parallel wires separated by insulation act like capacitors
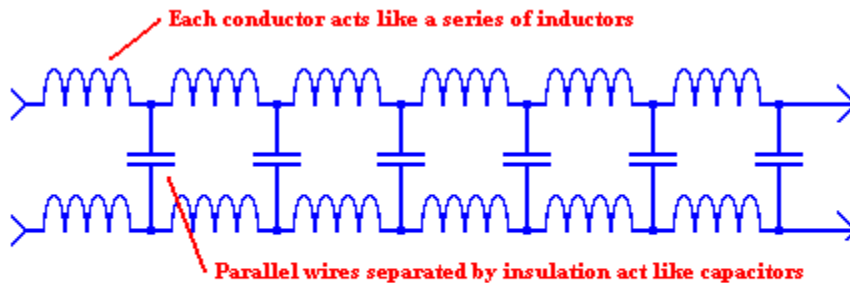
Two parallel wires separated by insulation make up a transmisison line.

A radio transmission line is a distributed, LC resonant circuit. We saw in the chapter 2 that a simple wire has inductance. Similarly any two wires separated by an insulator comprise a capacitor, whether we planned on making a capacitor or not. Consequently, when we run two parallel, insulated wires over any distance, there will be a measurable capacitance between them and the wires will have a significant amount of inductance. To a radio wave, this construction looks like a long, LC circuit without end. As the capacitance and inductance are charged and discharged, the oscillation doesn't stand still, but rather moves down the pair of wires at nearly the speed of light. As you can see, propagation down a transmission line is analogous to propagation through free space, but it propagates only in one dimension instead of three dimensions. The electric field or voltage generates a current and magnetic field, which, in turn, generates a new electric field and so on. An example of a simple transmission line consisting of two parallel wires is the flat wire "300 ohm" TV line used to feed older TVs.

Coaxial cable

The round, shielded transmission line used to feed modern TVs is a *coaxial cable*. Instead of using two separate ordinary wires, the outer conductor of a coaxial cable is a metal cylinder that completely encloses the center conductor. The inductance of the shield conductor is far less than that of a simple wire, but it keeps the radio frequency signals on the inner conductor

from leaking out. Even better, it keeps new signals from leaking into the cable and interfering with TV reception.

The inner conductor is a simple wire surrounded with thick insulation.

The outer conductor is a cylindrical, metal shield that is usually grounded.

A coaxial cable is a transmission line with a cylindrical, outer conductor shield.
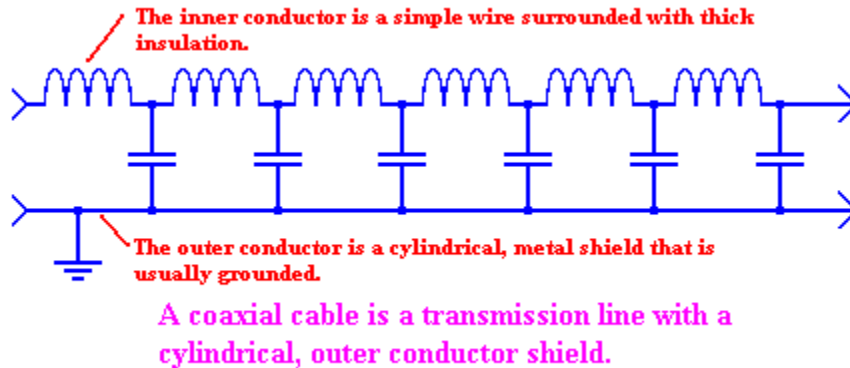
The ham radio dipole antenna described earlier uses type RG-58 coaxial cable to transport the radio frequency signals down into the house. You will notice that the outer shield is connected to ground. This is nearly always the case with coax. You could use cheap TV coax cable for your ham transmitter, but you will find it difficult to work with. The outer shield of cheap coax is just aluminum foil and is difficult to connect mechanically and electrically. In contrast, the outer shield of quality coax is braided copper wire that is easy to cut and solder. It also has considerable mechanical strength.

Transmission line impedance

An abstract characteristic of transmission lines is, that to a traveling radio signal, the line "looks like" a specific load resistance. For example, RG-58 coax appears to the radio signal to be a 50 ohm resistor. It isn't, of course, but the voltage and current levels along the wire suggest that it is. In other words, voltage divided by current at points along the line will give 50 ohms. Another reason not to use TV cable is that TV cable is usually designed for 75 ohms, while most ham equipment is designed for 50 ohms.

In general, the finer the wire and farther apart the two conductors of a transmission line, the higher the characteristic impedance. The flat, brown, ribbon transmission line that was formerly in common use for TV antennas has an impedance of 300 ohms. Sometimes hams use a wide "ladder line" in which bare copper conductors are separated by an inch or more of air and a few ceramic separators. Ladder line often has an impedance of 600 ohms. Ladder line is useful when transmitter power must be transmitted great distances to get to the antenna. Because a ladder line has little or no insulation in contact with the wires, the small dissipation of energy in the insulation is reduced to the absolute minimum.

Diode detectors

The diode is the "***detector***" that converts radio frequency sinewaves into audio frequency electric waves, ready to be converted into sound. The diode is a "one way electricity valve." In plumbing terms, it works like a check valve. The schematic symbol for a diode is an arrowhead pointed at a barrier at right angles to the wire.

In electronics, the convention for "***positive" current flow is from positive to negative***. Unfortunately, the flow of electrons is from negative to positive. So, what is actually "flowing"

from positive to negative is the <u>absence</u> of electrons. Confusing, no? I suspect this convention was established before electrons were understood. Referring to the symbol for a diode, positive current is allowed to pass if it flows in the direction of the arrowhead. Positive current will be blocked by the diode if it attempts to enter the diode from the perpendicular "barrier" side.

Semiconductors usually perform the check-valve function of diodes. A semiconductor is a crystal of an element like silicon or germanium that has a chemical valence of 4. That is, during chemical reactions this element can either take up 4 electrons, or give away four electrons. As we shall see shortly, semiconductors can also be fashioned by making crystals out of mixed elements with valences of 3 and 5, or even 2 and 6.

N-type semiconductors

To keep it simple, let's suppose we have a pure crystal made out of silicon, which has a valence of 4. If we put some multimeter (ohm meter) probes across this pure silicon, it will act like an insulator – there will be no significant current flow. However, if we make a new crystal with just a touch of phosphorus impurity in it, suddenly it becomes a conductor. Phosphorus has a valence 5 and is almost the same as silicon in atomic weight. This means that in chemical reactions it normally accepts 3 electrons to complete an outer shell of 8 electrons. But when silicon crystal is contaminated with phosphorus, lone atoms of phosphorus are trapped among a frozen, rigid crystal of silicon. The phosphorus atom fits in the matrix, but it has an extra electron that is "loose" and free to move around the crystal. The electron can't move over to silicon atoms because they are joined with neighboring silicon atoms so that each silicon atom has a stable outer shell of eight shared electrons. However, the extra phosphorous electron can move over to other phosphorous atoms that have already lost their 5th electron. In other words, *a silicon crystal with just a touch of valence 5 impurity acts like metal.* It has electrons that are free to migrate through the whole solid. A semiconductor with extra electrons is called an ***N-type semiconductor.***

Silicon atoms have 4 outer electrons

Phosphorous atoms fit in the crystal maxtrix but have 5 electrons in the outer electron shell.

N- TYPE SEMICONDUCTOR
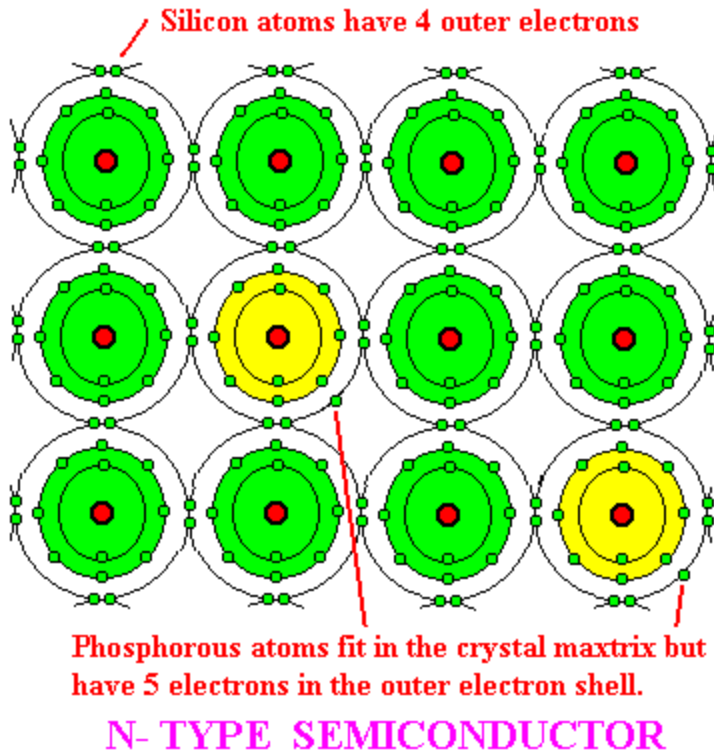
P-type semiconductor

P-type semiconductor is a bit abstract. Instead of making a silicon crystal with valence 5 impurity, now suppose we add an impurity such as Aluminum, Indium or Gallium with a valence of 3. The impurity fits into the crystal matrix, but it needs one more electron to reach an equilibrium of 8 electrons shared with its neighboring silicon atoms. In other words, this semiconductor has "*holes*" in the crystal matrix that can be filled by electrons passing through. Now when you place multimeter probes across a P-semiconductor, it will conduct just like the N-type semiconductor. However, the conduction mechanism is different. With P-type semiconductor, the negative metal probe touching the crystal supplies all the free electrons flowing through the crystal. These electrons are moving from hole to hole to cross the crystal.

Like phosphorus, aluminum atoms are almost the same atomic weight and size as silicon. Aluminum atoms fit perfectly in the silicon crystal matrix.

Silicon atoms have 4 outer electrons

hole

hole
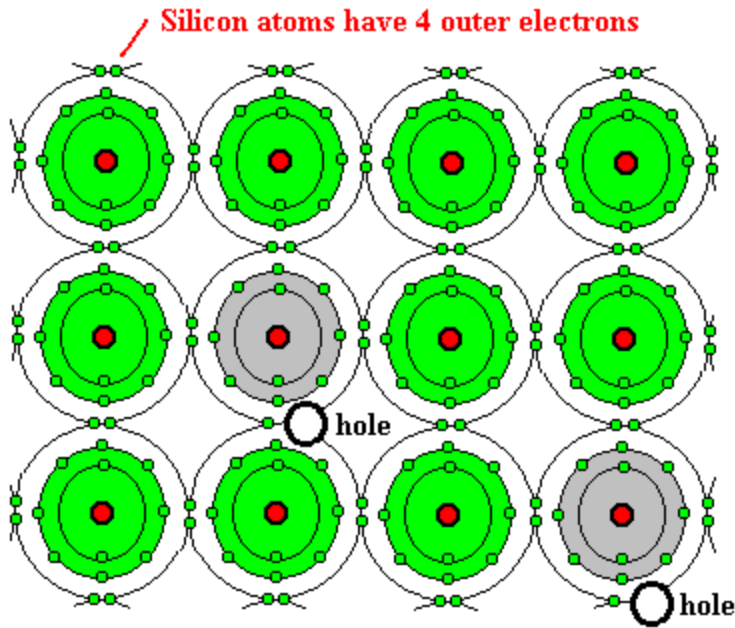
**Aluminum atoms fit in the crystal maxtrix but
have 3 electrons in the outer electron shell.**

P - TYPE SEMICONDUCTOR

Diodes are P-N junctions

Semiconductor diodes are constructed by placing P- type semiconductor in contact with N-type semiconductor. In other words, for electrons to flow through the diode, the electrons must enter the N-type crystal and then move across the junction into the P-type where they complete the journey by hopping from hole to hole.

Schematic symbol

holes   **Electrons**

P- Type   **N - Type**
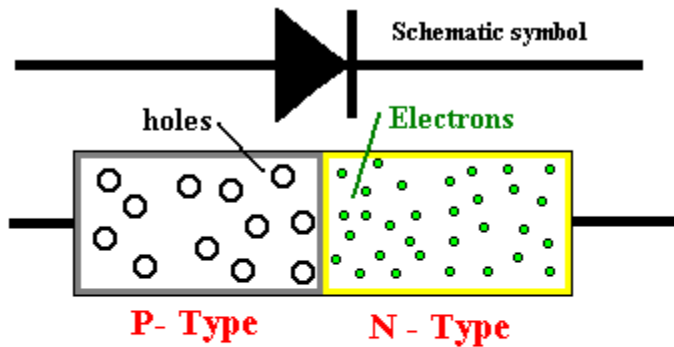
Direction of positive current flow ⟶

"Positive to P conducts"

P-N SEMICONDUCTOR DIODE

"positive to P conducts"

OK. Now let's reverse the probes of the ohmmeter. Now we are placing the positive probe against the N-type semi-conductor and the negative probe against the P-type. Electrons flow off the metal probe and into the P-type semiconductor. No problem so far. On the other side of the diode the extra electrons from the N-type silicon are being attracted or "sucked" into the positive metal probe. Thus the conduction seems to start out all right, but it isn't long before the extra electrons in the N-type silicon along the P-N junction are depleted. All that remains in this region is depleted valence 5 atoms that are now acting like pure silicon. This whole region now acts like pure silicon and the conduction stops.

So why can't the electrons that are migrating through the P-semiconductor holes hop across the P-N barrier and move onto the valence 5 atoms? The reason is the same. The migrating electrons have filled in all the holes in the P-type and the crystal has also become pseudo-pure silicon that is an insulator. When thinking about PN diodes, remember, **"positive to P conducts."**

Detection of AM radio signals with a diode

In amplitude modulation, (AM) the audio speech signal is impressed onto the radio signal by varying the AMPLITUDE of the radio signal. An AM transmitter literally increases and decreases the output power of the transmitter in time with the speech and music being broadcast. The drawing below shows an unmodulated radio signal of the sort used to send Morse code. The radio frequency sinewave remains the same amplitude throughout the time that the transmitter is keyed. Because the sinewave maintains its amplitude during the "dots" and "dashes," Morse code signals are known as *continuous wave* or "*CW*."

Unmodulated Radio Frequency Sinewave used to send Morse Code (CW).

Radio frequency sinewaves much too high frequency to hear in headphones.

One "dot" or "dash"

Expanded view to show actual radio sinewaves.
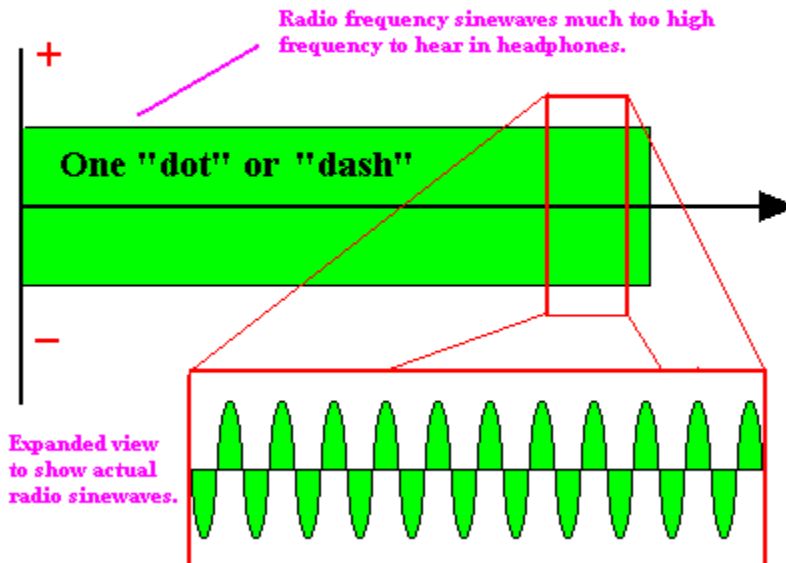
In an *AM radio broadcast, (550 KHz to 1.750 MHz)* a graph of the RF signal looks like a psychiatrist's Rorschach. But of course the outline of the audio signal is actually made up of hundreds of thousands or millions of RF sinewave cycles.

Amplitude Modulation of a Radio Wave

Low frequency, audio signal is impressed on the strength of the high frequency sinewaves.
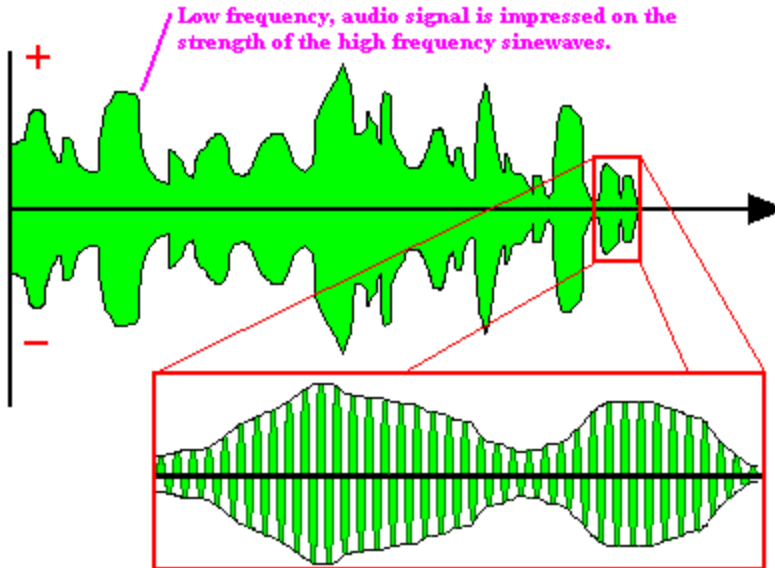
The diode detector recovers the audio signal by "shaving off" one of the two polarities of the RF signal. Sinewave currents have both positive and negative polarity. Diodes only allow conduction in one direction. So, when a radio frequency sinewave current is passed through a diode, one of those polarities will not pass and will be eliminated. What remains is a series of narrow, direct current pulses, all with the same polarity.

DIODE DETECTION OF AUDIO MODULATION ON A RADIO WAVE

The diode clips off the negative half of the radio frequency sinewaves leaving a DC outline of the audio.
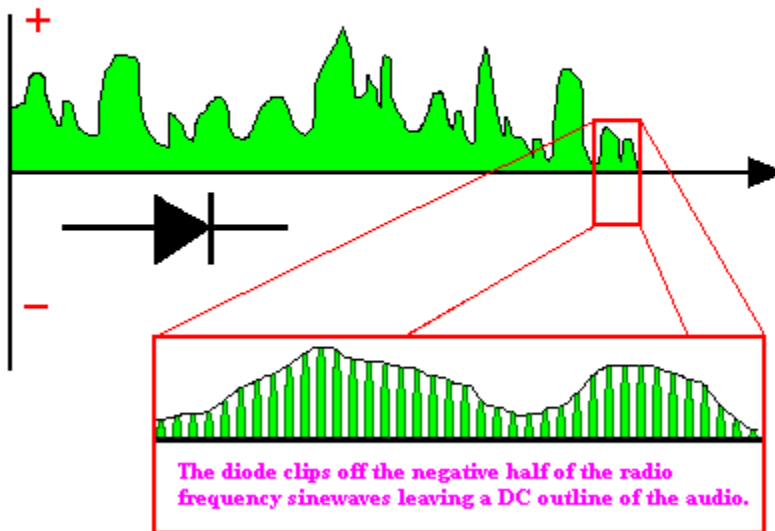
This detection process, which is also called *rectification*, produces a varying DC signal that may be passed through a headphone to convert it into sound. Physically, a modern diode is

usually a tiny glass cylinder typically ¼ inch long with two wires extending from the ends - not much to look at! As will be described below, it's more fun to make a diode out of sulfide ore, or even out of razor blades or safety pins.

Headphones

After the diode has generated the varying DC current representing the audio signal, a device is needed to convert the current into sound. The classic way to do this is to use a magnetic headphone. As we shall describe below, a headphone is an electromagnet that attracts a thin, steel diaphragm and makes it vibrate in time with the speech and music.

A practical crystal set schematic

The crystal set can be extremely simple.   A schematic is shown below:
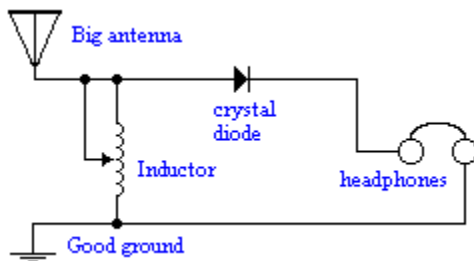
Crystal Set Parts List:

Big antenna – 50 feet of wire strung up in a tree will be ideal. Or, use the 40 meter dipole described above. For this application, use the entire dipole assembly as if it were a single piece of wire. Connect the center conductor and the braided outer shield of the coaxial cable together and fasten the resulting "wire" to the "big antenna" location above.

Good ground – A connection firmly clamped to a household copper water pipe would be ideal. Alternately, you may use a second length of wire strung up in another tree. The second wire should be far away from the first wire. I happen to have a 30 meter ham band dipole in my back yard. I used my 40 meter dipole as the "antenna" and the 30 meter as a "ground." Or, as an antenna would be known in this application, the 30 meter dipole became a *"counterpoise."*

Inductor - Wind about 20 turns of bare copper wire around a large diameter cardboard tube. Cardboard Quaker Oats boxes are the classic coil form for this purpose. In general, the larger the diameter coil, the better it works. I believe large coils work better because the coil is acting as a magnetic antenna, as well as a tuned LC circuit. In other words, a large diameter coil snags more magnetic field component from the radio wave. To tune the crystal set, you need to rig up a slider or shorting clip that allows you to short out some of the coil.

Crystal diode   It's great fun to build your own diode as described below. However, to get started, use an ordinary, small silicon diode such as a 1N4148 or a 1N914, which is available at Radio Shack.

Headphones. You may construct a working headphone from ordinary parts as described below. This will be fun and educational, but sooner or later you need to buy a good pair. You may buy either old-fashioned high impedance (2000 ohms) headphones or modern low impedance (8 ohms) headphones. The modern ones are extremely efficient, comfortable to wear and have hi-fi

sound. The high impedance headphones are historic and little more can be said in their favor.

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Homebuilt diode detectors

My experimentation with crystal sets as an adult began one day when I was hiking near Jamestown, Colorado. I was scrambling up a yellow-colored abandoned mine dump. Mine tailings up there are mostly yellow, sulfated, powdered rock that consists of broken-down granite or gneiss. Suddenly right in front of my face were chunks of the shiny, black sulfide ore that was the reason for the mine. Without an assay, I don't know exactly what's in this ore, but it's a safe bet that it's a mixture of sulfides of silver, lead, and maybe zinc, a dash of arsenic, tin and copper. There might even be a trace of gold telluride in those crystals. Galena, which is lead sulfide, is the stuff used in old-time crystal sets to make detector diodes. "Gee! I wonder if I can make a crystal set out of this ore?"

It seems to me I once saw a war movie in which a POW in a Nazi Stalag made a radio out of barbed wire, a razor blade and silver paper from a chewing gum wrapper. Well, that's Hollywood, but maybe a receiver can be built without using parts specifically manufactured for radios. I happened to have a toy crystal set radio dating from about 1950 in my attic, so I hauled it down and checked it out. The "diode" consists of a tiny chunk of gray galena sticking out of a little puddle of solidified solder. The positive pole of the diode is a metal "cat whisker," a piece of thin copper wire poked against the crystal.

The above picture shows my crystal set with all three homemade components. An LC resonant circuit is vital to select the AM radio band (or other band). An actual tuning capacitor isn't really needed at AM radio frequencies. A big coil, at very least two inches in diameter with 20 to 60 turns wound on a cardboard tube, has enough inter-winding capacitance to resonate in the AM band. From a physics point of view, the circuit in the "practical" schematic is

functionally the same as the circuit that contains the variable capacitor across the coil.

Where's the variable capacitor?

A capacitor consists of two pieces of metal separated by an insulator. If you wind a big loop of wire around a cardboard tube, then there is capacitance between one loop of wire and all the neighboring loops. "But, hold on! That can't be! They're shorted together!" you say. Yes, you're right. But if you look at an LC circuit as a whole, the inductor is a kind of "short circuit" across the whole capacitor and we know that works OK. The hard part about physics is that you have to learn to think abstractly. A lot of phenomena seem fuzzy and inconsistent. We are forced to "get a feel" for what works and what doesn't. The coil of wire is said to have "***intra-winding capacitance***" that acts the same as if it were a separate capacitor across the whole thing, honest.

Anyway, without a variable capacitor, you will have no way to tune in particular stations. A tap on the winding can be added for peaking a station. A "tap" is just a way to short out part of the inductor. Using this method you can crudely (very crudely) select the loudest stations at the top or bottom of the AM broadcast band. However, if you prefer to use a variable capacitor, homemade or otherwise, be my guest. You will find that tuning a crystal set is sloppy no matter how you do it.

The crystal diode rectifies the radio frequency voltage ringing on the LC circuit and the headphones turn it into sound. Some crystal sets also have an audio signal filter or "integrator" capacitor. This capacitor, about 0.01 microfarad, is placed across the headphones. However, in my crystal set, it didn't do anything useful, so I left it out. Leaving out parts is great way to find out what they do.

Try leaving out the LC circuit and just connect the diode and headphone to the antenna and ground. At my house all I could hear was weak static that sounded like power line noise. That implies that power lines generate the biggest AM signals over the entire radio spectrum. In any case, without the LC circuit, I heard no radio stations.

The Jamestown crystal diode

To make my crystal detector out of sulfide ore, I melted a puddle of solder about 3/8 inch wide on a piece of PC board. Then I used tweezers to press a bit of ore into the puddle so that, when it hardened, half of the crystal was exposed. Next I soldered a tiny loop of copper wire onto a pad on the board for a cat whisker.
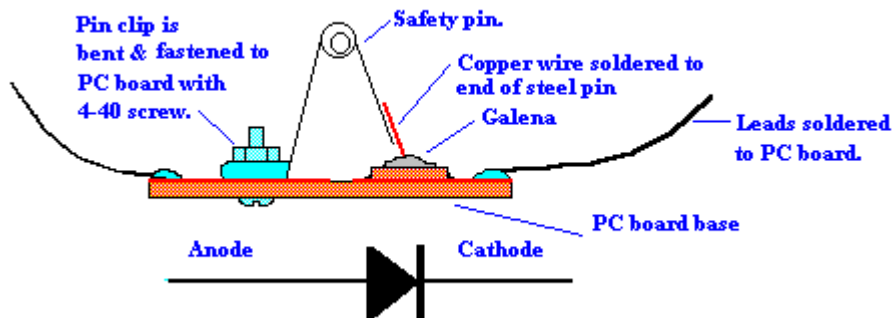
A safety pin pushes the copper whisker against the galena.

I made a copper ring cut from the end of 1/4 inch copper tubing which serves as a deep "tub" of solder into which I could push the galena. My first diodes used loops of fine copper wire as "cat whiskers." The copper wasn't springy enough to poke into the crystal with enough force for reliable performance. Bob, NØRN, told me that when he was a kid, he used safety pins as cat's whiskers. Sure enough, the spring-loaded safety pin produced plenty of force and solved the mechanical problem.

Where is the P-N junction?

If you are a thoughtful person, you must be asking, "Where is the P-N junction with the impurities imbedded in the pure semiconductor and all that?" It turns out that crude diodes can be made by throwing together pretty inferior materials. For example, pure galena crystal consists of lead and sulfur that have valences of 2 and 6, that sort of averages to 4. But there are also all those other atoms in typical galena ore. These impurities, like silver or copper have valences of plus 1, while other transition metals like tin have valences of 2 or 4. Let's just assume that because of arsenic (valence 5) impurity, my ore is a N-type semiconductor. So where is the P-type semiconductor? It turns out that if you press a metal against N-type semiconductor, metal ions will migrate a few microns into the N-type crystal and make a tiny P-type region surrounding the contact point of the "cat whisker."

As you might expect, the disadvantage of such crude diodes is that P-N junction is quite fragile. That is, the check valve function only works with very low voltages and extremely small currents. The P-N junction is easily destroyed if you put large reverse voltage across it or try to pass large currents through it.

Carbon steel is a semiconductor

When I put my new diode with the safety pin cat whisker into a crystal set, it was stone silent - nothing. No matter how I moved the sharp steel pin around on the galena, the headphones were dead. The pin happened to strike the solder at the edge of the galena and the crystal set came to life with music from KBCU, our loudest local AM station. At first I was mystified. The steel pin rectified well against either solder or copper. The signal was perhaps only 2/3 as loud has it had been with the copper-to-galena diode, but it was much easier to adjust.

It turns out that "steel" is a carbon-iron semiconductor compound. The surface of hardened steel is a crystal, perhaps not radically different from the galena (lead-sulfide) crystal. Carbon has a valence of four, just like silicon or germanium. So, if you want to build a crystal set for your kids, you don't have to find galena. Just use a safety pin pressing against copper or solder.

Another surprise for me was that copper-to-copper, solder-to-solder or solder-to-copper junctions also rectify and produce weak signals. The contact between the two metal surfaces must be extremely light - just barely touching. This phenomenon is poor for making crystal sets, but it's a warning about bad contacts in electronic equipment. ***Cold solder joints and loose screws can fill your circuit with accidental diodes.***

I tried measuring the volt/ ampere characteristic of a steel/ copper diode. As you would expect, it looks like a short circuit on an ohm-meter. I studied it carefully with a high impedance

multimeter and 10 megohm series resistors, but it still looked like a short circuit. I believe I just learned that *the world of RF detection is quite subtle*. At least the legend about POWs in WWII making radios out of barbed wire and razor blades is starting to make sense. The razor blade must have been the semiconductor.

As shown in the diode construction diagram, I used acid core solder to attach a piece of copper wire onto the end of the pin. Now the contact point of my diode is between semiconductor galena and copper rather than semiconductor steel-to-semiconductor sulfide ore. I connected my crystal set to the center conductor of my 40 meter dipole coax and my station ground. I scratched the copper whisker around on the sulfide crystal and suddenly I was again hearing our local station. Using commercial 8 ohm headphones, it was almost painfully loud. Too bad KBCU is mostly rap music.

Volt – ampere characteristics of homemade diodes

Once I had my cat whisker adjusted, the Jamestown diode was just as loud as the 1935 crystal set diode. I tried substituting a modern, hot-carrier Schottky diode for the crystal. In theory, a Schottky should be comparable to a point-contact diode. Schottky diodes are commonly used as detectors in relatively modern equipment. I was surprised to discover that the modern Schottky produced as big a signal as the crystal diodes, but no better. If these diodes perform the same, how do their volt/ ampere characteristics compare?
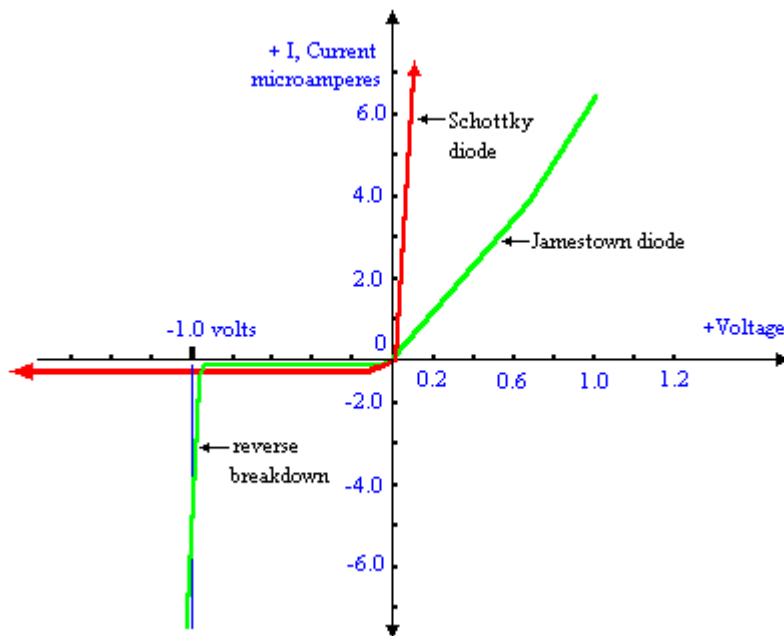
Volt / Ampere curves for the Jamestown diode and a commercial Schottky diode.

At big voltages and currents, (milliamperes), the Schottky diode acted as you would expect: It passed big currents (milliamps) above 0.2 volts forward voltage and leaked only 100 nanoamperes with reverse voltage. Notice that if the Schottky were "perfect," the red line would be directly on top of the vertical axis upward, and directly on top of the horizontal axis to the left. However at very low currents, microamperes, the commercial Schottky was pretty nearly perfect with a transition right at zero volts.

In contrast, with big currents the Jamestown diode behaved like a resistor in both directions. It wasn't obvious to me that it could rectify anything. The curves above show the behavior of both diodes at tiny current levels, microamperes, using a 1 megohm (one million ohms) load. For tiny currents, the Schottky and Jamestown diodes were both strongly non-linear at the zero current, zero voltage point. The surprise for me was that, for reverse voltages, the Jamestown diode broke down abruptly at minus one volt. It's no wonder it conducted so well in both directions with a "low" resistance 10K ohm load. This abrupt, reverse breakdown is called **"avalanche breakdown."** When it occurs with big currents it usually destroys the diode. As we'll see in chapter 8, some diodes called **"Zener diodes"** are designed to breakdown at specific voltages without being destroyed.

The Caribou headphone

Building my own headphone was the hardest part of my crystal set. A headphone uses a high impedance coil of wire to make a magnetic field proportional to the audio signal. The changing field pushes and pulls against a thin steel diaphragm to produce sound vibrations. Even if you decide to build one of these crystal sets, I strongly suggest you buy a good pair of headphones so you will have them for your ham rig. Also, with commercial headphones the speech and music will be perfectly clear and loud, even with a safety pin diode.
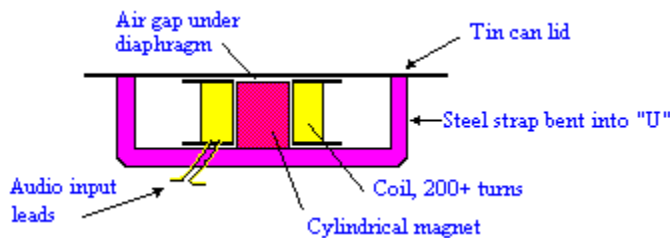
The Caribou headphone

A cross section of my homemade headphone is diagramed above. Its construction is basically the same as old-fashioned high impedance headphones. Sure the sound is tinny! What do you expect from a headphone diaphragm made from a genuine tin can lid? The coil is hundreds of turns of #36 wire wound on a paper coil form. Inside the coil is a cylindrical magnet I took out of an old loudspeaker. A piece of steel strap conducts the magnetic flux around to the edges of the lid. The magnetic force holds the lid on. By completing the magnetic circuit, the magnetic force is concentrated in the gap between the tin-plated steel and the magnet.

Crystal set showing homemade headphone. The tin can lid diaphragm has been removed.

I started out using a small magnet from an old loudspeaker, but that felt like cheating. Would Heinrich Hertz have been able to use a loudspeaker magnet? Anyway, it seemed to me that the magnet wasn't essential. Why couldn't the coil just magnetize ordinary iron? I tried substituting a big steel nut of the same size. Sure enough, it worked, but the sound was too faint to be audible in a crystal set. However, when I plugged the homemade headphone with the steel nut into my shortwave radio, it was surprisingly loud. Not Hi-fi, mind you, but loud. No, for a sensitive headphone a magnet is needed to overcome the hysteresis.

Hysteresis

What's hysteresis, you ask? Whenever iron is magnetized with a DC coil, the tiny "magnetic domains" in the iron line up to make a big magnetic field. But when the DC current is shut off, some of the magnetic domains remain aligned and leave a residual field. To magnetize the iron in the opposite direction, a current of the opposite polarity must first overcome the residual field. This means that hysteresis interferes with the sensitivity to weak signals. Since crystal sets are powered by the radio waves themselves, sensitivity is vital. A magnet is needed to overcome the hysteresis and "bias" the magnetic field so that it always operates in one direction. I could magnetize iron with a DC powered coil, but then to be a purist, I would need to build a homemade battery. And I would need to smelt and extrude my own copper wires. (Forget I said that.)

I had a sudden inspiration. I dug around in my rock collection and found a piece of magnetite ore from a mine dump at Caribou, Colorado. Magnetite is a specific iron oxide, Fe_2O_4,that retains a magnetic field. I machined the magnetite with my bench grinder into a small cylindrical magnet. Unfortunately, the grinding and heat ruined the magnetism. However, fixing it to a big, heavy permanent magnet, I was able to put my magnetite in a strong magnetic field. Then I banged on it firmly against my anvil. Believe it or not, that abuse restored the magnetic

field. Behold! - the completed Boulder County rock and toilet roll radio!

How does it perform? Well, frankly the homemade headphone is pathetic and needs lots of R&D. The sound is plenty loud when plugged into a real radio, but installed in the crystal set, I can just barely hear the rap music. Perhaps if I had a thinner steel diaphragm, a headphone for each ear, optimum impedance matching, better craftsmanship and other refinements, it might approach a commercial headphone. In other words, for serious listening, buy a good headphone! And, after your done playing with homemade crystals, I suggest you buy some silicon diodes. Type 1N914 or 1N4148 diodes work great in this radio. ***They don't work better than the diode made from sulfide ore***, but they are smaller, more rugged and don't need to be tweaked.

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RECREATING HERTZ'S RADIO EQUIPMENT

Most of what I've read about the history of radio was written by non-engineers. They describe the revolutionary apparatus invented by our heroes using old-time radio terms like "earth resonances," "aether" and "coherers." They tell us how far it transmitted, but they give us only the faintest clues about how the gizmo actually worked. Was it a spark gap transmitter? A high-speed alternator? What the heck was a "Tesla oscillator" anyway?

In 1884 James Maxwell published four equations that quantified and connected magnetism with electric phenomena. These equations also predicted the existence of radio waves. The changing magnetic and electric fields related to each other with sine functions. So, once physicists had the equations to stare at, it wasn't too huge a leap to conclude that sinewave-shaped electric and magnetic fields would generate each other in an oscillation and radio energy would propagate through space.

In 1889 Heinrich Hertz, a physics professor at the University of Bonn, Germany, was the first to demonstrate radio waves in the laboratory. Of course he might have done this in 1884, or 1887, depending on which website you visit - ah, the glorious information age!

That's fascinating, but **HOW** did he demonstrate radio waves? Using 1880 technology, that could not have been easy. How did he know he was detecting waves and not just magnetic coupling from one coil to another? Or if his "antenna" was capacitive, how did he know he wasn't observing capacitive coupling? ***If I were skeptical about the existence of radio waves, but I understood the full implications of Maxwell's equations, I would be convinced if I could see communication across a distance greater than one wavelength.*** A minimum of one wavelength means that "the alleged electromagnetic wave" would change from magnetic to electric field energy then back again at least once. ***Of course, I would also want to see evidence of standing waves and a way to measure frequency.***

Demonstrating Hertzian waves

Suppose you were Heinrich Hertz in the year 1884 and Maxwell had just predicted the existence of radio waves. Using components available in your time, how would you generate Hertzian waves and get those waves named after you instead of Hertz? If you are able to generate radio waves, how could you prove to a skeptic that you had actually done it? Hertz managed this feat and apparently his demonstration was convincing. Otherwise the unit of

measurement for frequency would not be the "Hertz." A Hertz equals one cycle (one complete oscillation) per second.

When I first had the idea of playing at being Dr. Hertz, I was not able to find a description of his apparatus. That was a good thing because it forced me to invent my own method to demonstrate Hertzian waves. If you already know enough about electricity to be able to handle the challenge, then get out your 1880 hardware and build a transmitter and receiver that will transmit at least one wavelength. If you don't know how to begin, keep reading.

Transmitting and receiving as simply as possible

The only detail of Hertz's apparatus I found described was that he detected his waves by means of a loop of wire. The wire had such a large current and voltage induced into it by the radio waves that a visible spark jumped across a gap in the circle of wire. Wow! It must have been a big radio signal that would induce that much energy into a loop of wire. And if the signal was that big, how far away from the transmitter had the loop been? I suspect the signal strength had to be big and loop had to be very close, like a foot or two away.

If were a skeptic who already knew about Faraday's transformers, I would not be convinced by this demonstration. How would I know that radio waves had propagated across the one foot distance to the loop? Maybe all I was seeing was a big magnetic field that reached from one coil to another.
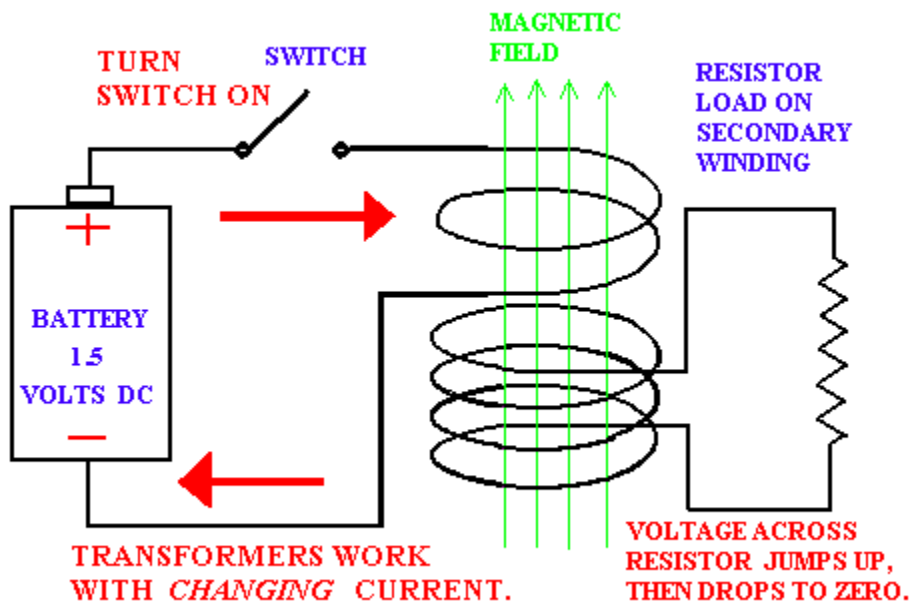
Maybe Hertz's demonstrator was just a transformer?

A transformer is a *magnetic* device that works by transmitting a changing magnetic field from one coil to another. Coils (inductors), convert the energy of an electric current moving through a wire into magnetic field energy that hovers in a cloud like region around the coil. If a second coil is close enough to the first coil to be inside the magnetic "cloud," then if the magnetic field is changed, then an electric field will be generated in the second coil.

Inductors store magnetic energy in the space around them, so long as current is passing through the coil. The energy will stay in space so long as the current keeps flowing in the same direction through the coil.   But when the current stops flowing, the magnetic energy is "stranded" in space. The magnetic energy then returns to the coil and induces a voltage in that coil in a direction that would force the current to continue flowing. That is, the induced voltage will try to keep the status of the magnetic field and coil the same. If the current is gone for good, then the magnetic field will collapse completely and the energy will dissipate into the coil and any circuit connected to it. But if the first coil is open circuit and even high voltages cannot restore current flow, then the field will collapse into the second coil. If the induced voltage is able, it will cause current to flow in the second coil to maintain the field. Or, as in the case of Hertz's loop detector, the induced voltage caused a big spark to jump across a gap where the resistor is located above.

But I thought transformers were always made from iron

You may be thinking that transformers are not air-filled flimsy coils but rather large iron things like the big steel cylinder on the power pole in the alley behind your house. Yes, those iron things are transformers but they are designed for low frequency power lines. An AM radio frequency is on the order of a million Hz frequency, while the power company supplies current at 60 Hz. Therefore, instead of having air between the two coils, power transformers have iron. The magnetic field from the coil magnetizes the iron temporarily. Recruiting iron and turning it into a magnet increases the magnetic field a thousand times or more.

With a huge magnetic field stored in the iron, the power transformer can transmit big amounts of energy with only 60 direction changes per second. A similar transformer without an iron core could transmit the same amount of energy, but would have to repeat the magnetic field cycle perhaps a thousand times more often to transfer the same amount of total energy.

I am getting ahead of my story, but why do you suppose the power company doesn't use 1 million Hertz and do away with all that iron? After all, at one million Hertz the RF voltage would still be a burn hazard, but it could not electrocute anyone and would be considerably safer. Unfortunately, at one million Hz the power lines would act like antennas and radiate the energy into the sky instead of delivering it to your house.

How far should it transmit to demonstrate the existence of Hertzian waves?

To be sure that the waves are Hertzian and not just magnetic fields, I would be impressed by the demonstration if the detector (the receiver) were more than one wavelength away. A wavelength is the distance that a radio wave travels during the time it cycles from magnetic field, to electric field, and back to magnetic field.
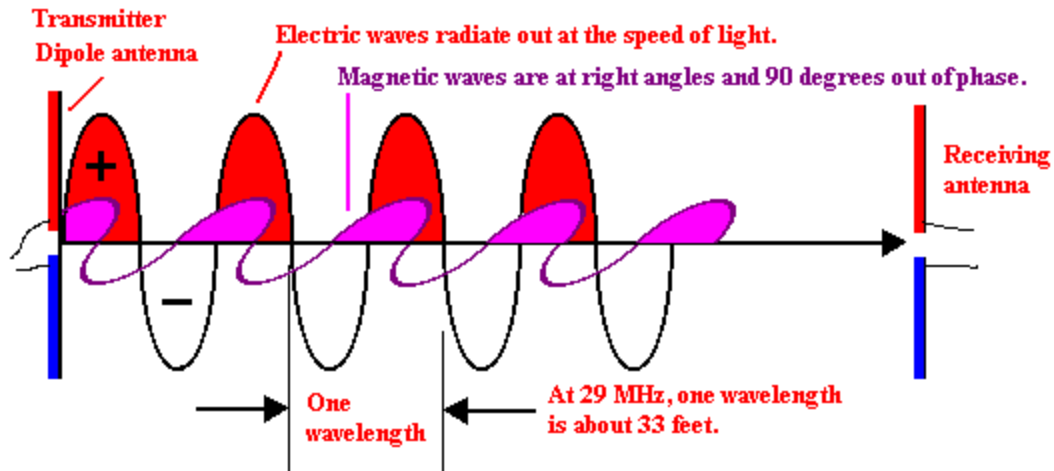
The speed of light is 186,000 miles an hour, or 300,000,000 meters per second. (A meter is about 39 inches) A wavelength is the distance a wave travels while going through one cycle of magnetic to electric energy conversion. The wavelength of the forty-meter amateur radio band (7 MHz) is obviously 40 meters. It turns out that typical, (total) antenna lengths for radio transmitters are either one half wavelenth or one quarter wavelength. On 40 meters, a typical vertical pole antenna is one quarter wavelength or 10 meters (33 feet) tall. The 10 meter ham band extends from 28.0 MHz to 29.7 MHz.

What exactly is the frequency in Hertz of the 10 meter ham band? To convert wavelength to frequency, divide meters per second of light speed by the wavelength:

$$f \ = \ c \ / \lambda$$

Where f represents frequency, c represents the speed of light and λ represents wavelength

Speed of light/ wavelength = Frequency in Hz.

300,000,000 meters/ second / Ten meters = 30 Million Hz (30 MHz) frequency

Remember that the AM radio band extends from 550,000 Hz to 1.7 MHz. Channel 2 television starts at 54 MHz . So the 10 meter ham band is roughly halfway between AM Radio and TV.

Getting back to the Hertzian demonstration, if I wish to transmit one wavelength, on 40 meters, my loop would have to be 132 feet away from my transmitter. Frankly, I don't think Hertz's loop detector will work at that range. And if it did, I would be arrested for using a transmitter that powerful. As a rule of thumb, the FCC will not object to experiments like this if the radio waves don't go past 50 feet at easily detected signal strengths. On the other hand, maybe I could use a higher ham band like 10 meters. Now I only have to go 33 feet. This is better, but the loop is still more than one foot away. If I go up to UHF frequencies, the wavelength can be down to a foot, but those frequencies would be hard to generate and harder to measure with 1884 technology. I have since been told that Hertz actually used 4 meters wavelength for his demonstrations.

Designing the 10 meter transmitter

For the sake of symmetry I used to identical LC circuits for my transmitter and receiver. To imitate what little I knew about Hertz's apparatus, I used one loop of wire about a foot in diameter. I knew from experience that seeing sparks on the receiver side was hopeless, so I also made the receiver an LC circuit that I knew would trap an oscillation from the transmitter.

At this point, you may want to depart from the year 1880. It all depends on how pure you wish to be playing the historical game. For a capacitor I used a modern variable capacitor. That way, I could adjust the capacitance and tune the oscillation to a particular frequency. If I wanted to be a purist, it would not be hard to make a homemade capacitor made from sheets of metal with paper for insulation between the plates. Personally, I was confident that such a capacitor would work. I just didn't want to spend hours to make one.

My first problem was how to start the oscillation in the transmitter LC. In theory, by shorting a battery across the loop, it will charge the loop with a big current limited only by the internal resistance of the battery. Then when the battery is removed, the coil's magnetic field will discharge forcing a voltage to appear across the capacitor. The loop will then be shorting out the capacitor and the oscillation will begin.

Like the variable capacitor, this project will go faster if you use modern tools to make sure your components are working. For example, to see if my transmitter was really transmitting, I used a ham band receiver tuned to ten meters. Sure enough, when I clicked the battery on the capacitor terminals, I could hear a click in the receiver loudspeaker. And when I tuned the capacitor, I could get the sound to reach a sharp maximum volume at a specific setting of the capacitor. Of course, if this were 1880, I would have to do everything by guess, trial and error. Those old guys were darn sharp.

Designing the receiver

The next problem was how to detect when the receiver loop was oscillating due to waves from the transmitter. What to use for a detector? The 1880 solution would be to use a detector called a ***"coherer."*** Coherer detectors were developed for the wire telegraph. By the time a signal had propagated miles down a telegraph wire, signal was often too weak to close a mechanical relay. Coherers were used to "amplify" a weak Morse code signal. A coherer was a little vial of powdered iron or carbon granules. When a tiny voltage appeared across the vial of powder, the resistance of the powder dropped abruptly. This drop in resistance then allowed enough current to pass through the powder and trigger a relay called a "sounder." The sounder made a clickity-clack sound that the telegraph operators recognized as a dot or dash. Using a coherer, a weak signal could drive a sounder that could not be run directly. To reset the coherer for each pulse, the little vial was mounted on the sounder so that the vibration would shake up the powder and keep it working.

Unfortunately, coherers are a low frequency device. They are suitable for "detecting" a DC signal on a cross-country telegraph wire. I doubted that they would be useful for tiny radio frequency signals. Being lazy, I didn't build one to find out. Besides, my crystal detector made out of local rocks certainly fit the 1880 criterion. I decided to build a 10 meter crystal set.

What about headphones? Are they 1880 technology? Yes, just barely. Alexander Bell built his first telephone in 1879. He used a headphone designed like the homemade device described earlier. Actually, for my 10 meter receiver I used old commercial high impedance

headphones instead of the homemade earphone. I couldn't afford to waste any sensitivity.
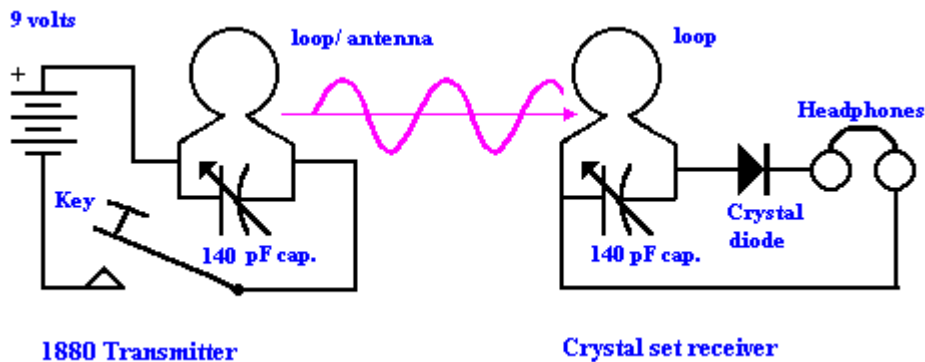
The simplest 10 meter communicator

I began with identical loop antenna/ inductors about 1 foot diameter for both receiver and transmitter. Instead of Hertz's spark gap, I put 140 pF variable capacitors across both loops to give me tunable LC circuits.

10 meter crystal set receiver.

To charge the LC circuit, I used a crude "***spark gap***." I just touched battery terminals across the LC circuit while listening to the crystal set. I positioned the crystal set a foot away from the transmitter loop. It wouldn't be "radio" communication, but it would at least tell me if I was on the right track. I made sparks on the transmitter loop while tuning the capacitor. When tuned to just the right spot, I could suddenly hear obvious clicking in the headphones. I was surprised how sharp the tuning had to be. The big loop had relatively low inductance, so the capacitor had a tuning range of over 30 MHz . Tuning was hardly sharp by modern standards, but the adjustment was critical. In any case I achieved a range of 12 inches from the transmitting loop. Amazing! Well, it's much farther than the obvious action range of a refrigerator magnet.
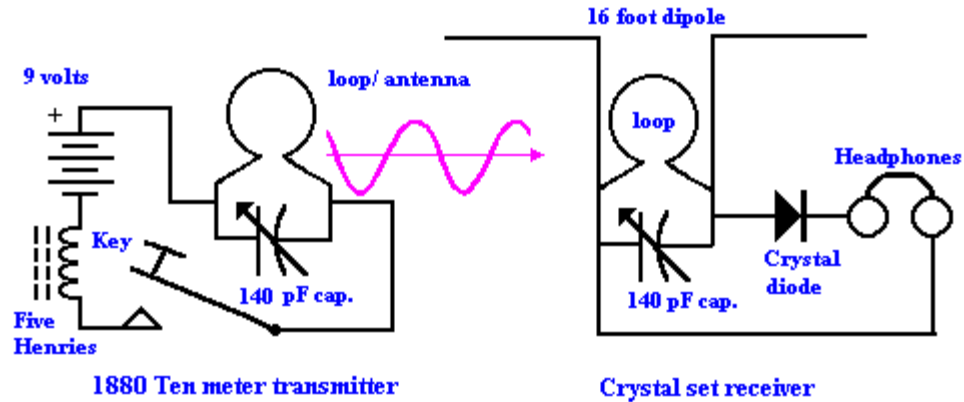
Improved spark gap transmitter & receiver

By adding a big iron core inductor in series with the battery, I got a much bigger, more sustained spark and a much louder signal in the crystal set. The inductor was the primary of a iron core filament transformer that I had in my junk box. The secondary of the transformer was left open circuit. Actually, I tried several transformer windings and inductors until I found one that gave me the biggest visible spark. The battery was six D-cell alkaline batteries in a plastic battery holder from Radio Shack. My telegraph key was made out of two pieces of printed circuit board separated from each other by a piece of wood. (See Chapter 9.)

10 meter sparkgap transmitter.

I drafted my XYL to listen to the headphones while I moved the transmitter across the room. (Wives are known as "XYL" in Morse code. XYL stands for "former young lady.") Now that I had the inductor and a larger spark, I got clear out to a range of 10 feet! I explained to Katie that she was doing the same job as Marconi's assistant, Mignani. When Mignani heard the repeated "S" in Morse, he fired a rifle into the air. "So where is my rifle?" she asked.

A relay for automatic keying

Unfortunately, a wavelength at 29 MHz is 33 feet and I was still short. Hmmmm…..

How to get the last 23 feet of range? First I added a relay to key the inductor. Yes, they had relays in 1880. The relay had nothing to do with extending the range, but it did enable me to continue doing experiments without having a Mignani to do the listening for me. You know, fire the rifle and all that.
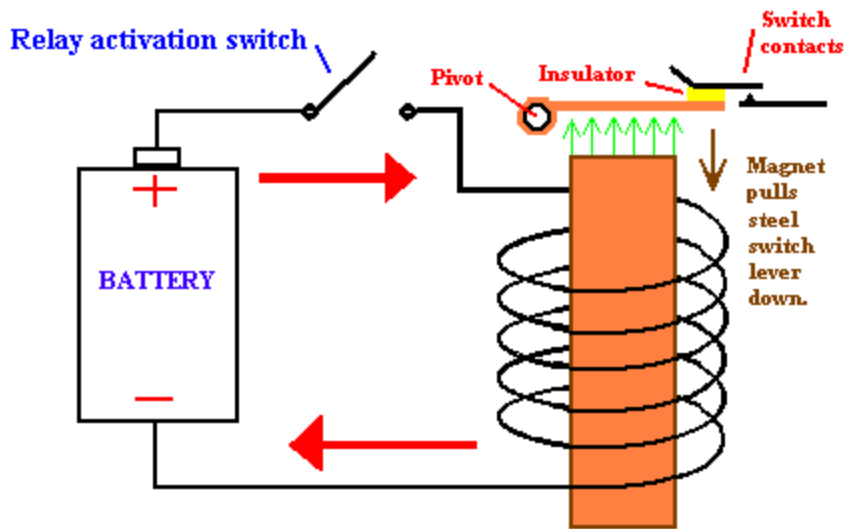
RELAY CONSTRUCTION

A relay is an inductor/ electromagnet wound around an iron core. A hinged piece of steel is suspended by a spring near the iron core. When current passes through the electromagnet, the steel hinge is attracted to the iron with an audible "clunk." The hinge, in turn, mechanically closes a switch that can be entirely independent of the electromagnet circuit. In this way, one current can control an independent circuit. In my transmitter the switch contacts on the relay became my "spark gap." Every time the switch opened, a big spark jumped across the switch contacts, not unlike the spark in an automobile ignition spark plug.

Using a relay, I could use my electronic telegraph key, a "bug" set on "dots," to key the transmitter automatically. This homemade "bug" is described in Chapter 9. If you don't have one of those, you'll have to have your "Mignani" key the transmitter for you. With the transmitter making a continuous signal, I could move the receiver around my house. The signal sounded just like automobile ignition noise that you sometimes hear in your AM radio.

More range = bigger, higher antennas plus bigger batteries

I could easily increase the range of the transmitter by using more and bigger batteries and a larger series inductor. If I really wanted to extend the range, I could add a dipole designed for 10 meters and put it up in the air about 50 feet. In fact, this is exactly what the early guys did – they made bigger and bigger transmitters and antennas. However this was 2002, not 1880. The trouble with using a wavelength of 10 meters is that, if I were to increase the effectiveness of my transmitter, I might easily hear it with my crystal set 33 feet away. Unfortunately, someone else might also hear it in Australia. That would be bad since sparkgap transmitters have been banned since 1927.

The simplest improvement I could make to the receiver was to add a 16-foot dipole antenna. The dipole consisted simply of two eight-foot wires soldered onto the sides of the receiver tuning capacitor. The dipole was oriented at right angles to the direct path to the transmitter. That did it. Now I could plainly hear the signal from the basement to the other end of the 2nd floor of my house, over 50 feet. That was well beyond one wavelength range! Whoopee!

Looking for standing waves

To measure wavelength, I set up a long wire transmitting "antenna" about 50 feet long across the floor and upstairs. I reduced the transmitter batteries from 9 volts down to 3 volts. Then I turned on the transmitter. I took the dipole off the receiver and then used the receiver loop as a "probe." Walking along the wire, I was able to hear peaks and dips in reception every 6 feet or so along the wire. What I was hearing was "standing waves." When the RF current reaches the end of an open wire, it bounces back along the wire. The returning waves cancel and reinforce the outgoing waves making the peaks and nulls I was hearing.   A big number of peaks means the wire length is different than one wavelength and the standing waves are complicated. If the wire were exactly one wavelength, I should hear just two peaks – just the two humps of a single sinewave.

Next I cheated. Since I already knew the frequency was 29 MHz, I calculated what the wire length should be for one wavelength. I trimmed the wire to exactly that distance and tried again. As expected, there was a single pronounced dip in the center of the wire. The sinewave signal was reflecting back and forth from one end of the wire to the other, with a dip, the zero crossing, in the middle. When the reflections don't come out even, you get many multiple dips and peaks.

Of course, knowing the answer before you start is not what Hertz experienced. He had to figure out all the details the hard way. Also, knowing the answer ahead of time biases the result. The exact alignment and distance of the receiver loop with respect to the wire were critical, so there's a chance I was just hearing what I wanted to hear. Craftsmanship and scrupulous honesty are essential when doing science. My frequency measurement obviously more needs work.

****
**

HOMEBREW TRANSISTORS

Here is another project you may enjoy. It will also introduce you to the basic principles of bipolar transistors. Schockley and Bardeen first invented bipolar transistors while working for the Bell Laboratories in 1947. Actually, I've read that the basic principles for field effect transistors were described in German patents from the 1930's. However, field effect transistors were not developed into useful components until the 1970's. We shall first use one of those in chapter 6, so they are discussed there.

The purpose of transistors is to "amplify" small signals or to control big currents or voltages using tiny control signals. Transistors can amplify a tiny signal that is audible only with sensitive headphones and make it strong enough to run a loud speaker or even deafen a stadium in a rock concert. Alternatively, a transistor can use a little control signal to turn on a huge

current and voltage. For example, an engineer at a power plant might push a keypad on a computer with a fraction of a millimampere of current flowing through the switch. This action is amplified and results in megawatts of power at hundreds of thousands of volts flowing toward a city.
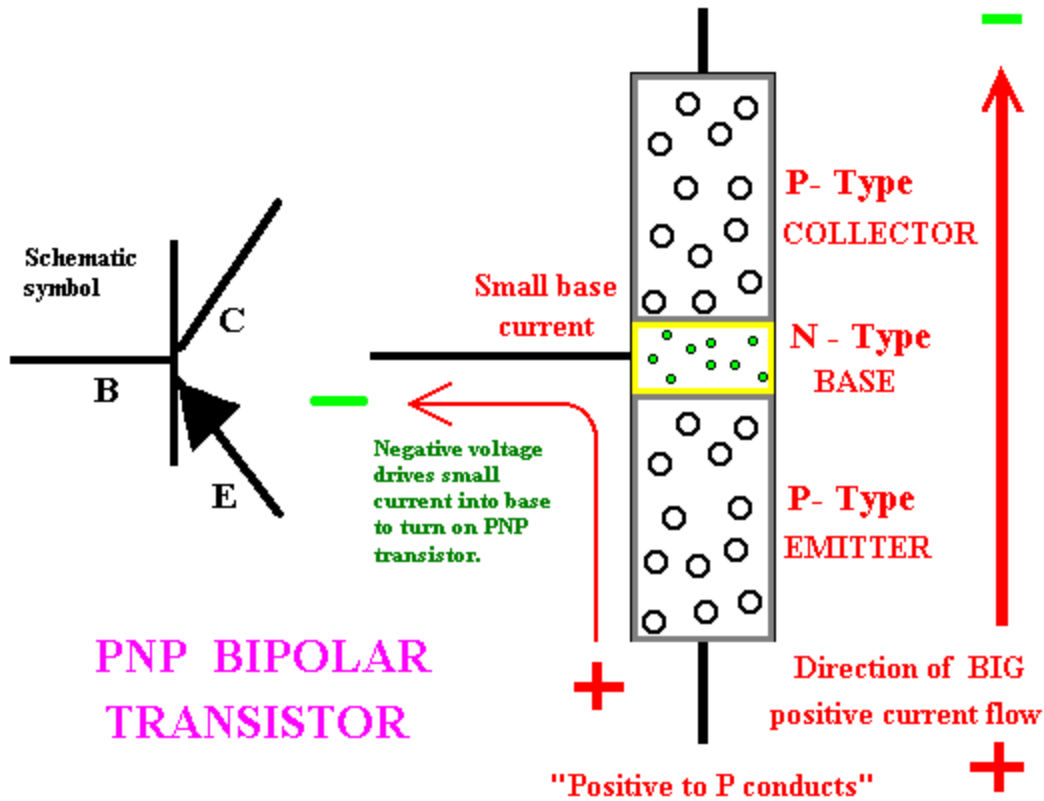
The homebrew transistor
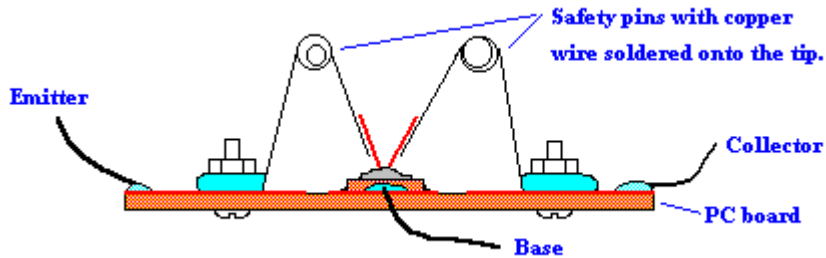
A point contact transistor.

The first bipolar transistors were the "point contact" type. They were much like the galena driode described earlier. After my diodes worked so well, I wondered if I could make a transistor.

Idealized construction of a PNP bipolar transistor

A *"bipolar"* junction transistor consists of two diodes made on the same semiconductor crystal.   In the experiment above, I am attempting to use galena as the N-type semiconductor. The diodes are connected back-to-back so that it will look like an open circuit from the terminals called "emitter" and collector "collector." The two copper points are supposed to touch the galena so close together, that the tiny semiconductor region between the two points can be biased by the base current. The bias current is supposed to electrically convert the semiconductor region into a "conductor" and thus turn the two back biased diodes "ON."

Schematic symbol

C

B

E

PNP BIPOLAR TRANSISTOR

Small base current

Negative voltage drives small current into base to turn on PNP transistor.

P- Type COLLECTOR

N - Type BASE

P- Type EMITTER

Direction of BIG positive current flow

"Positive to P conducts"

In theory, the metal from the copper points diffuses into the surface of the crystal and makes a tiny region of "P" type semiconductor where the copper touches the semiconductor. Unfortunately the "emitter" and "collector" are identical and aren't optimized for their different roles as they are in commercial bipolar transistors. I also tried making a copper/steel/copper transistor, but without any measurable breakdown voltage, it just acted like a short circuit. In retrospect I guess that was pretty obvious.

NPN transistors

A nifty advantage of bipolar transistors is that they can be built two ways. By reversing the P-type and N-type semiconductors, an NPN transistor can be built that operates exactly like a PNP transistor, except all the polarities and current directions are reversed. The advantage of having two polarities is that the circuits can often be simplified by using both kinds in the same circuit. In practice, NPN transistors are usually slightly more robust and less likely to fail at high power loads. For this reason, the power amplifier stages in modern transmitters are almost always N-channel devices. On the other hand making an NPN transistor out of crude crystals and safety pins is inherently difficult!

Schematic
symbol

C

B

Notice that
arrowhead is
reverse of PNP.

E

**NPN BIPOLAR
TRANSISTOR**

Small base
current

+

Positive voltage
drives small
current into
base to turn on
NPN transistor.

—

+

N - Type
COLLECTOR

P- Type
BASE

N - Type
EMITTER

Direction of BIG
positive current flow

—

"Positive to P conducts"
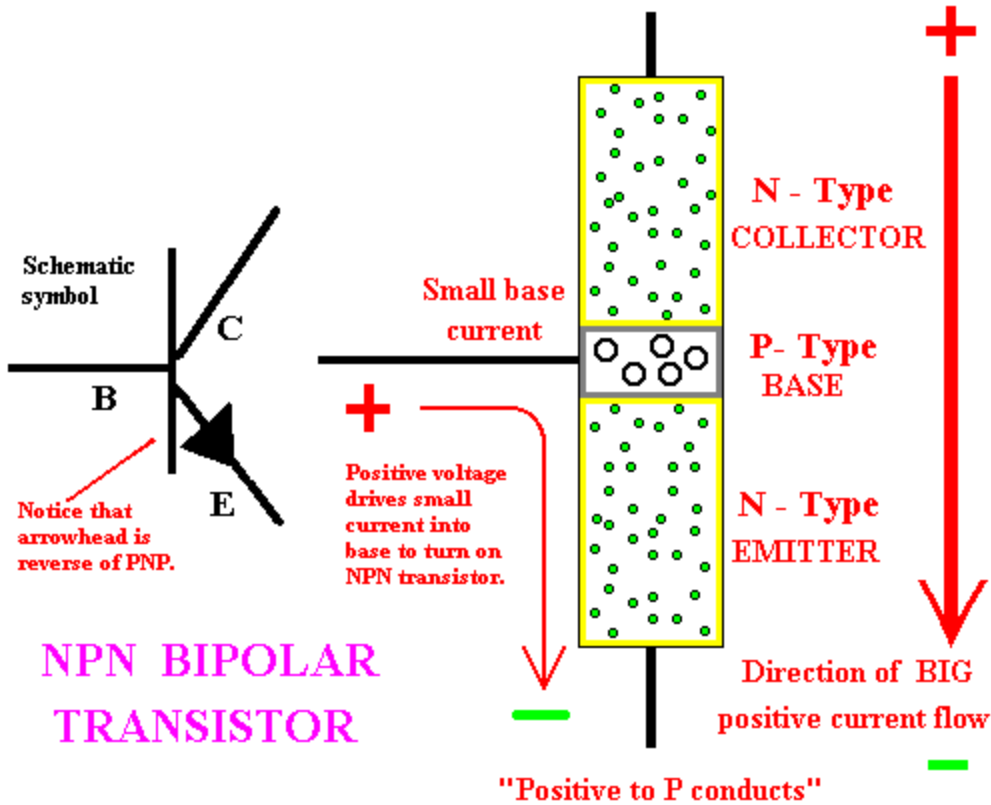
Proving the homebuilt PNP transistor has gain

I measured the static volt/ ampere characteristics of my galena, point-contact transistor but couldn't show any gain with static DC currents even in the microampere range. Before I gave up, I thought I would try it as an amplifier in the crystal set. Maybe I could demonstrate gain in "the subtle world of RF detection."

I decided my "transistor" was most likely to work as an **"emitter follower."** In an emitter follower, there is no voltage gain, only current amplification. The load, the headphones, would be located between the emitter and the positive side of the battery. That would match the impedance between the high impedance detector and my low impedance (8 ohm) commercial headphones. Because galena diodes break down with typically 1 volt of reverse bias, I used a 9 volt battery with a 10K pot in series so I could limit the voltage on the collector to 1 volt or less.

10k resistor

diode

Transistor

Tapped
coil

Headphone

9V
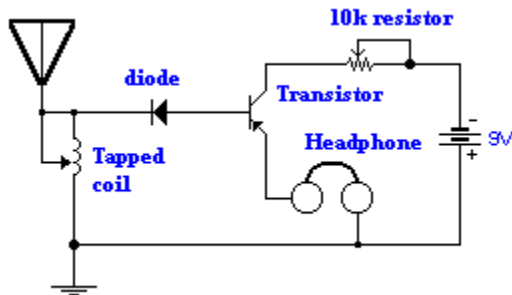
Rock radio schematic

As I moved the emitter pin around on the crystal, a loud radio station abruptly appeared in the headphones. I disconnected the battery. Sure enough, the music was far louder with the battery connected.

An accidental crystal microphone

With the battery in place, but the signal diode disconnected, I heard a faint "sea shell" roaring sound - you know, like a live microphone. Tapping on the transistor assembly, I heard the scratching sound greatly amplified in the headphones. I seemed to have built a "crystal microphone!" I replaced the homebrew transistor with a real PNP transistor, a 2N3906, which amplified just as well but had no microphone-like characteristic.

Repairable transistors

While listening to a radio station, I slowly increased the battery voltage by lowering the resistance of the 10K pot. As the collector-to-emitter DC voltage rose higher, the volume increased higher and higher. I monitored the average collector to emitter DC voltage with a high impedance voltmeter. Then suddenly the voltage and sound crashed. I lowered the voltage again, but the sound didn't return. Good grief! I blew my transistor! No sweat. I just scratched the collector pin around on the crystal until I found a new "sweet spot" and I was back in business. Repairable transistors! Now there's a concept. After several trials I found sweet spots as high as 5 volts before the transistor died.

Now that I had an amplifier on my crystal set, I replaced the commercial headphone with the homebuilt "Caribou headphone" which I described earlier. You may remember that this headphone was made from a piece of magnetite ore and a tin can lid for a diaphragm. Sure enough, the sound was loud enough to understand actual words, rather than just distant music. Progress!

Is this gain or what?

In fairness, most of the "gain" or amplification I observed was just DC bias to the headphone which helps overcome the hysteresis of steel components in the headphone. I replaced the transistor with a variable resistor so that the battery's sole function was to bias the headphone. That produced extra sound, especially for the homemade headphone that has such a weak magnet. After switching back and forth between resistor and transistor, the transistor was clearly louder, about 5 dB (decibels) on my multi-meter.

As I fiddled with the contact points, I soon ruined the crystal. Under the microscope I could see copper smeared on the surface of the galena. When I built replacements, they never worked as well. I spent another morning trying to conclusively demonstrate gain by building an RF oscillator. I never got so much as a peep out of it, although of course the real PNP transistor worked just fine.

In conclusion

Yes, Virginia, there are homemade transistors. But science that isn't reproducible isn't science. Without better basement technology, my homemade transistors have no future except maybe as microphones. Oh, well. Keep thinking and dreaming!

35. Chapter 4, Harris

CRYSTAL SETS TO SIDEBAND
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CHAPTER 5

GETTING ON THE AIR

Deciding what to do first

Earn an amateur license!

If your going to build your own ham station, you will need an FCC license to transmit. Testing for licenses is conducted by hams in your local area. The simplest first step is to contact a ham in your area. He or she will tell you what to do. Failing that, contact the Amateur Radio Relay League, www.arrl.org. They will fix you up with study guides and point you to the nearest ham radio club where you can meet other hams and take your test. Working on a license can be an interesting side project while you build your receiver and transmitter.

Figuring out a plan for your station

Most hams are content to buy one of those marvelous commercial transceivers. They plug it into the wall, put up an antenna and start talking. In contrast, a growing number of hams are building small, low power transmitters called "QRP" transmitters. "QRP" is an old Morse code abbreviation meaning "turn down the power." In modern usage QRP means a transmitter delivering less than 5 watts of RF power. QRP guys are usually fellows who have been using commercial rigs for years and want to try something more adventurous and primitive.

Most QRP enthusiasts buy tiny transmitter kits with pre-printed and pre-drilled circuit boards. The assembly procedure consists of following a picture, plugging components into the correct holes and soldering the leads. These kits teach soldering technique and you learn what the components look like. Unfortunately, if the kit is well designed, it offers little chance to learn how the circuits work.

A few hams start with a circuit from the ARRL handbook or QST magazine. Following the circuit diagram, they build their own version of the circuit out of individual components. Their components are bought or scrounged one at a time and rarely exactly match the components used by the author of the article. A QRP like this usually doesn't work properly without sweat and rebuilding. This sounds like work, but the compensation is that now you're learning something! This kind of project is educational whether we planned on learning or not. Frustration, persistence and triumph is what ham radio used to be.

Rules of the game

Scratch-building your own station is a kind of game. ***Our chief opponents are the amount of free time we have and modern frequency stability standards.***   In my fantasy it would be neat to build all the components from raw materials and invent and design totally new circuits from scratch. Unfortunately, these tasks are too much for me. Rather, I use discrete parts I scrounge from junk and components I buy through catalogs or local stores. For circuit design I borrow circuit blocks from examples in the ARRL handbook and other sources. Then I assemble the circuit blocks into my project.

After I retired and had plenty of time, I got out my ARRL handbooks and studied plans for homebuilt receivers and transmitters. I quickly encountered my other nemesis, <u>integrated circuits:</u> Tracing the circuit diagram of a typical modern receiver, one finds that the antenna is connected to a chip marked "RF amplifier." Then the signal goes to another chip labeled "mixer." The mixer receives a local oscillator signal from a large chip called a "frequency synthesizer." The output from the mixer goes to a "crystal filter" sealed in a tiny metal can. Well, you get the idea. ***Modern radios are just block diagrams soldered onto printed circuit boards.***

I find that 1980 technology is usually a good compromise. Few integrated circuits appear in the parts lists from that era. And if you're a purist, most of the integrated circuits can be replaced with discrete components. In summary, I try to use individual transistors and passive components exclusively. This teaches me how the circuit works and I can still build equipment that's reasonably modern. One compromise I have had to make was integrated circuit voltage regulators. In order to hold the frequency constant, the voltage supplied to the oscillators must be more stable than I know how to build using discrete parts.

Another compromise I've made is the use of integrated circuit operational amplifiers. An operational amplifier is an array of transistors that functions as though it were a "perfect transistor." It is usually easy to substitute real transistors, but you need to use many more of them to get the same performance. After a while I became bored making the same complex circuit again and again using discrete transistors. So, my rule is that, if I have proved I can build the equivalent of an integrated circuit with discrete parts, I feel I have "earned the right" to use a certain kind of integrated circuit.

My rules have taught me how the circuits work. I've learned plenty. And by golly, when I'm done, I really feel that I built it myself! Also, because I have struggled to understand it and make it work, I rarely have the feeling I am using "magic." You don't have to use my rules. Make up your own!

Planning your station

A simple receiver and a QRP transmitter are a great start on a homebuilt station. (See Chapters 6 and 7) However, before you can go on the air with your transmitter, you will also need:

- A ham radio license. Contact local hams in your area or the American Radio Relay League in Newington, Connecticut. (888) 277-5289.

- A 12 volt DC power supply for the QRP. (Chapter 8.)

- An antenna (See end of this chapter, Chapter 5)

- An antenna tuner (Chapter 9)

- A telegraph key for Morse code. (Chapter 9)

- Basic test equipment to ensure that your equipment is operating correctly. (Chapter 9).

Equipment for later on:

- A selective, sensitive all band hamband receiver (Chapter 13)

- A Class B or linear amplifier. (Chapter 12)   Although QRP is fun, you will probably eventually wish your signal were more powerful. With a loud signal more stations will hear you without a struggle and your contacts won't say "73" (good bye) so quickly. There are two ways to achieve a bigger signal. Build a better, high gain (directional) antenna, higher above the ground. The other way is to build a linear (or Class B) amplifier to raise the QRP power from 5 watts up to 50 or more watts.

- **A lowpass filter**. (Chapter 9). If you have a high power Class B amplifier, it is a good idea to build a low pass filter to make sure that harmonics of your signal are not interfering with the neighbors' cellphones and television.

- **VFO**. As you'll soon learn, being restricted in frequency mobility by crystal control is awkward and you will soon want to build a variable frequency oscillator to replace the clumsy and expensive crystals. (Chapters 10 and 11)

- **Single Side Band Generator.** (Chapter 15) After you have been a ham for a few years, you will eventually want to get on phone (voice) so you can talk to the majority of hams. Otherwise you be stuck just talking to funny old Morse code geezers like me. Almost no one ever builds their own SSB, so if you get that far, you will have joined an extremely exclusive club of homebuilding hams.

Divide and conquer

Building an entire ham radio station from discrete components is a huge project. The secret to having fun is to build it in carefully planned pieces that can be used and enjoyed right away. How big the challenge becomes depends on where you start. If you're a retired electrical engineer like me, the project begins by wandering down to the basement, dusting off the workbench and getting started. If you are still working for a living, your free time for this effort may be just a few hours a week. If you have never worked as an electronics technician or an engineer and you have no formal electronics training, your road to homebuilt ham radio will be lengthy. If you have no electronic experience at all and little free time, then maybe buying a receiver and a QRP kit may be the best way for you to begin.

The author's 100% homebuilt station. It isn't flawless and it isn't the latest technology, but it talks around the world and sure has been fun. Oh, by the way, the oscilloscope and frequency counter are NOT homebuilt.

Many guys try to do too much too soon. This can easily result in many hours invested in useless junk that does nothing except get hot and generate acrid smoke. A better plan is to focus on small projects that can make you proud as soon as possible. Try to decide what it is about ham radio that turns you on and then zero in on those aspects. Your ambitions will always be greater than the time you have to achieve your dreams. Plan carefully.

Pick an HF band

40 years ago it was practical to build simple ham transmitters that tuned several bands. Unfortunately today a ham transmitter must meet strict frequency stability standards. Actually, the government is only interested in having you stay inside the hamband and radiate a reasonably narrowband signal. However, other hams will almost always complain about your signal if you drift more than about 100 Hertz per minute. This degree of precision is hard to achieve, but it's easiest if you start with crystal frequency control and just build for one hamband at a time. Later you may expand your capability as your time, knowledge and enthusiasm permit.

There are ten different HF bands and seventeen VHF, UHF and microwave ham bands. In addition, a ham is free to operate anywhere he likes above 300,000 MHz, provided output power is limited. As the frequency goes up, the basic principles are the same, but the construction methods change radically and the precision and craftsmanship needed soar with the frequency. This book only considers the HF bands because scratch building equipment for VHF and higher frequencies needs expensive test equipment and a good understanding of HF building principles. In other words, walk before you run.

40, 30 and 20 meters

In my experience, the easiest and most versatile frequencies to build for are the 40, 30 and 20 meter hambands. (7 MHz, 10 MHz and 14 MHz .) The signals on these bands are strong and these bands are usually "open" throughout the year. It's easy to talk to hams all around North America on all three bands. Talking around the world is relatively easy on 30 and 20 meters. Optimal antennas are relatively small. On 40 meters (7 MHz) a dipole is 66 feet long while on 20 meters (14 MHz) a dipole is only 33 feet long. A vertical antenna on 20 meters is only 16.5 feet high. A typical suburban house is about 50 feet long so it's usually possible to put up a 40 meter dipole somewhere on the property.

40 meters (7.000 to 7.300 MHz)

This is a great band for CW contacts around the US. However, for us Americans, often only the bottom 50 KHz is usable. Yes, we're allowed to operate from 7.00 MHz to 7.30 MHz . Unfortunately, foreign broadcast stations often obliterate the upper two thirds of the band. On the other side of the world most of this band is available for commercial shortwave broadcasts. Also, from 7.05 to 7.10 the band is filled with foreign hams talking on single side band phone (SSB, voice transmission). We Americans can't use phone below 7.150 MHz , so we can't join in. From 7.10 to 7.15 MHz one sometimes hears American novice CW operators sending at slow speed. Unfortunately there are rarely more than one or two novices on the air. Consequently, most of the time American hams just use the bottom 50 KHz for CW. OK, maybe 40 meters is useful for local sideband phone contacts during the daytime. But at night most of 40 is unusable.

30 meters (10.10 to 10.15 MHz)

Thirty meters resembles the CW band on 40. It's only 50 KHz wide and no phone is allowed. Typically there are only 4 or 5 CW stations on the air. It's a terrific band for homebuilders. The power input on this band is limited to 200 watts worldwide, so it is a good band for talking to DX (foreign stations). Nearly everyone on 30 is using comparable equipment, so you won't have to compete with kilowatt stations and giant, multi-element beam antennas. Another advantage is that contesting isn't allowed on 30. Hams often hold weekend contests to see how many stations one can talk to in a 24 hour period. All the bands except 30, 17 and 12 meters become packed with guys just exchanging call-letters. It is pretty boring if you aren't competing in the contest.

20 meters (14.0 to 14.350 MHz)

Twenty meters is the single most popular band. It is large and usually usable 24 hours a day and "open" year round. It normally has hundreds of stations. In fact, 20 is usually so crowded, you will often need a receiver with great selectivity to carry on a conversation. If you can copy fast Morse code, foreign CW stations are easily heard at the bottom of the band. Because of the crowds and high speed, talking to them isn't so easy. Most of the band is filled with powerful stations on single side band phone. It is hard to build a homebuilt station that will compete up on the phone band.

17 meters (18.068 to 18.168 MHz)

Seventeen meters is a fine little CW and phone band. It's mostly inhabited by single side band phone stations. However, there are usually a few CW stations on at the bottom of the band.

When conditions are good, many of these stations are DX on the other side of the world. It isn't my first choice for a QRP CW transmitter, but other than scarce CW stations, there's nothing wrong with 17 meters.

15 meters (21.000 to 21.450 MHz)

Fifteen meters is slightly harder to build for than 20 meters, but it's an excellent band for beginners. 15 meters is a large band, 450 KHz wide. It's not crowded but there are plenty of stations. 21.150 MHz is a great place to meet beginner CW (telegraph) operators. 21.040 to 21.060 MHz is where most of the QRP CW guys hang out. 15 meter QRP transmitters are crystal controlled and are usually locked onto that frequency. After your code speed gets up over 20 WPM, you can move down to the bottom of the band where the DX (foreign) stations and high-speed, old-time CW operators hang out.

Extra care in construction and antenna tuning are needed as the frequency goes up. You may find that your homemade receiver is slightly less sensitive than it was on 20 Meters and your transmitter probably won't produce as clean an output waveform as it did on 20 meters. On the other hand, a 15 meter vertical antenna is only 11 feet tall and a dipole is only 22 feet long. Another reason for selecting 15 meters is that a 40 meter dipole (or 40 meter vertical) will work well on both 40 meters and 15 meters. This simple antenna is ideally matched to both bands.

Some hams successfully string 15 meter antennas in their attics or along the ceiling of a large second story room. When I was in high school, a friend of mine, Al Beezer, KØKZL, had his 15 meter antenna strung across his bedroom. He used florescent lightbulbs for insulators at each end of his dipole. The bulbs flashed every time he pushed the telegraph key. Great show biz! Yes, Al's signal would have been stronger if his antenna had been 20 feet higher outside in a tree, but his indoor antenna was adequate to make contacts all over the U.S.

Open bands and sunspots

The disadvantage of 17 meters and higher bands is that these bands are often not "open." When the sunspots are few, the Earth's upper atmosphere is minimally ionized. When the band is "dead" the radio signals are passing through the ionosphere right out into space. 15 meters is often closed for months at a time, especially in the summer. During these times all you'll hear is the hiss of static. On the other hand, 15 meters can still be used for local communications during these periods. The higher the frequency, the less often the bands are open. Ten and 12 meters are even more erratic.

10 and 12 meters

I found building receiver converters for 10 and 12 meters was as easy as it was for 15 meters. However, building the transmitters was more difficult. My final amplifiers and antennas were hard to tune. It took me several attempts and many modifications before I got more than a few watts of power output on 10 meters. For example, my transmit-receive antenna relay had too much reflection (high SWR) to work properly on those bands. I had to bypass the relay and use a separate antenna for the receiver. However, once I was able to transmit just two watts on 10 meters, I could easily talk to other continents. In that sense, I believe 10 meters is the best QRP band. But as I said, sadly, months often go by when there is nothing to hear on 10 meters but static.

When I was in high school, my buddies and I built handheld 10 meter walkie-talkies. They put out 1/4 watt into a 2 foot long antenna with a loading coil. One of my biggest thrills in ham radio was standing on my chimney in Colorado and talking to a guy in New Jersey. That was nothing. My friend, Bob (KØIYF, now NØRN), was walking down the street and talked to a fellow in Morocco. Forty years later, he still remembers the call letters, CN8NN.

6 meters

Six meters is a huge band, 50 to 54 MHz . It closely resembles 10 meters in that a few watts will talk around the world using high ionospheric propagation. Some years, on ham field day at least, (the last weekend in June) it is crowded with signals from all over the world. The catch is that 6 meter propagation is rarely "open." You might have to listen for many months before you hear stations. With good craftsmanship, it's possible to build homebrew equipment for 6 meters using the technology discussed in this book. However, I don't recommend it until you have become bored with 10 meters.

80 and 160 meters

80 meters (3.5 to 4.0 MHz) and 160 meters (1.8 to 2.0 MHz) are large, lightly used bands. Of all the hambands, transmitters are most easily built for these bands. There are plenty of SSB phone stations on 80 meters at night, but relatively few CW stations on these bands. Good receivers are hard to build for these bands because the atmospheric noise is so heavy that it takes a sophisticated receiver to pull signals out of the static. Also, if your homebuilt receiver isn't well filtered, it may be overwhelmed by your local standard broadcast AM stations, which are located just below 160 meters. A modern commercial high-end transceiver can often hear dozens of stations while a simple homebuilt receiver might only hear a few. During the day, these bands buzz with noise and are usually only good for across town. Sometimes at night, if the thunderstorm noise isn't too bad, there are lots of stations from all over the country.

Another barrier to 80 and 160 meters is that large antennas are needed for good performance. On 80 meters a vertical antenna must be about 66 feet high and a dipole antenna is 135 feet long. For 160 meters, ideal antennas are twice those sizes. Yes, you can use small antennas equipped with "loading coils" and antenna tuners, but in my experience without a good antenna, you will rarely get out of town. In spite of this, once you have a big antenna, much to my surprise QRP transmitters can talk all across the country on 80 meters.

60 meters

As of July 4, 2003 hams are allowed to transmit single sideband phone (USB SSB) on five narrow channels, 5.332, 5.348, 5.368, 5.372 and 5.405 MHz. This band is noisy and is shared by several services. Each channel is like an old time party-line phone on which everybody tries to talk at once. Moreover, at any one time, you will find that two or three of the channels are occupied by commercial teletype (RTTY) stations. It's interesting, but frankly it isn't worth the trouble for a beginning ham.

In summary, I recommend starting off with CW on 40 and/ or 15 meters. A 40 meter dipole works well on both bands and the equipment is relatively easy to build. Both bands will let you talk all over North America with ease. On 15 meters you will have the chance to work foreign stations (DX) even with simple equipment and minimal code skill.

Phone (voice) transmissions

For a homebrewer in the modern world, building a phone transmitter is a difficult project. Actually, amplitude modulation (AM) voice transmitters, like those used on standard broadcast radio, are relatively easy to build and they are still legal for ham radio. To convert a CW transmitter into an AM transmitter, all you have to do is impress an audio voice signal onto the power supply line of the transmitter's last stage of amplification. Occasionally you can still hear AM stations on 10 meters, 80 meters and 160 meters. But in general, AM is rarely used anymore by hams.

The modern replacement for AM is *single sideband (SSB) phone*. SSB is similar in principle to AM phone, but it takes up about a third of the bandwidth of an AM signal. Sideband can be thought of as AM radio with half of the signal plus the carrier wave removed with precise filters. This allows more stations to share the band and makes your transmitted power three times more effective. The SSB signal must be generated at a fixed frequency then translated up to the desired frequency using mixer technology. To maintain the purity of the signal, all of the amplifiers along the chain must operate perfectly in linear mode so that the speech is not distorted.

A sideband generator is described in the final chapter of this book. Scratch-built sideband phone is definitely an advanced project. Frankly, I found mine hard to get working and spent many months on the project. I rebuilt some stages of the transmitter several times. Perhaps homebuilt single sideband should be something to look forward to when you have loads of free time. After you have worked on an SSB transmitter for a while, you may decide that good old Morse code isn't so bad after all!

On the other hand, receiving single sideband is easy. A filter made from a single, off-the-shelf, microprocessor crystal is all you need to receive clear, interference-free speech. The homemade receiver described in chapter 13 works great for SSB.

Instant high quality communications

Perhaps you have read all of the above and decided that your primary goal is to talk to people by radio as soon as possible. For you, building equipment is a secondary interest. If that describes you, you should probably buy a modern high frequency (HF) transceiver then begin work on your ham license as soon as possible. Modern commercial ham stations are usually "transceivers" that combine the transmitter and receiver in one unit. Many of the circuit blocks in transmitters and receivers and transmitters are almost identical. So logically enough, the transceivers use the same circuits for both send and receive.

A modern, top-of-the-line HF transceiver – the Yaesu Mark V Field, FT1000MP

I recommend buying a transceiver that can tune all nine high frequency bands. If you buy a modern, quality **used** transceiver, the price can be well under $1000. This will give you a (nearly) complete station that is more sophisticated than you or I could build with years of effort. Even if you don't have your license yet and can't transmit legally, you should buy or borrow some kind of receiver as soon as you can. That way, you can at least listen to shortwave radio. Really, listening is more than half the fun. Many commercial transceivers or receivers can receive the entire shortwave spectrum from 1.6 to 30 MHz. This includes all the commercial broadcast, foreign stations, and time and weather stations. Listening will make studying for your ham license much less theoretical. If you want to experiment with the built-in transmitter, you may not transmit on the air without a license. However, you can practice loading a "dummy load" instead of an antenna. If you have an antenna tuner, it's fun to load up ordinary filament lightbulbs as dummy antennas and watch the light pulsate as you talk or send Morse code. See Chapter 9.

Occasionally I think about buying a modern transceiver like the one above. These tranceivers are "easy" in the sense that they can instantly perform virtually every feature and communication method you have ever heard of. For example, when the new 60 meter band opened, it was possible to reprogram the Yaesu FT1000MP to cover 60 meters just by pushing the right combination of buttons. And, as you might expect, practically everyone on 60 meters was using an FT1000MP. The bad news is that the instruction manuals make operating your VCR look like child's play. All those buttons, menus, and operating modes are enough to drive you to drink.

Yes, I occasionally think about buying one, but for me, it wouldn't be satisfying. As soon as I had read the manual and tried out the features I was interested in, the transceiver would become boring. I can name several hams who have superb transceivers gathering dust in their home stations. They haven't turned them on in months or even years. On the other hand, if your ham radio bliss is working all the 335 plus call signs in the world, then you will need the best possible equipment. Building your rig yourself is going to slow you down for many years or decades. Maybe that's a good thing. You decide!

Pursuing a dream

When I was in high school 40+ years ago, television was "exotic." Although black and white TV receivers were commonly in our living rooms, almost no one could afford a TV camera. Because I couldn't afford a camera, their unavailability made them fascinating. I spent hundreds of hours building and experimenting with TV cameras. Only one of my five camera projects actually worked properly. Later when I was grown, my wife bought me a fantastic TV camcorder which today is a big yawn. Because camcorders are routine today, to me the camcorder was just another way to take baby pictures. I have hardly done a thing with it. Familiarity and ease of acquisition breed boredom.

VHF/ UHF Hand-helds

The simplest and cheapest kinds of commercial ham transceivers are VHF hand-held walkie-talkies for 2 meters (144 MHz) and/or 70 centimeters (420 MHz .) These walkie-talkies are slightly more adventurous than a cellphone, but in my opinion they aren't as useful. They

also require a ham license. Another limitation of hand-helds is that the communication is basically line-of-sight. In other words, if you are behind a mountain and want to talk to the other side of the mountain, you need a relay station (a repeater) that just happens to be on top of the mountain or in some location that is visible to both you and the guy you're talking to.

The latest toy in hand-helds is "IRLP." This is an Internet connected network of VHF and UHF repeater relay stations or "nodes." The idea is that you use your handheld transceiver to key codes into your local repeater node. The repeater uses the codes to connect you via the internet with other nodes anywhere in the world. The repeater node in Boston, Australia or Berlin then rebroadcasts your VHF signal as if it were local. Guys in those distant cities hear you and reply as if you were located in their own town. This system is mostly used for ragchewing and isn't burdened with contests and guys who are just interested in collecting call letters and QSL cards.

A 2 meter hand held transceiver (walkie-talkie) with a spare battery pack.

Personally, I use my 2 meter walkie-talkie as an emergency radio for hiking. Honestly, I think a cellphone would serve me better in an emergency, but I've been too cheap to buy one. Most owners of VHF walkie-talkies use them like citizens band radios to talk around town. In general, the quality and range of the commercial amateur radio hand-helds is far superior to citizens band radios. On the other hand, citizens band is another "quick and dirty" way to get on the air without a license.

If you buy a hand-held, be sure to buy an extra battery pack or two. To make mine reliable in an emergency, I replaced the rechargeable batteries inside the battery packs with alkaline batteries. Although they aren't rechargeable, alkalines store several times more energy and tolerate cold temperature much better than rechargeables.

HF versus VHF and UHF ham radio

Among serious hams, the spectrum is generally divided into two halves, "High Frequency" (HF = 1.8 to 30 MHz) and "Very High Frequency" (VHF = 50 MHz extending up to Ultra High Frequency (UHF = 220 MHz and above). Above UHF are the microwave bands with frequencies measured in gigahertz and wavelengths in centimeters.) Most HF hams like long distance communication with either CW or voice. There are also HF packet-radio modes and slow speed picture transmission which resembles e-mail with a very slow modem. RTTY

and "PSK-31" are modes that resemble instant e-mail messaging on the Internet.

There are two kinds of VHF/UHF guys. Most just own hand-helds, but a few UHF hams are extremely technical and do high tech experimentation. This can be ham-television, exotic voice modulation like spread-spectrum and transmissions using satellites. Because VHF/ UHF signals rarely bounce off the ionosphere like HF, a simple VHF/ UHF hand-held is inherently limited to local, line-of-sight communication, unless it goes through a local relay station to extend its range.

Much like my effort to build a TV camera, what you do with great effort is more rewarding than following the crowd. So it shouldn't be a surprise that, for the technical guys, a lot of the VHF fun is organized around trying to talk to distant stations using ionosphere substitutes like satellites, or bouncing radio waves off the moon or even the aurora and falling meteors. Instead of using repeater relay stations, these guys get their kicks by using these exotic substitutes.

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BUILDING AN ANTENNA

Every shortwave radio station needs an antenna and building one should be your first project. Shortwave reception with a modern receiver can be adequate with as little as a few feet of wire dangling off the antenna connector. Many commercial short wave receivers built for non-hams have coil antennas (magnetic antennas) built inside the receiver case. Tiny antennas like this are adequate for hearing powerful stations such as "Voice of America," "Deutsche Welle," (Radio Germany), "Radio Moscow," or the BBC (British Broadcasting Corporation).

Amateur radio stations, by law are limited to 1000 watts average (2000 watts peak) and most of them run 100 watts or less. This means that hams are hundreds of times weaker than the commercial stations mentioned above and a big antenna is important to hear them. The lower the frequency, the bigger the antenna you will need. A good transmitting antenna needs to be at least ¼ wavelength long. A good transmitting antenna for shortwave radio signals must be high enough to send signals toward the horizon with as few obstructions as possible. Although an adequate receiving antenna can often be small and close to the ground, a large, high wire antenna works well for both jobs.

The long wire

The simplest, most versatile antenna is a "long wire." It is literally a long piece of wire, ideally 1/4 wavelength long or larger. For example, for 40 meters, it must be at least 33 feet long and should be strung up in a tree or other place as high as possible. In general, if you connect a random length of long wire to a transmitter, it will not be resonant with your hamband and you must "match it" with an impedance transformer called a "***transmatch***" or "***antenna tuner***." Fortunately, the transmatch or antenna is quite a simple device and can be put together in a couple hours. An antenna tuner is described in Chapter 9.

The 40 meter dipole

If I could only have one antenna, this is the one I would build. This simple antenna works well for both 40 meters and 15 meters (7 MHz and 21 MHz .). As will be explained later, extra antenna arms can be added so it will work on most of the other hambands. The advantage of a

dipole antenna is that they have an impedance of roughly 50 ohms that is easily loaded by a ham transmitter. So, although an antenna tuner is still helpful, this antenna will transmit quite efficiently without much tuning.
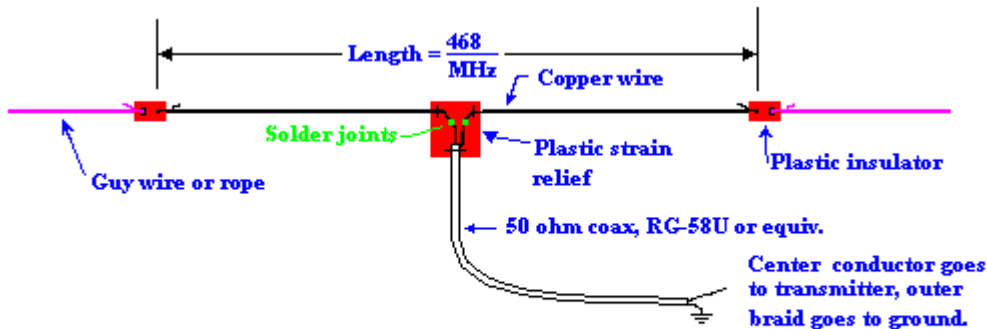
Where do I get antenna materials?

Radio Shack stocks RG-58U coax, insulators and heavy, multistrand copper wire that are perfect for dipoles. I usually make my insulators out of plastic scrap from a local plastic fabrication shop or I use ABS plastic pipe sections from the hardware store. If you have trees, a roof or other tall objects on which you can mount an antenna, you're in business. Hang it as high as you can.
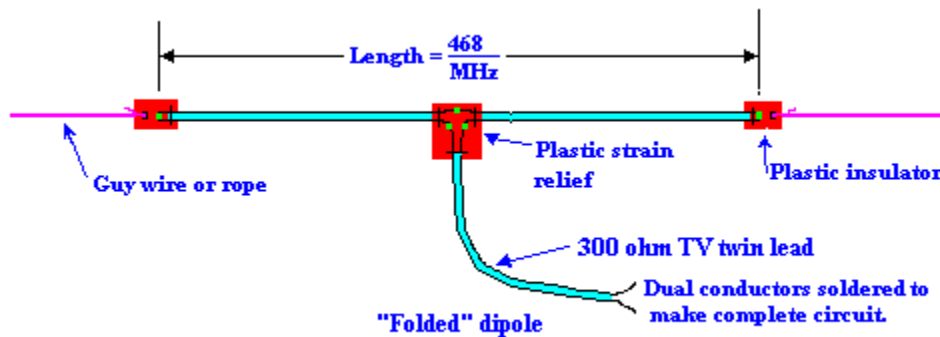
The folded dipole

Homebrew dipoles come in two basic flavors, "regular" and "folded." Back when I was young and poor, my favorite dipole was "folded" and made entirely from 300 ohm TV twin lead. The dual conductors of all three arms of the "T" are soldered together to complete the circuit in a "loop." I had one antenna cut for 40 meters that I used primarily for 40 and 15. It even worked OK on 75 meters for the local round tables our club used to hold. Aside from being made from cheap wire, another advantage of the folded dipole is that flat 300 ohm twin lead can slip through a slightly open window without mashing a fat, round cable or without drilling holes in the window sash.

Yeah, I know. 300 ohm balanced folded antennas need a "**balun coil**" and a transmatch

to match the transmitter. When I was a happy, dumb novice, I just loaded it directly with my π (pi) output class C vacuum tube transmitter and it worked well, thank you. Then, when I learned how balanced antennas are supposed to be driven, I bought the fancy balun coils. I was disgusted when I observed no difference in performance.

Multiband Dipoles

Today we have four more HF bands than 40 years ago and I can't resist trying them all. Any band I can't work MUST be wonderful, right? I have a "regular" 40 meter dipole in the front yard and a 30 meter one in the back yard. I guess I have room for an 80 meter Zepp, but I've been too lazy to build one. Jack Ciaccia, WMØG, uses the gutters and drainpipes on his house as an 80 meter "longwire." This sounded like a terrific solution. Unfortunately, my laziness soared when he began talking about "the buried radial ground field." In other words, I was supposed to dig long ditches across the lawn in several directions and bury multiple ground wires.

Several years ago the 80 meter band was exceptionally "hot" with dozens of CW stations on every night. I was eager to get on the air. I tried loading my 40 meter dipole on 80. I managed to do it, but there were hundreds of volts at the station end of the coax. (The transmitting impedance is a tad high on 80 meters.) After a couple hours of calling and tweaking, no one answered me. It seemed clear that I wasn't getting out and it was time for a better plan.
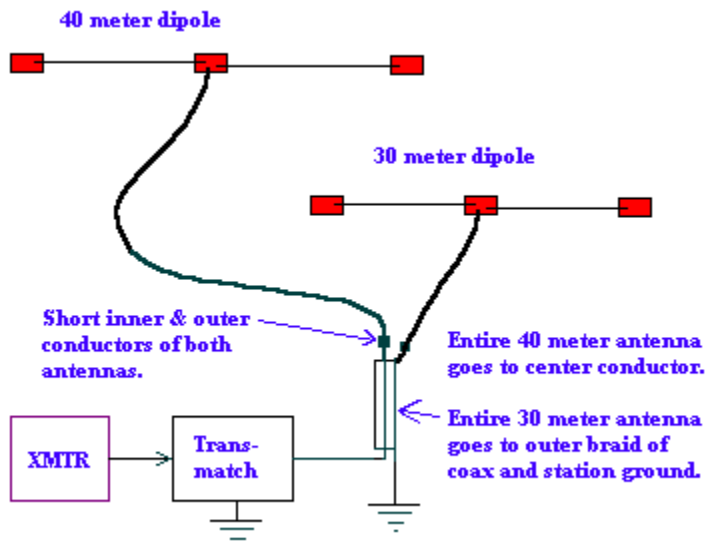
Then the cerebral lightbulb dawned! Why not use the entire 40 meter dipole, coax and all, as a longwire? For a counterpoise I first used my station ground, which is heavy copper wire connected to a water pipe. This loaded better than the 40 meter dipole but still didn't work very well. Next I connected the entire 30 meter dipole, coax and all to the station ground. Presto! I suddenly had a low impedance 80 meter antenna that loaded beautifully. There was one little glitch: My wife stormed downstairs and told me that I was obliterating the TV pretty much on all channels. Oh well, after that I got on 80 after she went to bed. I think (pray) the TVI is limited to inside my house. My theory is that I'm loading up the house wiring and the TV is immersed in

the antenna near field. More recently we bought a new, much more modern TV. It seems to be immune to not only my 80 meter signal, but my signals on all the HF bands.
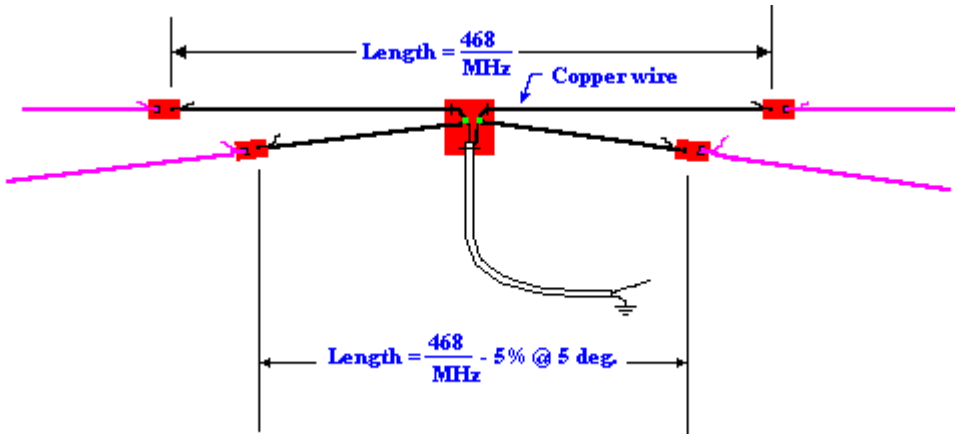
The multiband dipole

When I tried to get on 20 meters with my 40 meter dipole, I had a high impedance problem similar to using the 40 meter dipole on 80. However, using the antenna tuner described in chapter 9, I was still managing to work folks. Consulting the ARRL handbook, I added 20 meter elements to my 40 meter dipole to make it into a two-band dipole. A simple formula for the length of both of the secondary elements taken together is 468/ frequency in MHz minus 5%. Each arm of the dipole is offset from its neighbor by about 5 degrees. This lowered the impedance to something near 50 ohms and has been quite successful.

Now suppose you want to add elements to the 40/20 meter dual band dipole to cover other bands such as 30, 17, 12 and 10. Yes, it's possible to do this. Steve, WØSGC, built a five band dipole just like this. The ARRL handbook doesn't recommend this because such an all-band array tends to radiate every stray harmonic your transmitter may generate. In other words, it works too well! On the other hand, three-banders, such as 30/17/ 12 meters; or 40/20/10 meters are recommended. Notice that you don't need to add an element for 15 meters because the 40 meter elements already work well on 15 meters. Therefore a tri-bander built for 40, 20 and 10 is actually a four-band antenna.

The length of the third dipole is calculated just like the second dipole. Suppose you already have the 40 and 20 Meter dual band dipole and want to add another dipole for 10 meters (28.1 MHz). The length would be 468/ 28.1 MHz or 16.65 feet minus 5% or 15.82 feet. (15 feet 9.8 inches). The third antenna would also be offset from the center (20 meter) dipole by 5 degrees. Do NOT decrease the length by 5% a second time.

A limitation, or possibly an advantage, of a dipole, is that it transmits the most energy perpendicular to the wire. That is, it has some directionality. Therefore, if you wish to talk to South America or over the North Pole to Russia, ideally your dipole should be oriented east to west. Conversely, if you wish to talk across the US to the east and west coasts, the dipole should be oriented north and south. This isn't a big deal in performance, but if you have your choice in places to string the antenna, it is something to consider.

The curtain rod vertical
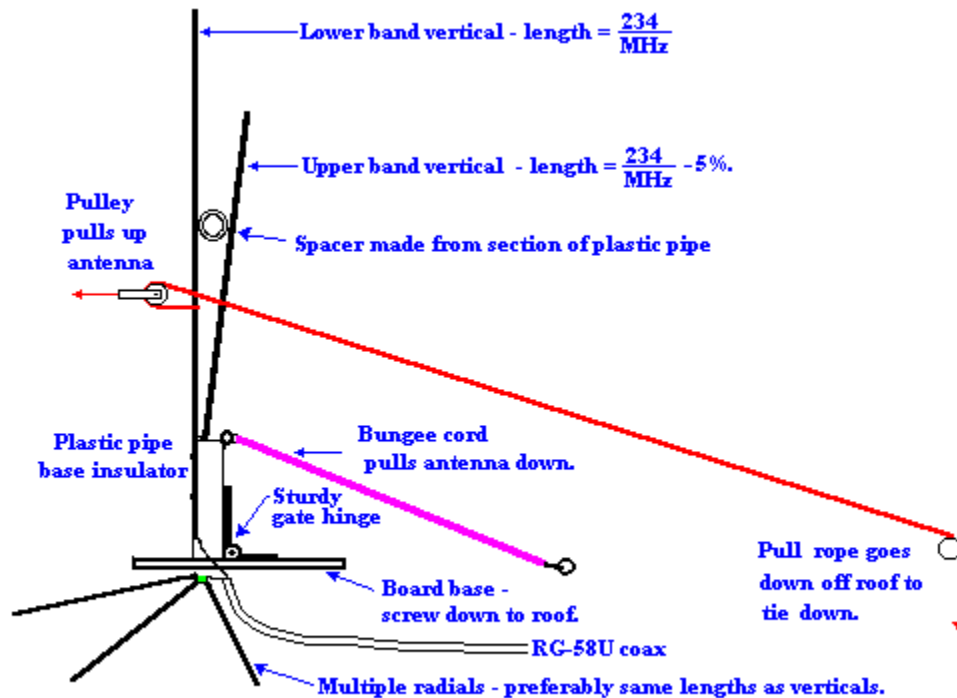
A dual band, dual vertical, hinged for lightning protection

I wanted antennas for 10 and 15 meters that would be higher and less directional than my dipoles. I started with a 15 meter vertical consisting of an 11 foot curtain rod lashed to my chimney. (234 divided by 21.1 MHz) Four thin wire radials fanned out down the roof in four directions. It worked well the first time I loaded it. The fun of a real curtain rod is that, when you tell someone your using "a vertical made from a curtain rod," they usually comment on it as if you had built a nuclear reactor out of a washing machine. Interesting psychology. Obviously these are guys that have never built anything themselves.

Trap antennas

Next I tried to add 10 meter capability by adding a parallel LC resonant trap tuned to 10 meters about 8 feet up the vertical. The idea is that, if a tuned LC resonant circuit is added at the right distance up the antenna, the trap will prevent RF current from traveling up the antenna past the trap. In other words, for high frequency bands the trap makes the antenna appear shorter than it really is. In this way a long antenna can also work well for a frequency much higher than its length would suggest. After I built a trap resonant for 10 meters, I adjusted the distances above and below the trap dozens of times. But even with a transmatch antenna tuner, I could never get it to load well on either band. It turns out that homemade trap antennas are hard to build.

You may have noticed that in an LC resonant circuit, the sizes of the L and the sizes of the C are not fixed. In other words, the LC circuit will be resonant at the desired frequency so long as:

$$\omega = 1 / (LC)^2$$

where ω = (2   x π   x Frequency)

$\quad$ π = Pi, 3.1416.

$\quad$ L = inductance

$\quad$ and, C = capacitance

2   x π   x Frequency = 1 / (LC)^2

$\quad$ Unfortunately, the sizes of the L or C do matter in a trap. This is because a capacitor or an inductor shift the phases of the current and voltage and effect the reflections of the waves along the wires. To design a trap properly, the distances above and below the LC as well as the sizes of the L and the C all have to work together to make the whole apparatus look like a 50 ohm resistor as seen by a radio wave. Good luck!

$\quad$ I haven't figured out a practical way to do this and the handbooks don't help, unless you copy their trap antenna designs exactly. In the end, I just applied the same dual-dipole principle as the multi-band dipoles discussed earlier. I added a second vertical to the first, separated by about 5° degrees and about 5% shorter than it would have been if it were standing alone. I added two more radial wires cut for 10 meters, but I'm not convinced they were essential. Once again, it worked perfectly the first time I loaded it.

$\quad$ Caution: ***Remember that the "vertical antenna" begins at the exact inch where the coax inner conductor first separates from the outer braid.*** A common mistake is to ignore an extra 6" of inner conductor that may be adding to the effective length of the driven element. The dual band vertical has worked beautifully. I've also used it on 12 meters successfully. Much to my surprise, it also worked on 17 meters, although the SWR (Standing Wave Ratio) isn't great. In other words, when there are standing waves on the antenna because the length is wrong, it takes extra voltage to drive it. I am probably losing some power on 12 and 17 meters.

Kaboom! What about lightning?

$\quad$ Looking up at the metal poles on my roof, they looked more like lightning rods than curtain rods. I'm probably more paranoid than necessary, but I've bad experiences with lightning. When I was a novice, fuses blew in my rig during a thunderstorm. A buddy of mine had his oscilloscope fried and a hole blown in his roof. On mountaintops I've felt my hair stand on end and heard my ice axe hiss as we galloped down the mountain in terror. Once I had the grim duty of carrying deceased lightning victims off Arapaho Glacier. Lightning scares the heck out of me and that vertical looked like a disaster waiting to happen.

$\quad$ My solution was the base hinge and bungee cord shown above. During the summer I raise the antenna by tugging on the rope whenever I need it, then lower the vertical when I'm done. The hinge also has stealth advantages. One important point is that the rope pulls it UP, while the bungee makes sure it folds back DOWN. I tried to have the bungee pull it up, but that worked poorly. There was too much torque on the vertical and the bungee wouldn't let the antenna fold flat against the roof.

Fuzzy metal brushes on an antenna make a lightning strike less likely

$\quad$ A relatively new approach to lightning prevention is to bleed the excess charge off a vulnerable metal rod before it can attract a full-fledged lightning bolt. It has been known for over

a hundred years that lightning is attracted to tall, pointed objects, like vertical amateur radio antennas. Electric charge and a high voltage gradient gather on pointed objects. Therefore, it was logical that having a blunt, rounded tip on a vertical metal pole should retard lightning, rather than attract it.

Recent research has demonstrated that a rounded tip on a pole may make an actual strike more likely. Bundles of metal rods were placed on a mountain top and lightning strikes were recorded to determine whether rounded, sharp or square-ended rods were the most likely to be hit. Contrary to intuition, the rounded tips were hit most often.

As charge builds up before a lightning strike, voltage appears at the top of the pole. If the pole is tipped with a sharp point, or a bunch of sharp points as in a metal brush, the charge is rapidly bled off into the air. The discharge is not instantaneous in the form of a gigantic electric arc, but rather as a small current, a "***corona discharge***" that continues for many minutes. This slow discharge gets rid of enough charge on the pole to reduce the static voltage and make a strike less likely.

In order for this to work, the vertical must be grounded so the current has somewhere to go other than your transmitter. To pass DC current without interfering with the radio frequency currents we connect a big RF choke between the vertical and the grounded radials. The choke needs to be 2.5 millihenries rated at hundreds of milliamperes. Frankly, lightning still scares me. So, grounded metal brushes or not, I still crank my vertical antenna down every day in the summer whenever I'm not using it.

CRYSTAL SETS TO SIDEBAND
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Chapter 6

BUILDING A HOMEBREW QRP

Among the guys I work, QRPs seem to be the most common homebrew project, second only to building antennas. Therefore this chapter describes a simple QRP design I have settled on. I use my QRPs as stand-alone transmitters or I use them to drive a final amplifier to produce higher power, 25 to 100 watts.

It's true that before you build a transmitter you'll need a receiver. Unfortunately, a good selective, all-band ham receiver is complicated to build and most guys don't have the time and enthusiasm to do it. (See chapter 13.) The next chapter describes building a simple, 5 transistor 40 meter receiver which I have used with the QRP below to talk to other hams. This simple receiver will work best during off hours when 40 meters isn't crowded. It can also be used to receive Morse code for code practice.

A 40 meter QRP module.

The QRP transmitter above is designed exclusively for 40 meters, (7.000 to 7.300 MHz.) The twelve-volt power supply comes in through the pig-tail wire up on the right. The telegraph key plugs into the blue-marked phono plug socket on the right of the aluminum heat sink. The antenna output is the red-colored socket on the left end of the heat sink.

The transmitting frequency of the QRP module is controlled by a quartz crystal. That's the silver rectangular can plugged into the box on the right front. The knob on the far right is a variable capacitor for adjusting or "pulling" the crystal frequency about 3 KHz. As we shall explain in chapter 10, variable frequency VFOs that can cover the entire band are hard to build. I don't recommend starting out with a VFO. You need success, not frustration.

Start simple

The easiest QRP is just a crystal-controlled oscillator. It usually has one to three amplifier stages to raise the power to between 1/2 to 5 watts. This will get you on the air quickly. Unfortunately crystal control means you must order $18 custom crystals for your favorite frequencies in each band. Because the oscillator only has a narrow tuning range, you can usually only call CQ (calling any station). As luck would have it, it always seems as though the other fellow calling CQ is just out of your crystal range.

The transmitter "mainframe"

You could use this bare-board little transmitter just as shown above. However, it will be more convenient to mount it in a larger chassis equipped with an ON/OFF switch, pilot lights, an antenna relay and other niceties. My whole transmitter assembly is shown below.

The transmitter "mainframe" is a box to contain your transmitter modules.

The large meter at the upper right indicates the current drawn by the final amplifier. It's helpful to know how much power the transmitter is consuming. The switches and lights on the lower left are the main power switch and the transmit/ receive switches. There are also LED lights to indicate which switches are active. The large red button is a "spot" switch. With the spot switch engaged, the QRP oscillator may be tuned to another station without actually transmitting. How big you make your mainframe depends on your plans and ambitions. As you can see, I had really big plans. By the time you add multi-band capability, a VFO, power supplies and single-sideband capability, even a large box may be too small. My previous mainframe was too small so I made this one extra large to eliminate crowding.

HF construction methods – building your own circuit boards

Back in the vacuum tube days we built hand-wired HF transmitters. Inside they had long wires running every which way. However, transistors generate high power with low voltage and

big currents. As a result, the inductance of the wiring must be kept as low as possible. This means you must build with a circuit board or the transmitter simply won't work.

For example, once I connected an output lead from a 15 meter transistor power amplifier to the base of the next stage with a bare wire 4 inches long. If this had been a vacuum tube circuit, this wire coupling would have worked well. But with high current transistors, the wire acted like an RF choke. That is, the wire blocked current flow as if it were an inductor. Sliding an oscilloscope probe along the wire, I could see an 80% drop in drive voltage from the output of the first amplifier to the base of the next stage. In contrast, a wide circuit trace printed on a circuit board acts like a coaxial cable and has very low inductance. With a PC board the same drive to the next stage can be nearly 100%, not 20%.

If you have already developed your own method of building printed circuit boards, you may skip ahead. But if you have never done this before, read on.

MAKING PROTOTYPE RF CIRCUIT BOARDS

PC board tools and materials

I usually use double-sided printed circuit (PC) board material such as Radio Shack part # 276-1499A. This board has sheets of thin copper bonded to both sides of a 1/16th inch fiberglass sheet. I only solder components to the surface of one side. The solid sheet of grounded copper on the opposite side provides distributed capacitance over the whole circuit. I believe this gives extra stability.

Traces on a PC board act like transmission lines

A transmission line, such as the coaxial cable that delivers your TV signals, is remarkably efficient. As explained in chapter 4, the wire in the center of the coax acts like a <u>distributed</u> inductance that rings with the <u>distributed</u> capacitance between the center wire and the outside insulation. In other words, a coaxial cable is a distributed LC circuit. The voltage and the energy are not dissipated as you would expect. In fact, the energy loses that do occur are only the heating losses in the insulation and the simple resistance losses that happen in copper wire.

A two-sided circuit board can be designed to act like a circuit wired with pieces of coax. The circuitry is mounted on one side of the board while the other side is ground. Each trace has a small amount of inductance and each trace has a proportional amount of capacitance with the grounded copper on the far side of the board. The result is that signals are almost unchanged as they travel along the traces of a circuit board. It would be interesting to build the exact same RF power amplifier on single and double-sided boards and compare the difference in performance at HF frequencies. I'm convinced double-sided is far better, but I've never done a controlled experiment.

In microwave printed circuit boards the traces are deliberately designed to act like transmission lines for the particular frequency that is being used. The precise, optimum dimensions for these "microstrip" traces can be calculated for maximum performance. Fortunately for us, high frequency circuit boards like ours don't have to be designed with so much care.

Etched circuit boards

There are at least four ways to make homebrew RF boards. Originally I tried etching "real" printed circuit boards with ferric-chloride solution. It's slow, messy and lots of work. Etching boards is an art that isn't easy to master. You may under-etch or you may over-etch, often on the same board! If you succeed, you'll have a result close to a commercial product. Unfortunately, when you use a circuit layout from an ARRL handbook or QEX, you are making the assumption that you can buy all the exact parts the author used. Good luck! The parts you can buy may not fit on the board. I found that the worst limitation of etched PC boards was that I couldn't build and test my circuits one transistor stage at a time. If I needed to add another component or add another amplifier stage, I was out of luck. ***The key to success in homebuilding is building AND TESTING one stage at a time.***

Gouged PC boards

My favorite method for making RF boards is carving them into a bare, two-sided PC board with a small wood-carving gouge. The gouge is a chisel with a cupped end, perhaps 1/8 to 3/16 inch across. I got mine from Brookstone Tools.

Two small wood-carving gouges
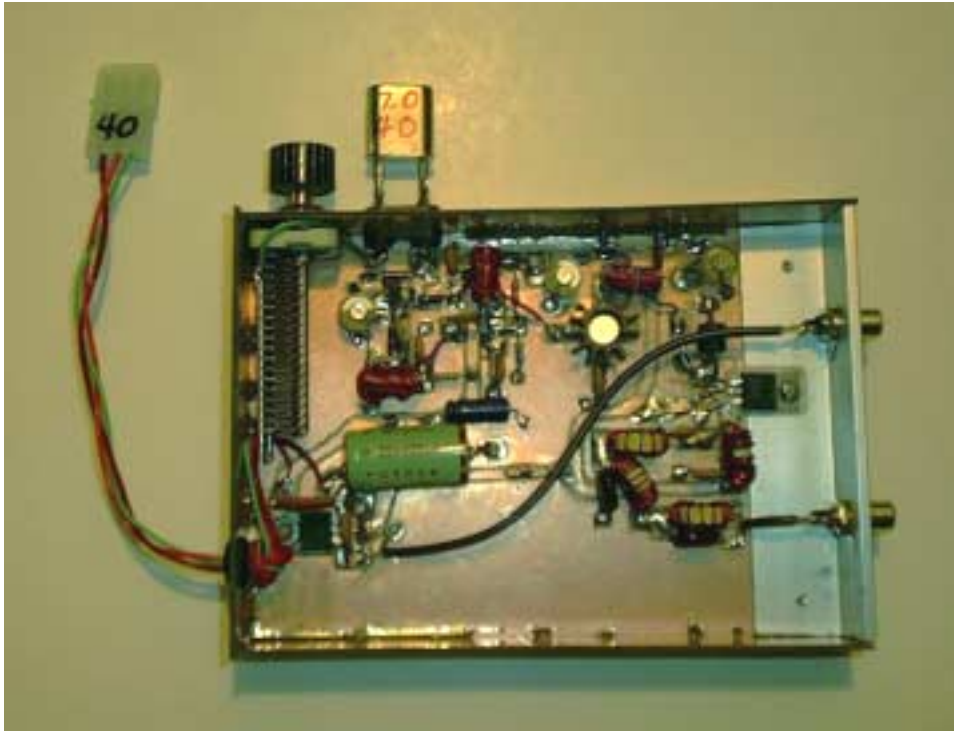
This QRP board was made with "gouged board" construction. Nearly all of the visible copper is "ground." The aluminum angle on the right serves a heat sink for the output transistor.

When you push the gouge along the board at a high angle and twist your wrist back and forth, the gouge carves out a little trench through the copper. Hint: Keep your elbow high and the gouge won't skate across the surface and into you hand. Ouch! Obviously two "trenches" can isolate a strip of copper that serves as wire or "trace." Often I just isolate little islands of PC trace onto which I solder short component leads. I usually solder components to the surface, rather than drilling mounting holes for each lead.
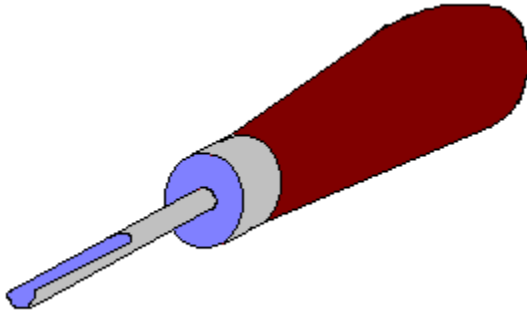
Notice the cupped end of the wood-carving gouge

PC boards for integrated circuits

A wood-carving gouge works fine for RF circuits made from discrete transistors, but is impractical for integrated circuits. For through-hole IC's I use punch-boards and wire-wrap methods. There is an example of this construction in chapter 7. Another method of working with integrated circuits is to etch (or buy) tiny boards for mounting for each type of IC. That is, you make 8-pin boards, 14 or 16-pin boards, etc. These little boards have big pads connecting each pin so that you can solder jumpers down onto your relatively crude handmade board. Isolated little IC boards are good for working with "surface mount" ICs which are otherwise too tiny to handle.

Coax jumpers

If you need to, it is still possible to run long wires from point to point. But instead of wire, you must use shielded coax. Sometimes I "pipe" an RF signal from one end of a PC board to the other without significant loss of voltage or power. If there's no room for a wide trace, I use a piece of skinny RG-174 coax transmission line for this purpose.

Another application for a coax jumper is to shield an audio or DC signal from the RF. If you run a bare wire across a PC board full of RF currents, the low frequency signal will be contaminated with RF signals by the time it arrives at the other end. For example, in the QRP board above, my DC (Morse code) keying signal is transported across the board with a length of coax. Because of the way my transmitter chassis was wired, my QRP board plugs into the mainframe with the telegraph key input at the wrong end of the board. The telegraph key needed to switch the MOSFET transistor on an off, but unfortunately it was on the opposite end of the board from the key input. To shield this low power, DC line, I used a coax jumper as shown in the photo.

Ground the shield braid at one end, not both.

COAX JUMPER CABLE
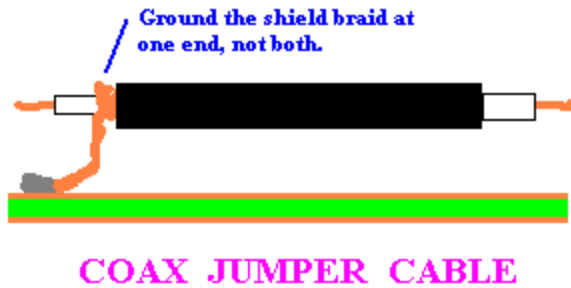
Just ground the coaxial shield at one end. The most common error when using coax jumpers on a board is to ground both ends of the shield. This introduces a current loop that can act something like a loop of winding on a transformer. This current loop might pick up stray currents and the coax might do more harm than good.

Disk and Super-glue boards

Another practical RF PC construction method is the "disk and Super-glue" method. Small disks or strips are punched or cut out of PC board material. The disks and strips are glued onto the PC board using superglue to form contact nodes and traces. An advantage of this method over gouged board is that the ground sheet is unbroken. That is, when you solder a component lead to ground, you will know that the entire PC board is "ground," and not just areas or strips of "ground." A continuous sheet of copper means that there will be virtually no voltage differences between one region of the board and another. The higher the frequency or the higher the power levels, the more important this advantage becomes.
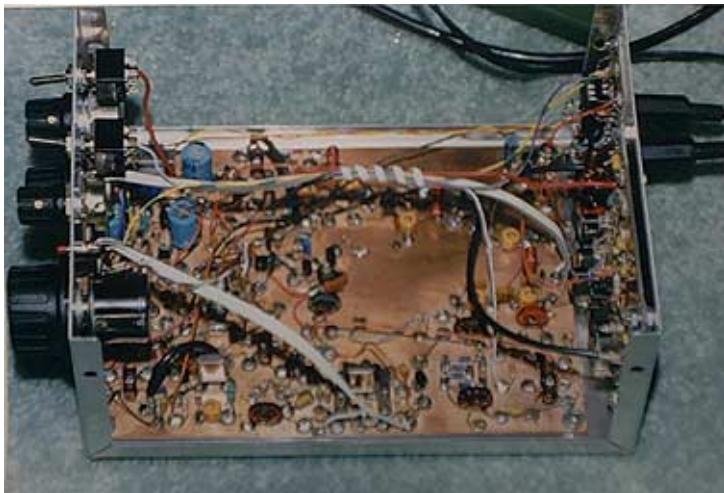
Mike Fitzgibbon, NØMF built the homebrew QRP transceiver shown above using the super-glue technique. I met Mike on the air while he was using this transceiver. The transceiver puts out about a watt and uses a super-regenerative receiver to pull in feeble 40 meter signals like mine.

Dead Bug construction

"Dead bug" construction resembles super-glue boards in that the PC board is used as an unbroken sheet of grounded copper metal. Traces are not cut or etched into metal. Instead, of

using disks glued to the board, the ungrounded component leads are soldered together up above the board as needed. Since the ICs and transistors are upside down, they resemble "dead bugs" with their feet in the air. Of course you must keep the leads as short as possible. When currents are low, lead inductance isn't a problem. For the low power stages (less than 100 milliwatts) I have found "dead bug" construction OK, but I don't recommend it for RF power amplifiers.
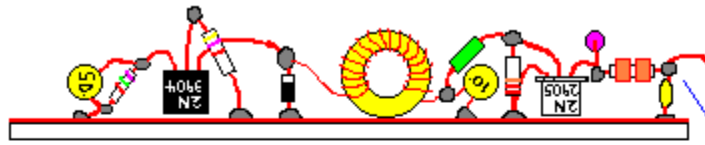
"Dead Bug" - Parts soldered to p.c. board ground plane.

Every ungrounded connection is made above the board.

Channels carved out to make circuit traces.

"Gouged Board" - Parts soldered to islands and traces on 2-sided p.c. board.

"Dead Bug" versus "Gouged Board" construction.

When you get into "high power," greater than 100 milliwatts, you should minimize the lead inductance by using wide traces on a PC board. Once I built a 10 meter power gain amplifier stage using extremely compact dead-bug construction. It worked well and gave me about 0.5 watt output. Since the stage was a success, I rebuilt it using gouged board construction. Using carved traces, the same circuit gave me 1.0 watt, a 100% improvement. When I have to connect an RF power lead across the board for a half an inch or more, I cut a wide trace on the board or I use a short piece of coax. For big, 10 ampere RF currents in a power amplifier my traces might be ½ inch wide or more. If I'm short of space, sometimes I use a wide rectangle of PC board material standing on edge as a wide, low inductance "wire."

Boxes out of PC boards

It's often necessary to shield circuit boards from other circuits. That is, the circuit needs to be completely enclosed in a metal box so that it does not radiate or receive radio signals to or from nearby circuit boards. A gouged board circuit can be shielded by building up the edges into a box. Solder inch-high strips of PC board material around the periphery of the board. Since the copper surface solders nicely, it's easy to build up a board into a sturdy open-top box. And because a gouge–board doesn't need to have through-hole components, the circuit inside is completely isolated from the grounded outside of the box and is enclosed on five sides.

To make a lid for the box, fold a flat piece of thin aluminum or copper sheet into a mating shallow box that fits over the top. The top should be just snug enough to hold it in place.

****

The complete crystal controlled QRP transmitter

The block diagram below shows the basic modules of the completed QRP transmitter from battery to antenna.
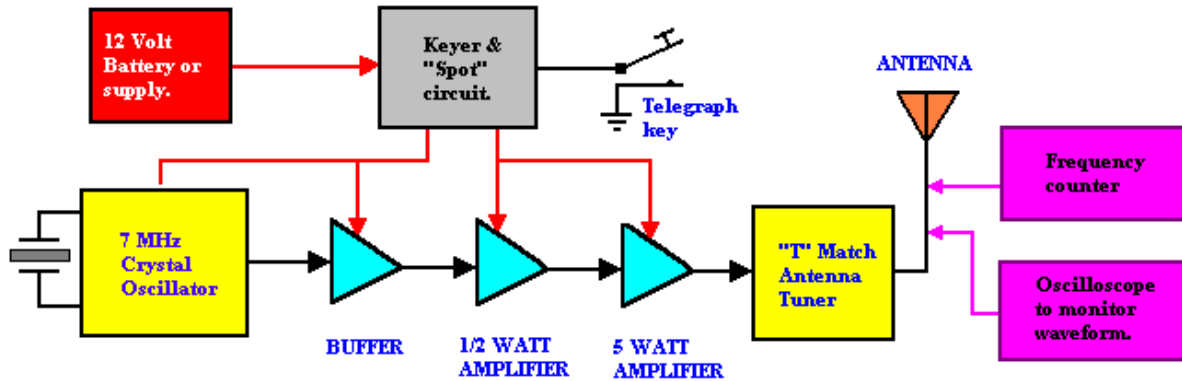
40 Meter 5 Watt QRP Transmitter Block Diagram

The bad news is that there are lots of circuit blocks. Two of the modules on the right, the oscilloscope and frequency counter, are test instruments you need to be sure you are operating on the correct band. These are items you will almost certainly buy. The power supply that I prefer is a simple car battery or a 12 volt deep-discharge marine battery. It's desirable, but not essential, to regulate the battery power to about 11 volts. In this way, the transmitter always has the same supply voltage, whether the battery is being charged or nearly dead. You can also build a power supply that plugs into the wall or buy a supply. Building a ten-watt, 12 volt power supply is fairly easy. But later, when you get into high power amplifiers needing 100 or 200 watts, building high power supplies is much harder and you may want to return to a battery. Power supplies are discussed in chapter 8.

The receiver is not shown above and is assumed to use a separate antenna. If you hook your antenna to the transmitter and receiver simultaneously, the receiver might be damaged. Accessories like the telegraph key, the transmitter keyer and the T-match antenna tuner are discussed in chapter 9.

Amplifiers and oscillators

In order to generate a radio signal, we first need to make an oscillator. A spark gap generates radiowaves by the electronic equivalent of banging on a bell. On the modern ham bands we need continuous, pure sinewaves. Think of it as the radio equivalent of an electronic organ. You hold down a key and a pure tone never stops. In fact, that's the origin of the term "continuous wave" or CW for radiotelegraphy. You may have already asked yourself, "If I'm pounding on a telegraph key, what's continuous about that?"

Continuous waves at Megahertz frequencies are most easily generated using electronic oscillators. A continuous wave oscillator is an amplifier that amplifies feedback from its own output. Before we can understand an oscillator, we need to cover bipolar transistor amplifiers.

Transistor Amplifier
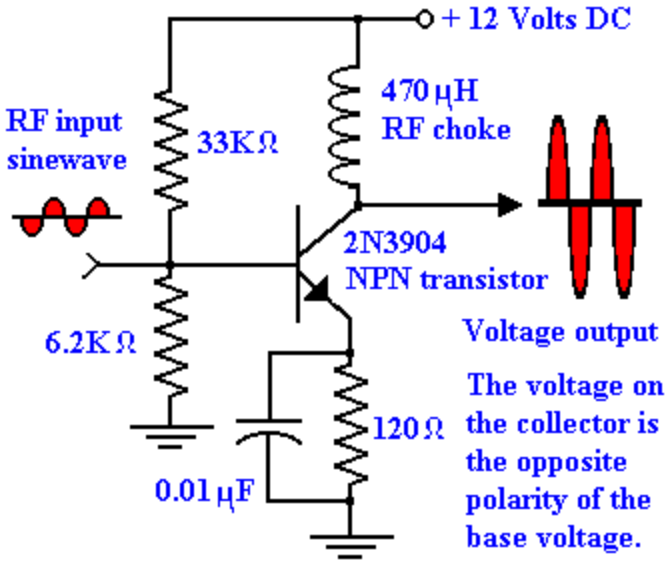
What is a linear amplifier?

The circuit above is a simple transistor RF (radio frequency) amplifier made from an NPN transistor. If you prefer, you could reverse all the polarities and use a PNP transistor and it will work just as well. The above amplifier is designed to be *linear*. Linear means that it can amplify big signals or tiny signals equally well over a wide range of frequencies. In other words, although designed for radio frequencies, this amplifier is "hi-fidelity" and is analogous to the audio frequency amplifiers found in your stereo. Another name for a linear amplifier like this is *Class A amplifier.*

As we saw in chapter 4, a bipolar transistor can be thought of as a structure made by merging two PN junction diodes. When a diode is forward biased, (positive to P conducts) relatively large currents, (milliamperes), can pass through the diode. However, current will flow only when the forward offset voltage, (about 0.6 volts) is exceeded. Just like a diode, when an NPN transistor is used, nothing significant will happen until the base voltage rises above positive 0.6 volt. When this occurs, a relatively small base current will "convert" the tiny region of P type semiconductor into a conductor. Big currents are then free to flow from collector to emitter. In the 2N3904 transistor used above, the transistor "gain" causes a big current to flow that is 100 times larger than the base current.

Suppose that we want to amplify a sinewave that has both positive and negative polarities. A transistor amplifier with a minimum of parts would be just a base connected to the input. That amplifier would only amplify the upper part of the positive half of the sinewave, above 0.6 volts. All the rest of the sinewave would be below the turn-on threshold. The purpose of the 33K ohm resistor in the above circuit is to turn the transistor "halfway on," like a faucet. Now when a sinewave current comes in on the base, the negative portion of the sinewave will turn the transistor MORE OFF. And when the positive half of the sinewave arrives, it will turn the transistor MORE ON.

What does the 470 microhenry inductor "choke" do?

The choke produces a voltage output without wasting energy. We could use a resistor instead, but a resistor would waste energy and become hot. This amplifier is designed to generate a big RF voltage. The output is the voltage that rides on the transistor collector. The current flowing through the inductor isn't really doing anything useful besides dropping the voltage between the 12 volts supply and the collector. Therefore, we use a large inductor relative to ham band frequencies. RF cannot pass through the choke, but DC current can. Remember that *the current through an inductor cannot change instantly.* The inductance is high enough so that, during each half-sinewave cycle, the inductor is too large to charge significantly with current. Consequently, a big RF voltage appears on the collector and little energy is wasted.

Stabilizing the transistor operating point

The **33K ohm resistor** is the component that turns the transistor "half –on." It "*biases*" the transistor on by injecting a small current into the base. The **120 ohm resistor** serves to add a small amount of negative feedback so that the transistor will not turn on too hard when the transistor becomes warm. As big DC currents flow through the 120 ohm resistor, a DC voltage will appear across it. This voltage "raises" the emitter voltage off ground, thereby decreasing the base to emitter voltage. When this voltage drops, the current flowing into the base decreases, thereby turning the transistor a bit more off. So long as this resistor isn't too large, it just serves to bias the transistor and make it more stable with temperature changes.

If you replace the 120 ohm resistor with a short circuit, you'll find that the amplifier still works, but the transistor will run hot to the touch. The **6.2K ohm resistor** makes sure that the charge in the base of the transistor always has a way to leave and turn off the transistor. The 6.2K resistor also stabilizes the operating point and insures that the circuit will work every time you build it.

Bypass capacitors

So what's the 0.01 microfarad capacitor across the emitter resistor for? This is a "*bypass*" capacitor. An RF amplifier can be thought of as two circuits superimposed on each other. One circuit establishes the static DC voltages and currents needed for stable, linear operation. The other circuit handles the transient RF sinewaves that modulate the static voltages and currents. As explained above, DC current passing through the 120 ohm resistor causes a DC voltage drop from emitter to ground. Radio frequency current passing through the resistor would also cause an RF sinewave to appear on the emitter. This voltage would be subtracted from the voltage on the collector and therefore would decrease the output. You may remember that *the voltage across a capacitor can't change instantly.* The bypass capacitance is chosen so that, although it will charge up to some DC voltage, at ham band frequencies the capacitor voltage will not change. For a capacitor this large, the fractions of a microsecond that the RF voltage oscillates up and down are insignificant. The result is that emitter will have zero RF voltage on it and all the RF voltage will appear on the collector. Another way to look at bypass capacitors is that they "shunt" RF to ground, but don't affect the DC.

How an amplifier becomes an oscillator

Transistor oscillator

Positive feedback
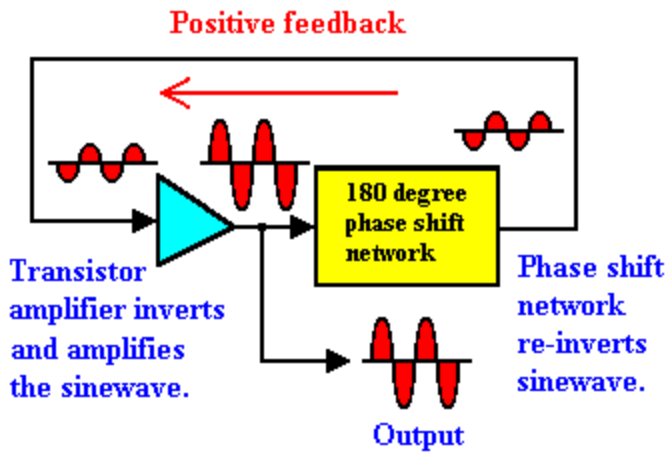
You already know that a public address system turns into an audio frequency oscillator when you place the microphone close to the loudspeaker. This results in a horrible, screaming oscillation. Electronic oscillators work by feeding the output back into the input.

Notice that a one-stage transistor amplifier inverts the polarity of the input waveform. Rising voltage on the base causes the voltage on the collector to fall. In theory at least, if you were to feed the output of this amplifier back to the base circuit, the opposite polarity of the output would cancel out any signal that begins to form on the input. For this reason, if you wish to make an oscillator, the waveform needs to be turned up side down or "*phase inverted*" before the feedback is introduced to the transistor base.

The need for a phase inverter circuit gives us the opportunity to use this inverter circuit as a filter that also restricts the oscillation to just one frequency. You have already met parallel L-C resonant circuits. A series LC circuit will attenuate every frequency except its resonant frequency. A series LC circuit located between the collector and base of a transistor amplifier will oscillate on a specific frequency determined by the series inductance and capacitance.
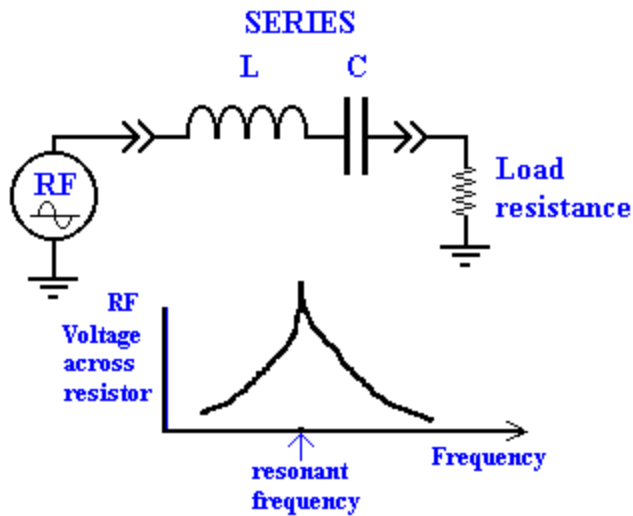
Series LC resonant circuit

In chapter 4 you were introduced to the parallel resonant circuit. The series resonant circuit also resonates at a specific frequency and can be used in much the same way. The parallel resonant circuit appears as an ***infinite resistance*** or ***infinite "impedance"*** at a specific frequency while shorting out RF voltage at all non-resonant frequencies applied across it. In contrast, the series resonant circuit looks like ***zero resistance*** at the resonate frequency. As shown above, it only passes one RF frequency current efficiently to the load resistor. To all other frequencies, it appears as a large inductance or as a tiny capacitance.

Transistor RF Oscillator
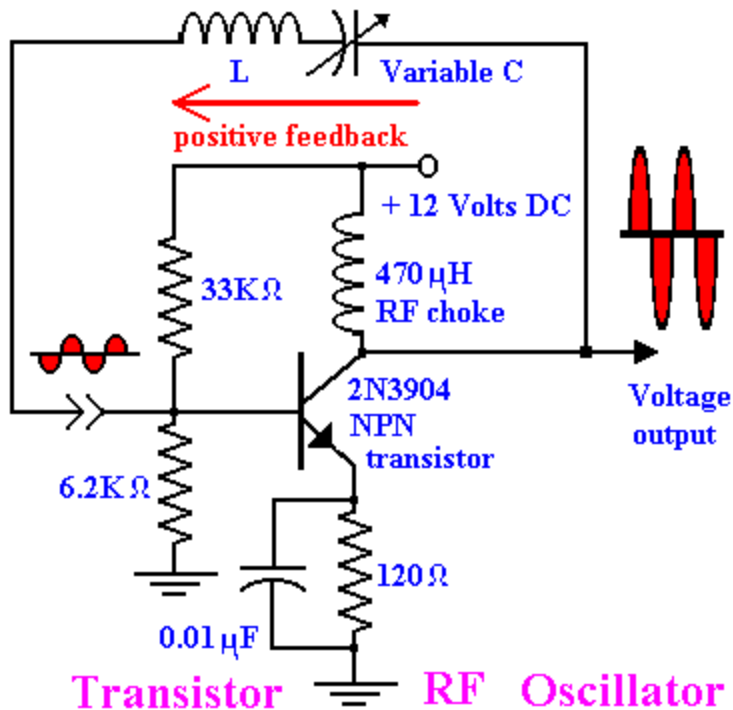
A working transistor oscillator

The circuit above oscillates in the range of 1 to 30 MHz, depending on the sizes of the inductor L and capacitor C. Unfortunately, if you build it, you'll find this oscillator too unstable for use in ham radio. However, it does produce a strong oscillation. Once you get it running, you can illustrate the importance of the 33K forward bias resistor. When you disconnect this resistor, the oscillator will continue to oscillate as though nothing happened. Well, almost nothing. If you look closely on your oscilloscope, you'll see that the bottom loops of the output sinewave are severely distorted. Without the 33K, the transistor turns off whenever the input drops below 0.6 volts.

Now turn off the power supply for a moment. Turn the supply back on and the oscillator will be "dead." The output will be just a straight line on your oscilloscope. Without this 33K forward bias, the amplifier cannot "see" it's own tiny random noise output and the oscillation never starts. That is, the random noise is way below the 0.6 volt threshold. Restore the 33K and the oscillation will restart immediately.

A non-linear amplifier with no forward bias is called a *Class C amplifier*. They are useful for amplifying CW signals that are greater than the forward base drop. That is, the drive for a Class C amplifier must be greater than 0.6 volt, otherwise there will be no output. Class C is not useful for amplifying voice or music signals because the 0.6 volt threshold cuts off much of the waveform and distorts it severely.

Quartz crystal oscillators - the key to modern frequency stability

Electronic wrist watches today use quartz crystals as the frequency standard that gives cheap everyday watches precision that rivals the old time mechanical chronometers that once

were vital for navigation. Analog color TVs use crystals as a time standard so that the color separation can accurately separate red, blue and green. Computers use crystals as clock standards so that modems will run accurately and remain in step with the sending station.

Quartz is a type of natural, crystalline, silicon dioxide glass. It is an extremely good insulator. Household glass is also mostly silicon dioxide, but the atoms are arranged in an amorphous structure, something like a random pile of bricks dumped from a truck. In contrast, quartz has a regular crystalline structure as though the bricks were neatly stacked in layers. The quartz is not perfectly pure, but contains ionized, contaminant atoms that are trapped in the crystal lattice. Notice that contaminant ions *do NOT* convert the quartz into a semi-conductor. Natural quartz from Brazil and a few other places occurs as large, clear crystals with sharp flat faces and uniform structure. This material can be cut and polished into thin, flat sheets that are cut up into tiny squares. Each square is then mounted between two metal plates as if we were building a simple capacitor with quartz glass as the insulator.

When voltage is applied across the quartz, the charged metal ions contaminating the quartz are physically attracted to the charged plates as shown below. The thin quartz sheet literally bends back and forth as the voltage changes polarity. If the voltage is an RF voltage, the polarity changes back and forth millions of times per second and the crystal vibrates at that frequency.
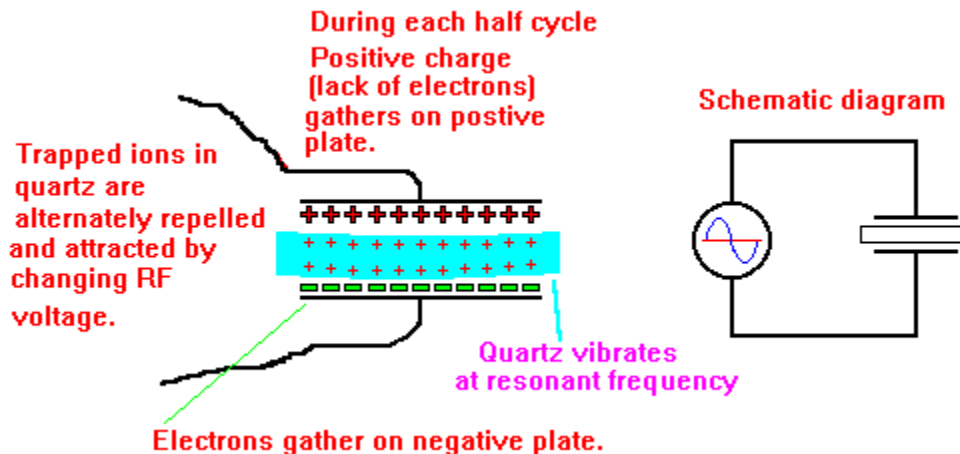
When AC voltage is applied to a crystal, it vibrates most easily at a frequency proportional to the mass and physical dimensions of the quartz. In other words, each crystal can be fashioned to vibrate at a specific frequency. As you would expect, big, thick crystals vibrate at low frequencies. Thin, tiny chips vibrate at high frequencies. Even though crystals oscillate at millions of vibrations per second, the vibration is mechanical and they resemble musical instruments. Just like musical instruments, crystals also have overtones or higher harmonic frequencies. Some crystals are designed to operate at the 3rd or 5th overtones, rather than the fundamental frequency. Overtone crystals can oscillate at frequencies as high as 100 MHz or more.

Capacitance between metal plates.

Lx   Cx   Rs
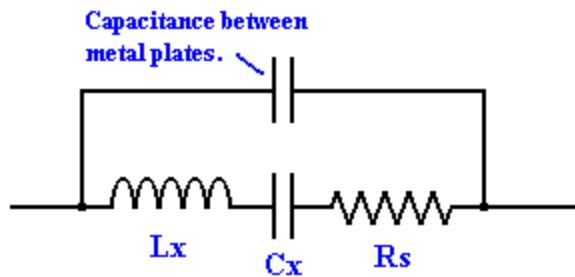
Series "equivalent" components are determined by the mechanical properties of the crystal.

Equivalent circuit of a crystal.

Quartz crystals oscillate mechanically, but they are simultaneously oscillating electrically. Quartz crystals act like a series L-C circuit. They are equivalent to the LC components we used to tune the crude oscillator above. The equivalent capacitance Cx and Lx are completely dependent on the physical dimensions of the crystal wafer. Think of a quartz crystal as an extremely stable, L-C circuit. Since the crystal is constructed from two metal plates applied across the quartz, one can also say that the crystal has an element of parallel resonance as well as series resonance. If the wafer were ordinary glass, this capacitance would probably be about the same value.

Notice the resistor, Rs, in series with Cx and Lx. This resistance is the electrical equivalent of the mechanical friction that happens when the quartz flexes back and forth. This resistance causes heating and, if the heating is significant, the heat will expand the dimensions of the mechanical parts and cause the frequency to drift. In general, the larger the crystal, the more slowly the temperature will rise and the more slowly the frequency will drift.
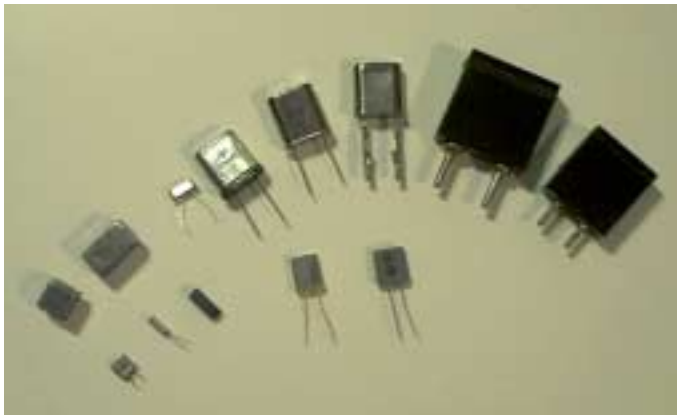
An assortment of quartz frequency control crystals

Typical crystals are shown above. Two large ancient, ham crystals are shown at the upper right. These can be good parts, provided they are still working after 50 or more years. The three crystals in center rear are size HC33 and are modern-manufactured, first-rate parts. The two medium size HC49 crystals in the front center are microprocessor crystals. They are good parts,

but often they aren't available for the exact frequency you happen to need. Sometimes it's necessary to order custom HC49s from companies like International Crystal Manufacturing, Inc. (ICM) for about $18 each. The little bitty crystals at the left front should be used with caution. Little crystals get warm easily and drift. The square and rectangular "crystal blocks" at the extreme left are complete crystal controlled oscillators packaged in little cans. These are intended for computer work, not RF frequency control. So far, I have never encountered a crystal block oscillator that didn't run hot as pistol and drift like crazy. Unless you've checked it out, don't use oscillator blocks!

Common Crystal Oscillator Circuits
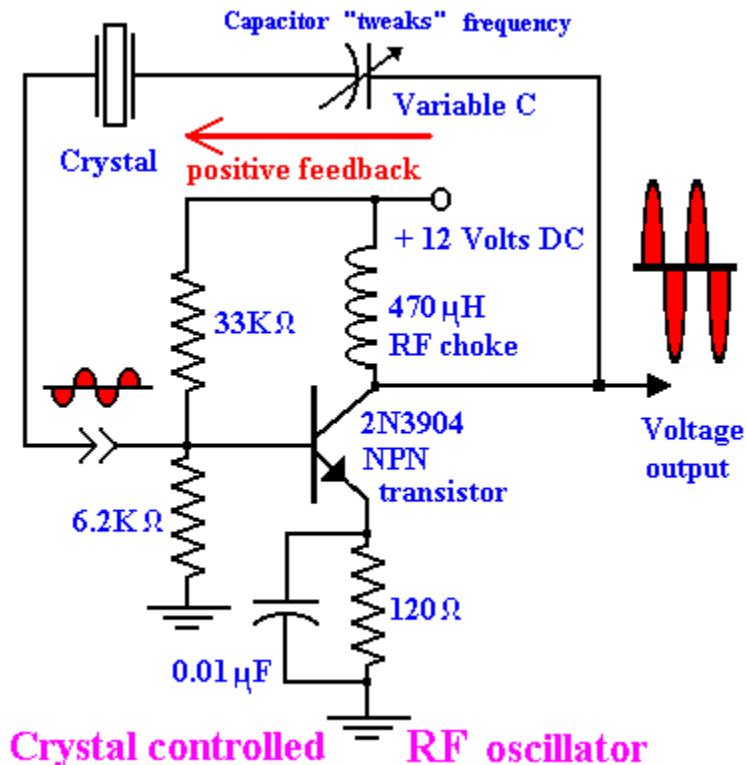
There must be a dozen or more transistor crystal oscillator circuits. The circuit above is practically the same as the crude LC oscillator illustrated earlier. The variable capacitor allows you to "tweak" the frequency a kilohertz or more above, on, or below the nominal frequency printed on the crystal case. The circuit above is useful and you will occasionally see it used in homebuilding projects. Yes, if you like, you can leave out the variable capacitor. However, it is not a good idea to put big sinewave voltages directly on the crystal. For example, if you leave out the variable capacitor, the collector voltage will be directly on the crystal. Too much RF voltage on a crystal can heat it and cause frequency drift. Crystal heating will cause the oscillation frequency to begin dropping the moment you turn on the oscillator. In extreme cases, such as exposing the crystal to big voltages in a vacuum tube oscillator, the voltage will literally crack it and ruin it. For these reasons, although this circuit is easy to explain, I rarely use it.

Series-cut and parallel-cut crystals

So called "**series cut**" crystals are designed for use with a capacitor in series with the crystal as shown above. This means that when the series-cut crystal has a specified size of capacitor in series, the crystal will oscillate on the exact frequency on the label. Otherwise, it might be a kilohertz off or more. Similarly, "**parallel-cut**" crystals are labeled to operate with a specific parallel capacitance as shown below.
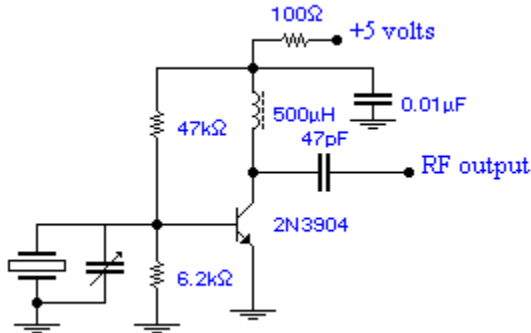
The oscillator shown above has the crystal connected to the base of the transistor. A variable capacitor is connected in parallel with the crystal. Again, when you first turn on the oscillator, the exact oscillator frequency may be hundreds or even thousands of Hertz off the nominal frequency. By adjusting the capacitor, the oscillation can be the exact frequency you need.

Butler is better.
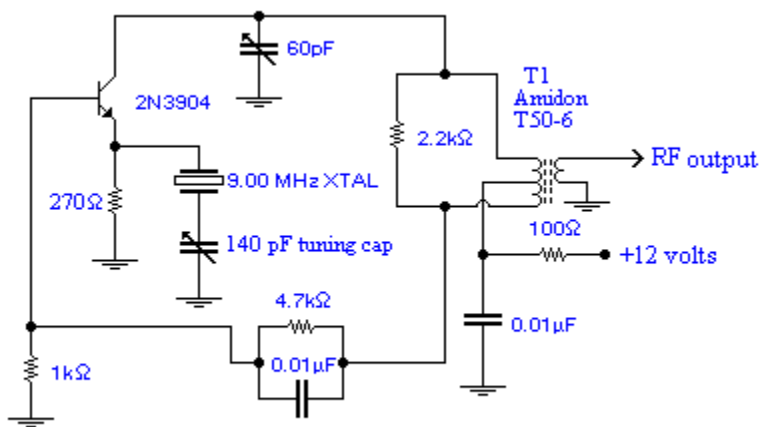
A Butler crystal oscillator.

I checked out every oscillator in my receiver and transmitter and discovered that some of them didn't have the warm-up drift when turned on. The stable ones were Butler oscillators as shown above. Notice that *the crystal and its capacitor are in parallel with the emitter resistor.* I don't really know why, but this circuit is stable the moment you turn it on. Maybe it's because the crystal isn't connected to a P/N base junction while it warms up. Anyway, Butlers typically drift no more than a hertz or two per minute. Two of my oscillators showed zero Hertz drift

during the first minute. One of them, my receiver BFO shown above, was on the same Hertz a half hour later!! Now <u>that's</u> what crystal control is supposed to be like. Also, it wasn't necessary to put these oscillators in heavy-walled, sealed metal boxes. Even built on an exposed board out in the breezes, they are impressively stable.

Depending on your application, the Butler also has the advantage that the series capacitor can pull the frequency lower than the base-connected oscillator shown above. I studied the oscillator circuits in my ARRL annual handbooks. In one of the examples of a modern commercial transceiver in the 1998 handbook there was a version of the Butler oscillator. These oscillators were touted as "low phase noise" but the low initial drift advantage wasn't mentioned.

Most modern equipment use anonymous integrated circuit (IC) oscillators, like "NE602." Among other circuit blocks, these ICs contain oscillators. To wire it, the crystal is just connected to pins on the little square package. Heaven only knows what's in there! I guess only we homebrewers care.

****

The 40 meter QRP circuit

The circuit shown below is the core of the QRP transmitter. The crystal oscillator on the left is a butler oscillator. The transistor RF amplifier on the right is similar to the example shown earlier, but is tuned with an L-C circuit for a specific band. Also, its output is a transformer winding that "matches" the high impedance output (roughly 600 ohms) to a 50 ohm dipole antenna.
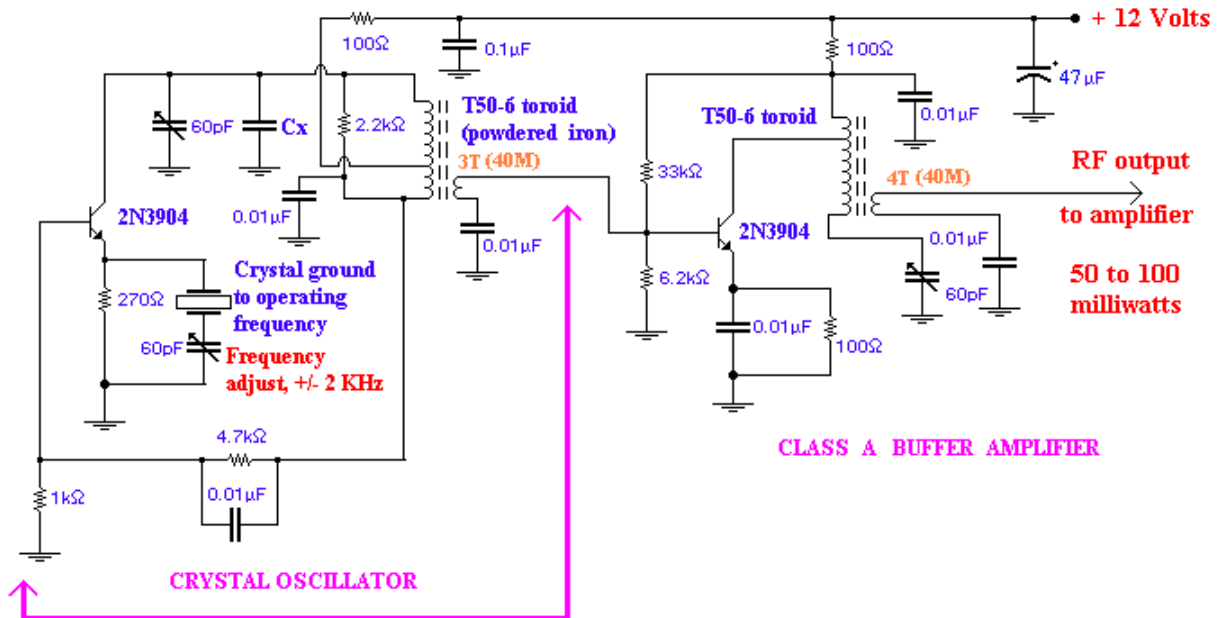
The Crystal Oscillator and Buffer

The diagram above shows oscillator and buffer stages for the QRP. This circuit puts out about 1/8 watt and could be used directly. Of course, you'd have to use a terrific antenna for anyone to hear you. How much power you get from this circuit depends on the crystal you use. I

used a big, new size HC33 that worked so well, my QRP (including the final amplifiers) put out 15 watts with 12 volts on the power supply instead of 5 watts. Oops! When I run it on 6 flashlight batteries (9 volts) it puts out about 7 watts.

The Butler oscillator circuit comes from a receiver project in the 1986 ARRL handbook and I've used it successfully several times. The tuned amplifier-buffer is part of a QRP design in the 1979 handbook. This basic amplifier circuit gives high voltage gain and can also serve as a tuned, active filter. Or, when it's coupled to a low impedance secondary, as it is here, it works as a power gain stage.

Building this QRP is really several small projects. Build the oscillator and get it working before you build the buffer amplifier. The important thing is that it works, not beauty or compact size. When building a project, use circuits you understand and parts you can get.

The diagram above doesn't include a detailed parts list. Parts lists are nice, but only if you can actually buy those exact parts. Manufacturers and distributors change every year and listing specific manufacturers will only frustrate you. The inductor cores are the only critical part. They should be powdered iron and designed for approximately the right frequency range. To work with a brand like Amidon (CWS Bytemark), Micrometals or Fairrite, you need the A_L inductance value so you may calculate the number of turns. This process is explained later in this chapter.

Inductor specifications for the QRP oscillator

Band	Toroid type	Primary turns	Secondary turns
80 Meters	T50- 15	41 turns, tapped 1/3	4 turns & 5 turns
40 Meters	T50- 15	30 turns, tapped 1/3	3 turns & 4 turns as shown.
Or,	T50- 2	51 turns, tapped 1/3	5 turns & 7 turns
30 Meters	T50- 6	36 turns, tapped 1/3	7 turns & 9 turns
20 Meters	T50- 6	28 turns, tapped 1/3	3 turns & 4 turns
17 Meters	T50- 6	22 turns, tapped 1/3	3 turns & 5 turns
15 Meters	T50- 6	22 turns, tapped 1/3	3 turns & 4 turns
12 Meters	T50- 6	16 turns, tapped 1/3	3 turns & 3 turns
10 Meters	T50- 6	16 turns, tapped 1/3	3 turns & 3 turns

Turns are NOT critical – if it tunes up well in the center of the variable capacitor range, that's the right number! (The toroids are CWS Bytemark, formerly Amidon)

Tapped toroid inductors

The crystal oscillator and following tuned amplifier stages of this QRP transmitter use tapped coils for the primary windings of the output transformers. The tap is 1/3 of the way from the power supply end of the coil. The DC current from the 12 volt source flows into the primary winding, then after 1/3 of coils, it leaves through the tap and enters the transistor which turns on every half cycles and shunts the current to ground. The opposite end of primary winding is
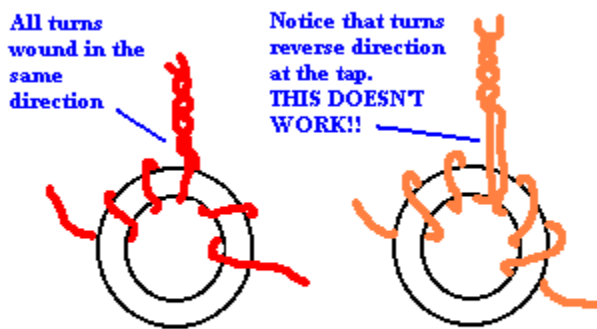
connected to the variable capacitor making a resonant LC circuit. At this end of the winding there is no exit for DC current. So 2/3 of the coil is only used for resonant "ringing" of RF currents. That is, most of the inductor is devoted to oscillating at a tuned frequency.

Pulses through transistor sustain oscillation in LC circuit.

+ 12 volts

RF oscillates between capacitor and ENTIRE COIL
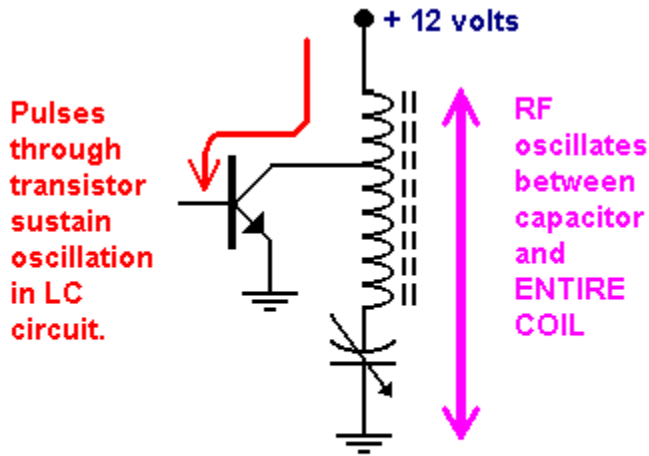
.**Tapped Inductor forms high Q tuned circuit**

Short pulses of DC current through the 1/3 end of the coil serve to prime the oscillation and keep it going. It is comparable to an adult pushing a child on a swing. The adult only pushes briefly at one end of the arc of the swing. The pendulum system of the swing does most of the oscillating, not the adult. This tapped coil makes the oscillations much larger than they would be if the winding weren't tapped. Also, the oscillation is much more confined to a specific frequency. In other words, the "Q" or quality of the resonant circuit is higher.

A mistake you might make

All turns wound in the same direction

Notice that turns reverse direction at the tap. THIS DOESN'T WORK!!

WINDING A TAPPED COIL

The drawing above shows the right way and wrong way to wind a tapped inductor. A tapped inductor is supposed to be a single coil that has an external wire connected to some spot along the coil. In other words, the coil must be wound from beginning to end in the same direction. In the drawing above, the correct tapped coil has three turns wound in one direction,

then three more turns wound in the same direction. If the coil winding direction reverses at the tap, the inductance of the first half of the coil will be cancelled out by the inductance of the second half. In other words, the device on the right has no inductance at all! The device on the right isn't even an inductor, it is just a "wire."

"Q" = equals quality

Inductors and capacitors have a quality factor called "Q." It is defined as the reactance of the device "X" divided by the resistance of the device, R. ***Reactance is the property of capacitors and inductors that resists the flow of AC current and acts like a resistor.*** Inductors are made from lengths of copper wire wound into a coil. Because of the simple resistance of the copper metal, the resistance of inductors can be significant, even without the reactance component. Therefore, inductors are sometimes "low Q." In contrast, the resistance of the wires in capacitors is rarely significant, so capacitors are almost always "high Q." In large capacitors that have dielectric plastic (or electrolytic) insulation between the plates, this insulation dissipates energy and appears as a "resistance" and lowers the Q.

Frequency multipliers

By the way, the tapped coil amplifier can also be used as a frequency multiplier. Suppose the input is a 7 MHz sinewave. Now suppose the LC circuit is tuned to 14 or 21 MHz. While the amplifier is running, your scope will reveal a 7 MHz sinewave on the transistor collector. Meanwhile, the whole coil and capacitor will be oscillating at the multiple of the frequency of the input determined by the LC circuit. To make use of the higher frequency, tap into it with a tiny capacitor, like 5 pF, between the coil and the trimmer capacitor. A bigger capacitor will load the ringing LC circuit too much and kill the oscillation. Alternatively, the higher frequency oscillation can be sampled with a one or two turn secondary wrapped around the coil.

If inductive and capacitive resistance is called "reactance," what's impedance?

Impedance is the sum or total result of all the reactances and resistances in a circuit. When we say a circuit has an impedance of "100 ohms," we are saying that every component in the circuit works together to behave like a 100 ohm resistor *at that particular frequency*. For example, as mentioned earlier, most ham antennas, receivers and transmitters are designed to work with 50 ohm impedance loads.

Impedance matching

If you wish to transfer power from one circuit to another and you don't have a perfect voltage source, then you can transmit the most power if you "match" the impedance of the load with the internal impedance of the voltage source.   In other words, real voltage sources always have internal resistance that limits how much energy you can suck out of the source. For example, a fresh battery has low internal impedance. In contrast, a dead battery (usually) has the same chemically generated voltage, but when the battery is exhausted, there is now a huge resistance in series with the voltage. This limits you to very little power that can be drawn out of the battery. However, even with a nearly dead battery, you can always maximize the power transfer by matching the load resistance to the internal resistance, no matter how high it may be.

## The buffer stage and power supply decoupling

A "buffer" amplifier follows the oscillator. The purpose of a buffer is to isolate the

oscillator from the final amplifier(s) as well as amplify the oscillator signal. Although it makes no intuitive sense, changes on the output load of an amplifier can couple back to the input of the amplifier and affect the oscillator. This feedback makes subtle changes in the frequency of the oscillator and contributes to "***chirp***." Chirp is a change in tone of the Morse code that makes it sound like a bird. One way to decrease chirp is to add a buffer amplifier between the oscillator and final amplifiers.

Ideally, all "communication" between one amplifier and the next is through the intended path between the output transformer and the base of the next stage. Unfortunately, other ways amplifiers "talk" to each other can be through the power supply or even through skinny ground traces. You can minimize the ground communication by using large ground traces or soldering ground points to an unbroken copper sheet "ground plane" as discussed earlier under PC board construction.

Power supply communication is more difficult. Suppose a big sinewave signal is being generated in a final amplifier. As the current rises through the large output transistor, this big current loads down the power supply voltage and can cause it to drop. The amplifier driving the final then loses supply voltage, just when it needs it to supply the rising current. The result of this interaction is that the sinewave can jitter and become unstable. On an oscilloscope the sinewave loses its focus and becomes blurry. A frequency counter will usually read below the crystal frequency and will be unstable.   This instability can be greatly improved by decoupling each stage as shown below:

RC Power Supply Decoupling
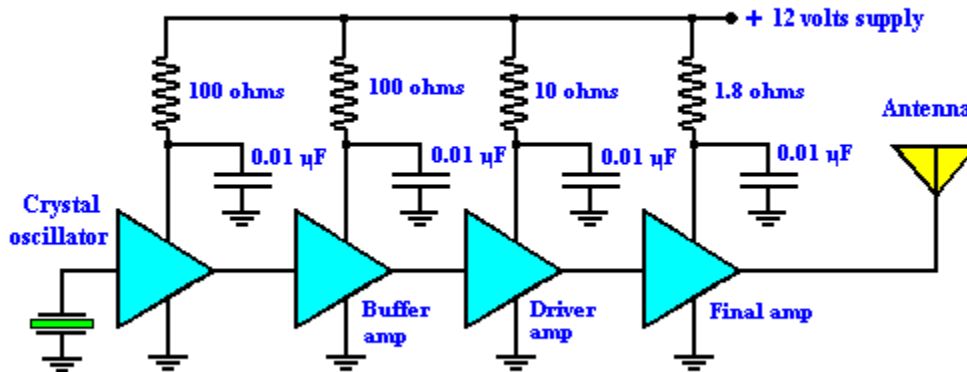
The resistor / capacitor feeding each stage slows the changes in the power supply voltage, RF cycle by cycle. This prevents these changes from feeding back to earlier stages. ***The less current each stage draws, the more resistance needed.*** If you leave out these RC circuits, the QRP will still work fine IF you have a stable 12 volt supply. However, if you use a weak supply, such as old flashlight batteries, it will be very difficult to maintain a clean sinewave output.

The final amplifier stages for the QRP

I was surprised by the big signal I got out of the oscillator stage described above using the large HC-33 size crystals. If you use small HC-49 crystals, the power output will probably not be so great and the first stage of the two-stage amplifier described below will be needed. In my

case, when I fired up the whole "QRP" with 12 volts DC input, it put out 15 watts! Oops. QRP is defined as less than 5 watts. Since then, I have powered the circuit on 9 volts from 6 alkaline D cells and I got 7 watts output. You shouldn't have any trouble getting enough power from this little transmitter.
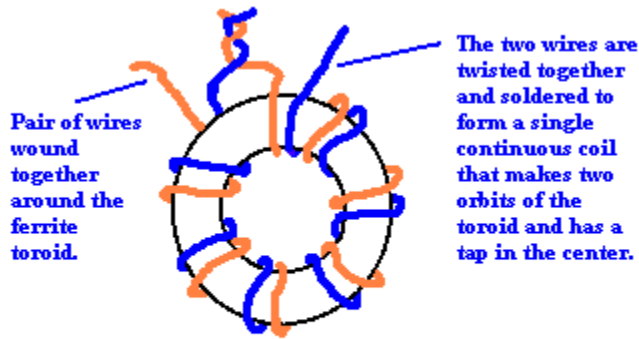
QRP 5 watt amplifier
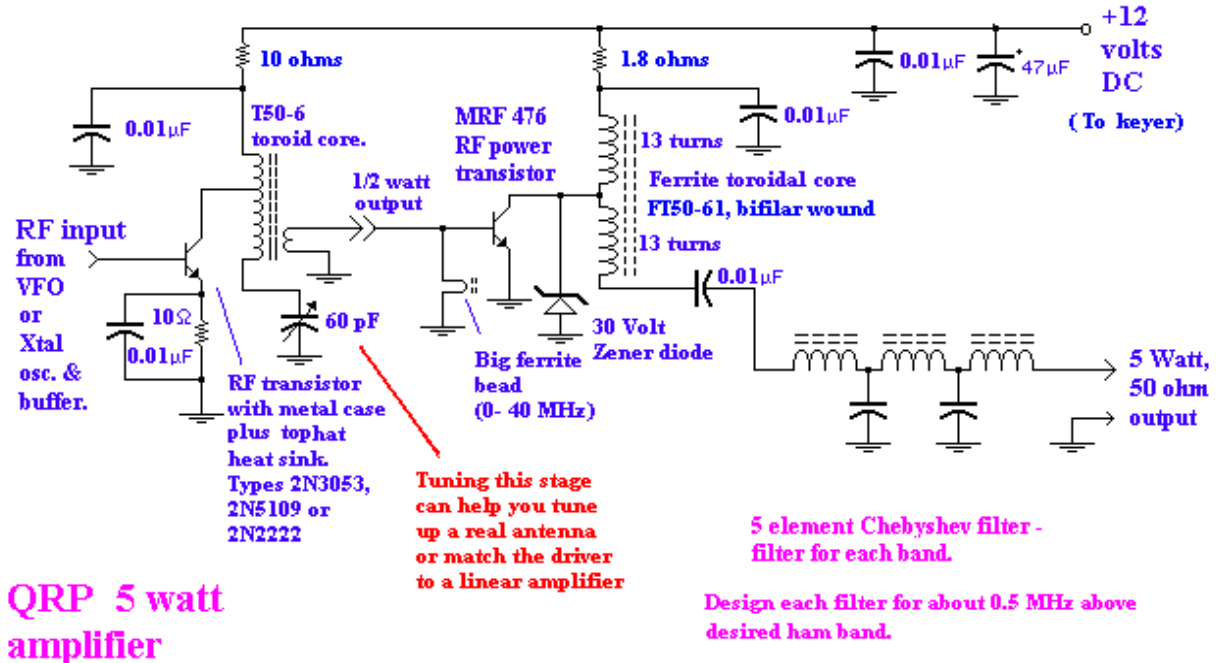
A QRP Two Stage Power Amplifier

The last two of the four transistor stages in the QRP are shown above. The first stage is tuned and resembles the buffer stage following the oscillator. Depending on the number of turns on the coils in the tuned amplifier stages, these stages can tune two or more bands. For example, with 27 turns on the primary, you can (barely) cover 20 to 10 meters.   Make the tap about 1/3 of the total number of turns, or about 9 turns in this case. The secondary would be about 6 turns. The input of a transistor amplifier is usually a low impedance. Therefore the transformer lowers the voltage and raises the current to "match" the impedance.

The buffer that follows the oscillator circuit is "*Class A*" because it's biased "on" with the 33K resistor. The emitter R-C circuit keeps the class A amplifier stable so it won't run away when the temperature rises. Class A is best when the signal levels are small. In the two amplifiers above, the first (tuned) amplifier runs *Class C.*   This means that the input voltage swing must be far larger than the base offset voltage, 0.6 volts. This Class C runs at relatively high power levels, so you'll need a bigger transistor, 2N3053, 2N2222 or equivalent. This moderate power transistor has a case like a tiny tin can to help conduct away the heat. Moreover, a "top hat" heatsink should be clipped onto this transistor to help radiate the heat. Look in your catalogs under heatsinks and you should find a large assortment.

Bifilar wound transformers

The two wires are twisted together and soldered to form a single continuous coil that makes two orbits of the toroid and has a tap in the center.

Pair of wires wound together around the ferrite toroid.

BIFILAR WOUND TRANSFORMER

The transformer for the broadband final amplifier stage is a "bifilar wound" transformer. This broadband transformer is untuned and will work on ANY HF hamband. The toroid core is an Amidon T50-61 ferrite instead of powdered iron. The ferrite provides much higher inductance than you would obtain if the same coil were wound on powdered iron cores, such as the T50-6. That is, the A_L factor is much larger for a ferrite core. The high inductance means that the input signal to the transformer will be passed along to the output before the inductor has a chance to charge. There is nothing resonant about this transformer.

Although the transformer is wound with two parallel wires, the two wires are soldered together to make one winding that orbits the toroid twice. Bifilar wound transformers are a kind of tapped coil. As a result, the impedance (voltage) can be stepped up or down by connecting the output to either all of the coil for high voltage, or just half of the coil to step down.

Before you wind one of these coils, examine the drawing extremely carefully. It works only when wound exactly as drawn. There is a really easy way to screw up! ***If you connect the one of the wires to itself, that wire becomes a shorted turn that will dissipate most of your RF energy.*** Before you solder your biflar into a circuit, use an ohmmeter to confirm that all three terminals have zero ohms betweens them. If you find that the "centertap" is an open circuit with respect to the other two wires, you have built it wrong. I have made this error twice and wasted considerable time finding it.

Tuned amplifiers versus broadband amplifiers

The QRP desribed above uses two amplifier stages that are tuned by trimmer capacitors and a broadband final amplifier that needs no tuning. Tuned amplifiers almost always work – that's a big advantage! A disadvantage of tuned amplifiers is that the tuning can be critical and may not cover the entire band. Tuning all the stages in a transmitter turns out to be a bad idea. As my car battery power supply discharged, sometimes my signal would "crash" halfway through a CQ. On the scope I could see a sudden loss of amplitude on the output and distortion would appear in the sinewave. My contact would say, "You're signal is breaking up."

Another advantage of tuned stages is that, when you tune up one stage, by subtle shift in the sinewave phase, you're also adjusting impedance matches in the following stages. It works much like an antenna coupler matching an antenna. I confess I don't fully understand this, but

the phenomenon is real and useful.

In contrast, broadband amplifiers just pass along whatever signal they receive. So, if you build all your stages as broadband amplifiers wired in series, they won't work unless you've done a wonderful job of matching impedances at every stage. When a broadband amplifier is mismatched, it goes into "noise mode." That is, you put a sinewave into the input and the amplifier puts out a blast of noise that contains only a ghost of the sinewave you hoped to amplify. If you don't have at least one tuned stage in your QRP, you'll have nothing to adjust when the final goes into noise mode.

The output stage in the QRP is a broadband amplifier that uses a five-element Chebyshev filter to suppress high frequency harmonics in the output. Chebyshevs are described in detail below. The filter component values can be found in tables and formulas in an ARRL Handbook, e.g., 1986 or later. This broadband amplifier is a universal circuit you may add to your bag of tricks. For example, in my ten meter QRP board I used two broadband stages in series to increase power from 3 to 9 watts. The first broadband stage used a 2N3053 and it didn't need its own Chebyshev filter.

Expensive RF transistors

The final amplifier uses a Motorola MRF476 transistor. They are pricey, $10. There must be hundreds of cheaper transistors that can put out 5 or 10 watts at HF frequencies. Unfortunately, the others I tried needed 24 to 80 volts collector supply voltage to deliver the same power. The virtue of Motorola "MRF's" for HF seems to be that they deliver big power with a 12 volt supply. To me it was well worth the cost.

Ferrite bead RF chokes
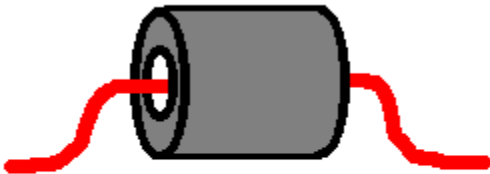
FERRITE BEAD RF CHOKE

Notice the bead RF choke on the MRF476 base. It's just a short, straight wire through a big ferrite iron bead. This eliminates low frequencies from the output and turns a "roller coaster," chaotic output waveform into a clean sinewave. This simple component looks as though it would act as a short circuit to ground. But even if you run the amplifier on 80 meters, the bead is vital and doesn't reduce output power. If this sounds illogical to you, unsolder the choke and look at your waveform.

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CONQUERING INDUCTORS

Inductors are often the problem

As you gather parts for the above QRP transmitter or any typical ham project, you may discover that the hardest parts to locate are the inductors. "Where do I buy a Miller # 233 anyway?" Or, maybe the parts list says, "6 turns on a Stackpole 4-12 toroid core." Who sells Stackpole cores? Where do I get a catalog? Then you think, "I know what to do! I've got an iron core-thing that LOOKS just like the picture. I'll use that!" With this optimism you are well on your way to building a useless piece of junk destined for your attic.

In contrast to inductors, capacitors are rarely a problem. If it reads 330 picofards on the capacitor, that's probably what it is. Electrolytic capacitors can be a little tricky. You have to get the polarity right and there are few rules about what kind to use when. But by and large, capacitors are easy. A capacitor meter usually tells you everything you need to know about the unlabeled capacitor in your junk box.

All of us who have wound inductors have wished our multimeters had "inductance scales." Sorry. Handheld inductance meters barely exist. And if you have one, it probably won't tell you much about core losses, leakage inductance, saturation and winding resistance.

A little math is as good as an inductance meter

Normal humans hate mathematics. However, simple calculations and toroid cores with known characteristics are a tool that let you wind the exact inductor you need. Your LC circuits will resonate in the right band, your filters will attenuate and pass the right frequencies and your equipment will work! The ability to wind the right inductance is as vital as a soldering iron, a good scope and a frequency counter.

LC circuits. What size inductor do I need?

Radio technology is based on LC circuits. Sure, some circuits use piezo devices like crystals and "SAWs" that only *act* like LC circuits. But they are LC circuits none the less. The "C" part is easy enough. Just pick a capacitor value. But how big does the inductor need to be?

$$\omega^2 = 1/LC \qquad \text{where } \omega = 2\pi \text{ (frequency in Hertz)}$$

$$L = \text{inductance in Henries.}$$

$$C = \text{capacitance in Farads.}$$

40 pF **3.2 μH**
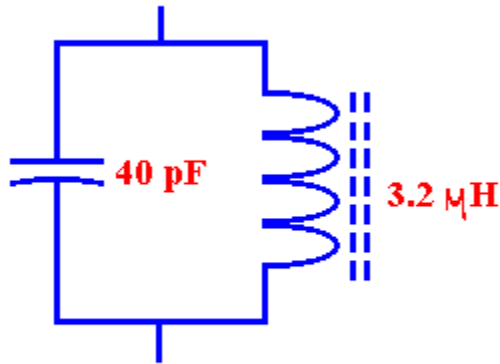
20 Meter   RESONANT CIRCUIT

Suppose you're building a transistor amplifier stage that has an LC resonant tank circuit. Your trimmer capacitor has a range of 5 to 60 picofarads. You need an inductor that resonates with that capacitor. Let's say the band is 20 meters, 14.1 MHz. We'll design the inductor to resonate with say, 40 pF. That way, you can tweak the frequency if necessary. Using the above formula:

$$[2 \text{ x } 3.1416 \text{ x } 14.1 \text{ x } 10^6 \text{ MHz}]^2 \ = \ 1/ \ (40 \text{ x } 10^{-12} \text{ Farads })(\text{ L})$$

Solving for L, $\qquad\qquad$ L $=$ 3.18 x 10^{-6} Henry or 3.18 microhenries.

Now that we know how big the inductor must be, we need to wind a coil on a toroid core.

Using CWS (Amidon) powdered iron cores

There are many quality brands of ferrite and powdered iron core toroids. I like CWS Bytemark cores (Formerly Amidon) cores simply because I know where to buy them, www.bytemark.com or www.coilws.com. The important factor is that the cores must have a known inductance factor, A_L, so that you can calculate how many turns you need for a given inductance.

Ferrite vs. powdered iron

Ferrite cores have high iron content and produce high inductance for a given number of turns. In ham projects, ferrite is usually used for inductors that are too large to charge significantly for several cycles of the design frequency. In other words, ferrites are used for RF chokes and waveform transformers. For example, the output transformers of WIDEBAND linear amplifiers are usually ferrites. The final amplifier of the QRP circuit above uses a T50-61 ferrite toroid. Ferrites are rarely if ever used for resonant LC circuits.

In contrast, powdered iron cores contain far less iron and more ceramic. They are used for high-Q resonant circuits and filters.   Notice the powdered iron cores are color coded for their permeability. In contrast, all the ferrites are just plain black, semi-shiny toroid cores.

First: Select the type of toroid core appropriate for the frequency and power level. There are several grades of powdered iron and ferrite cores that are designed for different frequency ranges. For resonant circuits or filters on all the HF hambands, I usually *use type 6 powdered iron (color code yellow and black)*. For the lowest HF hambands 80 and 160, I sometimes use type 2 (red/black) or type 15 (red/white). These give me more inductance for the same number of turns and allow me to use heavier gauge (lower resistance) wire. Type 17 powdered iron (yellow-blue) is useful for 30 MHz and above. Type 26 (yellow-white) cores are most useful for frequencies well below the ham bands. They are often found in switching power supplies.

The *power level* is proportional to the size of the toroid core. I've had bad luck with little bitty size T-37 cores. They produce low gain and are hard to wind. Don't use them unless you are pressed for space. On the other hand, type T-50 works fine from receiver circuits up to a few watts in a QRP. Type T-68 is good for 10 watts or more. Type T106 and T200 handle 200 watts or more and are used for output filters in high power linear amplifiers.

Second: Calculate the number of turns needed for a given inductance. The wire size is simply the largest gauge that will fit conveniently in the toroid. Don't go nuts with thick wires.   On the other hand, for low frequency, high inductance usually means many turns of wire. The coil will work best when you use the highest diameter wire that will fit in the core without overlapping the turns. For each core type, there is a constant, "A_L," that is proportional to the square of the number of turns.

The number of turns = 100 (Inductance in microhenries)/ A_L) $^{1/2}$

For example, using a T-50 type 6 powdered iron core, design a 3.18 microhenry inductor:

The T-50-6 core has an inductance constant, A_L, equal to 40. Note that when calculating, the "micro' part isn't in the calculation. 3.18 microhenries is just "3.18."

Number of turns $= 100 \,(3.18 \,/\, 40\,)^{1/2} =\ $ 28 turns.

Note: a bracketed number to the power ½ is another way of writing "the square root of."

You should be able to get 28 turns of # 30 enameled magnet wire onto the core. If not, use a finer wire, say # 34. If the wire doesn't cover up most of the core, use a fatter wire, say # 26.

****

Calibrating the trimmer capacitors

I used small, cylindrical variable "trimmer" capacitors to tune the first three stages of my QRP module. They are about the size of a grape and are adjusted with a small screwdriver. A problem with these devices is that you can't tell what capacitance they are set to just by looking at them. Since the adjustment screw goes around and around without stops, there is no way to know when they are at maximum or minimum.

Suppose you tune up an amplifier stage and you find that it produces the maximum signal at a certain setting. If you knew that this set point were the maximum capacitance point, you could guess that probably you need more capacitance to get the best performance. You could fix this by soldering a small capacitor, say 30 pF in parallel with the trimmer. Alternatively, you could add a few more turns to the inductor. On the other hand, if you knew that the best performance set point happened coincide with the minimum capacitance point, then you could conclude that the primary winding of the transformer probably has too many turns and needs to be reduced.

My solution is to measure the capacitance with a capacitance meter, then mark the minimum and maximum set points. With my ceramic trimmers, the maximum is 60 pF and minimum is about 7 pF. I use a fine felt-tip marker pen to indicate the maximum capacitance point. Minimum capacitance is 180 degrees from maximum. Ideally, when I have the amplifier tuned up for maximum signal, I will find that the screw is adjusted to roughly half of the capacitor's range. This means I have a good working amplifier stage and can't improve the LC circuit further.

****

Chebyshev filters

0.27 μH   **0.67 μH**   **0.27 μH**

230 pF   **230 pF**
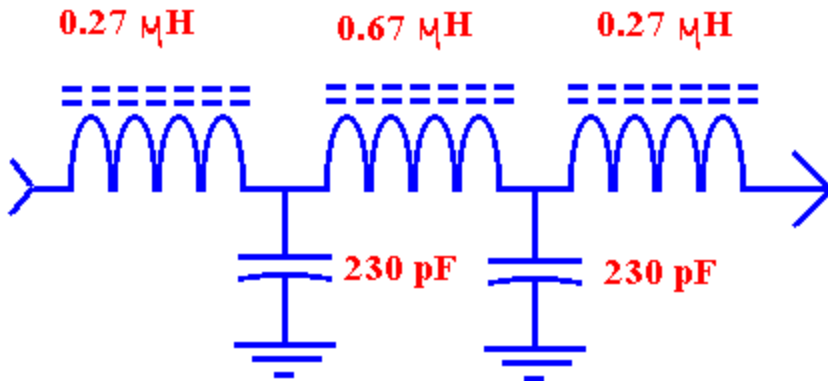
20 Meter CHEBYSHEV FILTER

LC circuits are vital to *tuned* amplifier stages. But many modern amplifiers are *untuned* or *linear* and just need a filter to prevent harmonics. The output stage of nearly every transistorized linear transmitter final has a 5-element Chebyshev filter to prevent harmonics above the operating ham band. Your ARRL handbook has is long, long, detailed explanations about designing different kinds of Chebyshevs. Most guys look at those pages and think, "Like heck I'm going to figure out all that!" On the other hand, you usually just need a 5 element low pass and here is how you do it:

First: What operating impedance do you need? Let's assume 50 ohms. That's the most common.

Second: What frequency is it for?   Let's assume we want to attenuate everything above the 20 meter band. That is, 14.35 MHz.

Third: Calculate the "normalized" capacitance and inductance for the filter:

Capacitance, Cs =   1 / 2 π (50 ohms) (14.35 MHz) =   222 pF

Inductance, Ls =   50 ohms / 2 π (14.35 MHz) =   0.55 microhenries (μH)

Fourth: Multiply the normalized C and L by the factors for each of the five elements.

The values of the five elements are:

L1 = 0.4869 Ls = (.4869) (0.55 μH) = 0.27 μH

C2 = 1.05 Cs   =   1.05 (222 pF) =   230 pF

L3 = 1.226 Ls = 1.226 (0.55 μH) = 0.67 μH

C4 = 1.05 Cs = 1.05 (222 pF) =   230 pF

L5 = 0.4869 Ls = (.4869) (0.55 μH) = 0.27 μH

For the capacitors, 220 pF will work just fine.

****

Heat sink for the output transistor

Use a big metal heat sink on your MRF476 and keep it cool. I haven't damaged any, even with as much as 15 watts RF output. However, supposedly this transistor is only rated at 3 watts dissipation, so maybe we should respect this specification. The metal tab on the MRF476 is the transistor collector and must be kept insulated from the grounded heat sink. Mica insulators with a touch of silicon grease are used for this purpose.

Zener over-voltage protection for the output transistor

The 30 volt Zener helps protect your MRF476 from open circuit operation. The Zener doesn't seem to be vital, but it doesn't hurt performance either.

Connectors for your QRP module

I use "RCA" audio phono plugs and coax for RF connections between HF modules. Yes, I should be using BNC or other connectors designed specifically for RF. However, phono plugs are cheap, easier to wire and there seems to be no difference in performance, so long as the power level (current level) is under roughly 10 watts and frequency is below 30 MHz. After all, phone plugs only have twice as much capacitance (4 pF more) than an equal length of coax. 30 MHz is probably as high as one should go with phono jacks, especially at high power levels. Small card edge connectors are another way to snap PC board modules together. For example, I use PC board card edge connectors for plug-in Chebyshev filters so I can change bands easily. You don't need gold-plated card edge fingers. However, you should use wide traces and connect several pins in parallel wherever you're worried about keeping inductance or contact resistance low.

****

Keying CW Transmitters

Some QRP designs put the telegraph key in series with the emitter of a transistor amplifier stage just before the final amplifier. To transmit, the key is pressed connecting the emitter to ground. When the operator wants to "spot" his signal to find out where the transmitter is with respect to a station, he or she turns on the power supply, but doesn't key the transmitter. Without drive to the final, the oscillator and first buffer stage deliver a loud (but not overwhelming) signal to the receiver.

Supposedly, an amplifier with no emitter current or no base drive won't put out a signal. That sounds right and in the old days it worked OK with tubes. Unfortunately, in my basement the transistors don't care and deliver RF anyway. The capacitor across the key and even the capacitance in the coax going to the key provide enough AC current to produce drive through emitter to deliver drive to the output stage. All I ever achieved with emitter keying was to lower the signal amplitude between the dots and dashes. If you just key the oscillator and leave the other stages active, that works fine as long as the oscillator is driving them. Unfortunately, when you let up the key, the following stages will often self-oscillate at whatever frequency they please.
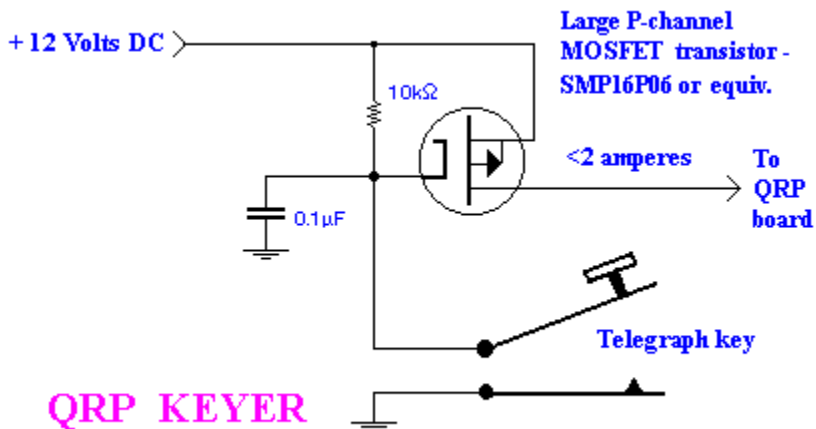
A P-Channel MOSFET Keys the DC Power Supply

      I like to key the transmitter by keying the entire power supply on and off. This circuit is not elegant, but it works. For micropower QRP's, like Altoids transmitters, I notice they just put the key in series with the supply. Altoids transmitters and "sardine senders" are homebuilt CW transmitters built in these little tin cans. That works, but for keying 10 or more watts of DC power, it's better for the key contacts to switch the current with a solid-state (transistor) switch. I use a P-Channel MOSFET as shown above. The resistor and capacitor in the gate circuit soften (extend) the turn-on and turn-off times to prevent key click. This circuit must be OK because I haven't heard any key click complaints ever since I gave up on vacuum tube transmitters.

****

MOSFET field effect transistors

      What is that weird transistor called "MOSFET," you ask? Metal Oxide Silicon Field Effect Transistors work differently than the bipolar transistor you met in chapter 4.   Fortunately, field effect transistors are easy to understand. A MOSFET transistor consists of a piece of either P or N-type semiconductor mated to a capacitor. The semiconductor strip or layer is necked down in middle so that it has a very narrow region in the center. The narrow region also serves as one plate of the capacitor. The other half of the capacitor is the control gate. The gate is insulated from the transistor by a thin film of glass. The control gate is half of a capacitor, while the main semiconductor current channel acts like the 2nd plate of a capacitor. The control gate is analogous to the base of a bipolar transistor. When voltage is applied to the capacitor, (that is, applied between the control gate and the piece of semiconductor), charge gathers on the conductive surfaces around the gate insulator. When charge gathers in the semiconductor, it changes the ion density in the semiconductor and changes its conductivity.

gate

Schematic symbol

source   drain

Notice that the arrowhead points AWAY from gate in a P channel, TOWARD the gate in an N-channel.

Positive voltage on gate.

++++++++++

Glass insulator separates metal gate from semiconductor.

Source   Drain

P- Type semiconductor

holes

Holes filled with electrons attracted by the positive charge on the gate.

P - Channel MOSFET field effect transistor

Filling in the holes, turns the transistor OFF.

N-channel MOSFET

Just like bipolar transistors, a complementary version that works with the opposite polarities can be made by replacing the P-type semiconductor with N-type.

gate

Schematic symbol

source   drain

Notice that the arrowhead points AWAY from gate in a P channel, TOWARD the gate in an N-channel.

Negative voltage on gate.

- - - - - - -

Glass insulator separates metal gate from semiconductor.

Source   Drain

N - Type semiconductor

Free electrons

Free electrons repelled by by the negative charge on the gate.

N - Channel MOSFET field effect transistor

Stripping out electrons turns the transistor OFF.

Depletion- type and Enhancement type MOSFETs

A simple MOSFET, like the one diagrammed above, is normally turned about half on. That is, when the gate voltage is zero, the transistor has a significant resistance, perhaps 300 ohms. This type of MOSFET is called a ***depletion-type.*** When one polarity of gate voltage is applied, the transistor turns full on. When the other polarity is applied, all the holes are filled in or all the free electrons are drawn out and the transistor becomes an insulator. That is, if the semiconductor is N-type, the extra electrons are pulled out of the crystal and the crystal becomes an insulator. Depletion MOSFETs are usually used in low power receiver applications.

Enhancement type MOSFETs

Enhancement type MOSFETs have been cleverly designed to be more convenient for typical power applications. When the gate voltage is zero with respect to the lead attached to the transistor semiconductor called "the source," the enhancement MOSFET is turned off. The SMP16P06 or the IRF9541 P-channel MOSFETs used in this book are enhancement types. This means that when the telegraph key is open, the QRP is fully off. Then when the key is depressed, the MOSFET turns full on and turns on the QRP. Power MOSFETs like these are also equipped with an internal diode to protect the transistor from being used with the wrong polarity. When the MOSFET is correctly biased, the protection diode looks like an open circuit and doesn't interfere. But if the polarity is reversed, the diode turns on and shorts out the piece of semiconductor and protects it from being fried.

Compared to bipolar transistors, MOSFETs have two major advantages:

1. There are no PN junctions in a MOSFET. This means that there is no PN junction to breakdown and no PN junction to cause temperature sensitivity. Because big MOSFET transistors are hard to break, they are often the best choice in high power applications.

2. MOSFETs are a voltage-controlled device. Once a voltage is established on the gate, no current is required to maintain the ON state of the transistor. MOSFETs are often ideal for power supply applications and switching big DC currents. And, they could be used for high powered audio amplifiers. Power MOSFETs, like the P-channel used to key the QRP transmitter, aren't so great for use as a high frequency power amplifier. The capacitor input means that every time the input voltage changes, the capacitor input must be charged or discharged. For very high frequencies, the driving circuit needs to stuff current into the gate and pull it out tens of millions per second. This makes driving a power MOSFET like the one above impractical for high power radio frequency transmitters.

For example, from time to time QST ham magazine has had transmitter plans using high power MOSFETs for 20 to 50 watt transmitters. The catch was, they didn't recommend them for hambands higher than about 40 meters. Above that frequency, the power needed to develop the drive current had to be so high, that the driver power began to be similar to the output power. In recent years however, special RF MOSFETs have been developed that can be used for transmitters running at hundreds of megahertz. However they are quite pricey and I haven't seen hamband transmitter designs using them.

Power enhancement MOSFETs made by different companies have various designs that make them more rugged, handle larger currents, work at high frequencies and dissipate more waste heat. Names like HEXFETs and V-MOS are examples of sophisticated MOSFET designs.

****

SPOT SWITCHES

Suppose you hear another ham calling CQ and you'd like to answer him. How can you tell whether your crystal and variable capacitor can reach his frequency? The answer is a "spot switch." The idea is to turn on the oscillator so you can hear your own transmitter in the receiver, but your signal will not be broadcast until you are ready to call the station. Using the spot switch, you turn on the oscillator and maybe the buffer, but not the amplifiers. This is done by separating the +12 volt power into the QRP into two wires, one for the oscillator and a second for the amplifiers.

In the circuit below, diodes are used power the oscillator from either wire under the appropriate circumstances. Strictly speaking, the diode in series with the spot switch isn't really needed, because the open spot switch will turn the oscillator off while the transmitter is in stand by. However, the voltage supplied to the oscillator will be more equal if diodes are in both supply lines.
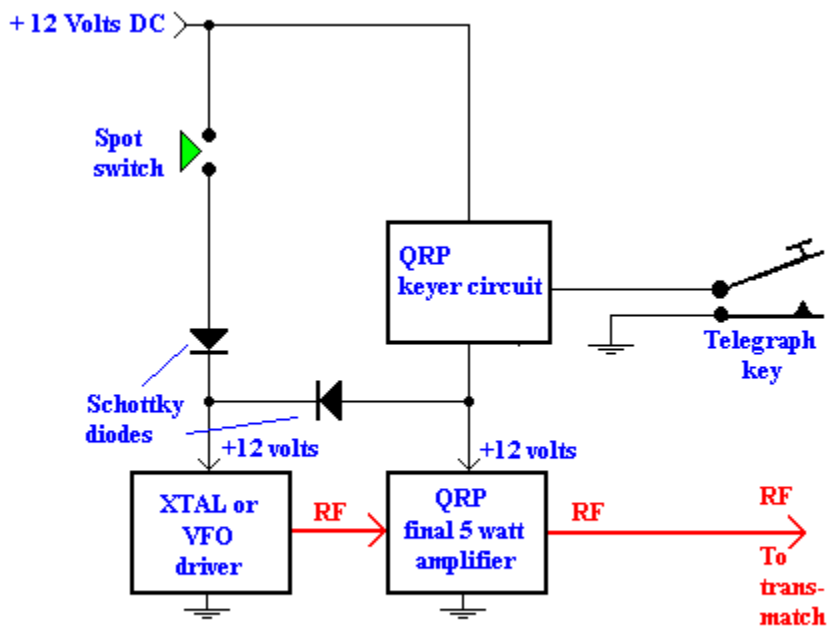
QRP KEYER WITH "SPOT" BUTTON

The "spot" momentary contact button turns on the oscillator and buffer stages with power through a Schottky power diode capable of handling 100 milliamperes or more. Then, when the telegraph key activates the final amplifier, the oscillator gets its power from a second Schottky diode connected to the P-channel MOSFET keyer. I have spent hours trying to accomplish these functions without big MOSFETs and diodes, but I have yet to succeed. Have a go at it. Maybe you can be more clever than I was.

Accessories and checking out your QRP

Building power supplies for your QRP module is explained in chapter 8. Other important accessories, such as a telegraph code key and an antenna coupler are discussed in Chapter 9. Checking out your QRP is also discussed in chapter 9.

CRYSTAL SETS TO SIDEBAND
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Chapter 7

A CODE PRACTICE RECEIVER

This chapter describes how to build a simple *"direct conversion"* ham receiver for the 40 meter CW band. This receiver can be used to listen to CW ham stations for code practice. It will also receive ham single sideband (SSB, voice) stations and foreign shortwave broadcasts. When combined with the CW QRP transmitter described in chapter 6, you could even use it to talk to other hams.

The main virtue of this receiver is its simplicity. The basic design has only 5 transistors and is an excellent first project for a new ham. It can be powered with a 9-volt battery. However a 12 volt battery made from small AA flashlight batteries will last much longer and provide more volume in your headphones.

This receiver has good sensitivity and good stability. Unfortunately, by modern standards the <u>selectivity</u> of the basic receiver is poor for receiving CW. On many evenings the 40 meter CW band will be too crowded to listen to a single station easily. Adding the 700 Hz audio filter described later in the chapter will improve it greatly. Also, if you have a powerful AM broadcast station in your neighborhood, you may need to build a high pass filter to get rid of that interference. The broadcast filter is the little box shown to the right of the receiver.

When you're ready for a first rate receiver with selectivity as well as sensitivity, you may want to buy a commercial receiver or begin work on a superhetrodyne receiver as described in chapter 13. It is possible to get the same performance out of a direct conversion receiver, but that will require super-selective audio filters, image-canceling and other R&D that I've never attempted. If you're interested, go for it!

Direct conversion receivers

A direct conversion receiver (DCR) has 4 basic circuit blocks. They are a band-pass filter, a variable frequency oscillator (a VFO), a mixer or "product detector" and an audio amplifier.
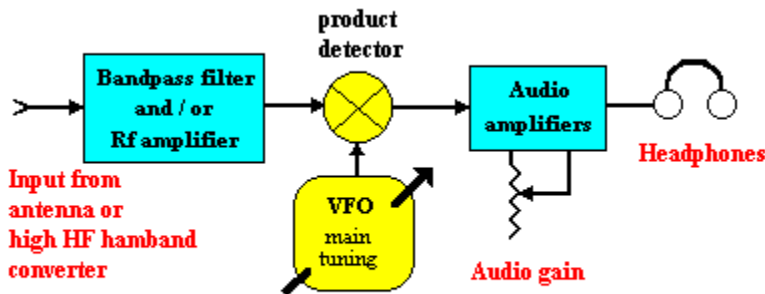
Direct Conversion Receiver

The frequency tuning of a DCR is accomplished with an adjustable frequency oscillator called a VFO (variable frequency oscillator). This sinewave signal is mixed with the incoming radio signals in a special amplifier called a ***product detector***. The signals heard in the headphones are those that <u>differ</u> from the VFO frequency by a difference within the audio range, say 20 Hz to 2.5 KHz. For example, suppose you are listening to a Morse code station on 7.100,000 MHz. You might tune the VFO to 7.100,700 MHz. That is, you tune 700 Hz above the actual transmitting frequency. The frequency difference will be heard as an audible, musical, 700 Hz Morse code tone.

The difference frequency is filtered, amplified and passed on the earphones. Pretty simple radio! Considering how few parts it has, it's amazing how sensitive it is. I measured the performance of mine and found it could easily detect a 0.5 microvolt signal on 40 meters.

The input filter

The product detector has a weak diode-like characteristic. That means it is prone to act like a crystal set and detect strong signals present on the antenna that are not near the VFO frequency. Consequently, the signals coming in from the antenna must first be filtered to restrict signals to approximately 7 MHz. As you may recall from your experience with crystal sets, the tuning selectivity of a simple input LC filter is extremely limited. However, a simple filter can get rid of background AM broadcast signals or strong foreign AM shortwave broadcast stations operating near 7 MHz.

40 Meter Hamband Passband Filter
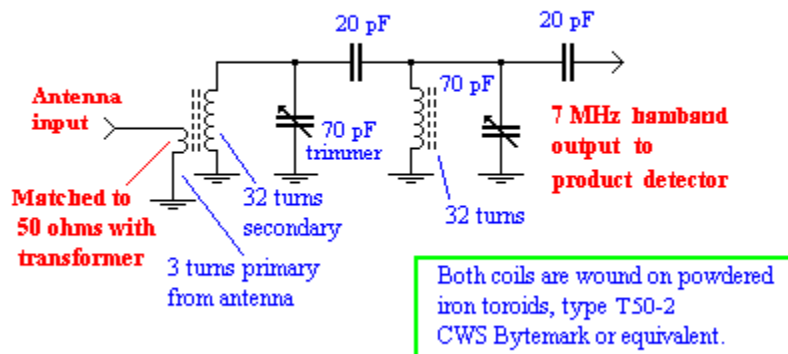
The input filter consists of two tuned LC circuits. The input from the antenna is wired as an RF transformer that matches the high impedance filter and high impedance product detector with a low impedance antenna. In other words, the antenna is assumed to be approximately 50 ohms, like a typical ham dipole with a coax lead wire. The transformer steps up the RF voltage about ten times using the 1:10 turns ratio. If the receiver will be used with a high impedance long wire or whip antenna, the input lead should simply connect to the top of the trimmer capacitor through a small blocking capacitor.

While listening to live CW signals on 40 meters, tune the trimmer capacitors until the CW signals are as loud as possible and any background voice stations disappear. If this filter is insufficient to get rid of local AM broadcast signals, a 1.8 MHz high pass filter is described later in this chapter.

This input filter section could also include an RF amplifier stage. However, this would probably not be useful on 40 meters because atmospheric noise is relatively high below about 20 meters. On the other hand, if you would rather build this receiver for 20 meters or above, an RF amplifier will be a great help to sensitivity. RF input amplifiers are discussed in chapter 13.

The RF tuning oscillator (VFO)

The circuit below shows the VFO tuning oscillator. As shown, the inductor and capacitor values will tune the 40 meter ham band and the shortwave broadcast bands above and below 7 MHz. The circuit is a tunable oscillator comparable in function to the crystal-controlled oscillator used in the QRP transmitter in chapter 6. Instead of a quartz crystal, the frequency control is a tunable LC circuit that has a range of hundreds of KHz. This VFO is too crude to control the frequency of a transmitter. It would drift too much and the guys you are talking to would complain about your unstable signal. However, because you will be listening to a KHz of audio at once, a drift of a 100 Hz per minute will be scarcely noticeable. Building a first rate VFO for a transmitter is described in chapter 10.
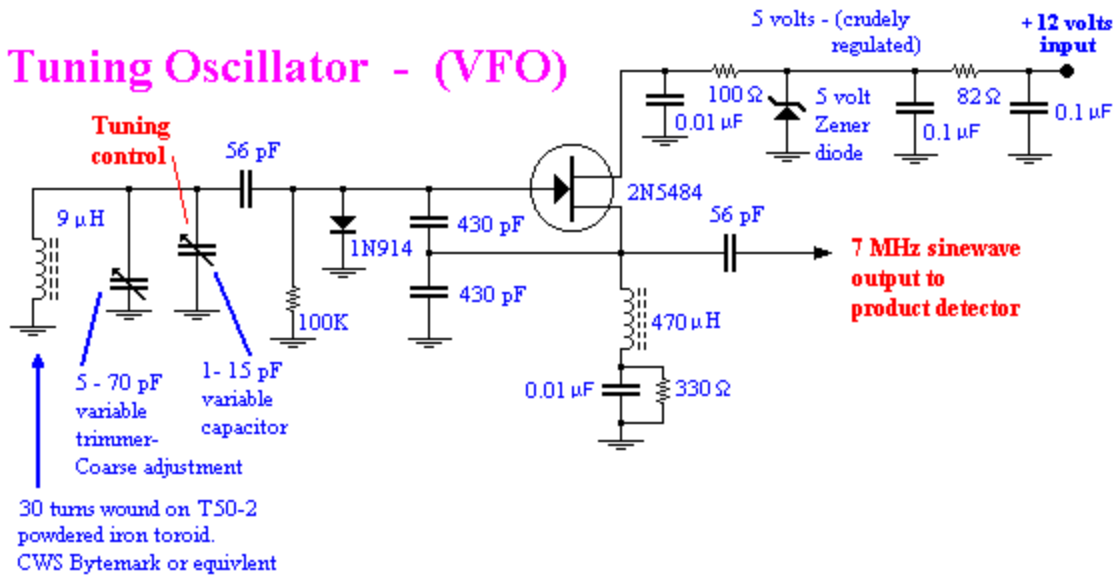
JFET TRANSISTORS

This tuning oscillator uses a Junction Field Effect Transistor, (JFET). They are ideal for building VFOs. Unlike bipolar transistors, the main current from the JFET drain to the source does not pass through any PN junctions. PN junctions change their characteristics with temperature. Therefore, VFOs made from bipolar transistors tend to drift more than JFETs. JFETs work on the same principle as a MOSFET transistor, but the control gate is a P-N junction diode rather than a tiny capacitor. Power MOSFETs were introduced in chapter 6 as a way to key the QRP power supply on and off.

P-N junctions

As you learned in chapter 4, *a semiconductor P-N junction conducts when positive voltage is applied to the P-type semiconductor*. Conversely, it does not conduct when positive is applied to the N-type semiconductor side. In the crystal set, we were dealing with such tiny currents (microamperes) that the transition at zero volts was plainly visible. Commercial diodes handle much larger currents, milliamperes or even amperes. With commercial diodes the forward conduction doesn't fully start until a forward offset is reached. For an ordinary P-N junction silicon diode, this is around 0.6 volts. For a commercial Schottky diode, this offset is around 0.2 volts. This threshold means that if we apply a positive voltage to the P-type semiconductor side below the threshold, say, 0.1 volts, the current will be far less than a milliampere. Since very little current flows, the diode is still essentially "OFF."

P-N junctions can work like capacitors

In a MOSFET, gate current is prevented from flowing into the main channel by means of a layer of glass insulation. In a JFET, the gate appears to be a forward biased diode but doesn't conduct much current unless the drive exceeds the forward breakdown voltage, about 0.6 volts DC. *With zero volts input on the gate, the JFET is already partly turned on.* In other words, with zero volts on the gate the transistor is already operating as a Class A amplifier and, unlike a bipolar transistor, no bias resistor is needed.

JFETs operate at input voltages less than 0.6 volts

The JFET turns full on, (that is, it saturates) when the gate voltage approaches or exceeds 0.6 volts. Notice the diode clamp that prevents the gate voltage from ever exceeding 0.6 volts. To turn the JFET completely off, reverse voltage must be applied to the gate so that the charge carriers, holes and electrons, are completely depleted. For example, in the N-channel JFET shown below, the transistor turns completely OFF when the gate goes negative with respect to the source lead of the transistor.

gate   Schematic symbol

source   drain

Notice that the arrowhead points AWAY from transistor in a P channel, TOWARD the transistor in an N-channel.

Negative voltage on gate fills in holes with electrons.

P - Type semiconductor gate
holes
Reverse biased PN (diode) junction.

Source   Drain

N - Type
semiconductor

**N - Channel JFET
field effect transistor**

Free electrons

Free electrons repelled away from gate by negative voltage on gate.

Absence of electrons, turns the transistor OFF.

As you would expect, P-channel JFETs are mirror images of N-channel JFETs with respect to construction and polarity. To turn a P-channel fully off, its diode gate is back biased with _positive_ voltage as shown below.

gate   Schematic symbol

source   drain

Notice that the arrowhead points AWAY from transistor in a P channel, TOWARD the transistor in an N-channel.

Positive voltage on gate attracts electrons away from junction.

N- Type semiconductor gate
Reverse biased PN (diode) junction.

Source   Drain

P- Type
semiconductor

**P - Channel JFET
field effect transistor**

holes

Holes filled with electrons attracted by the positive charge on the gate.

Filling in the holes, turns the transistor OFF.

The product detector

This receiver project uses a ***product detector***. The product detector amplifies and mixes the VFO signal with the signal coming in from the antenna. The resultant mixture of radio signals is amplified and sent to an audio amplifier. Since the only audio component present is the *DIFFERENCE* between the two radio signals, that's what the audio amplifier passes on the earphones.

The product detector circuit described here uses a dual gate N-channel MOSFET transistor. A dual gate MOSFET works like a single gate MOSFET (or JFET). But as the name implies, it has <u>two</u> control gates modulating the drain-to-source current instead of just one gate. With two gates this MOSFET is convenient for mixing two separate signals because the output of the amplifier is an <u>amplified</u> mixture of the two inputs. Mixers and product detectors can be built with single gate MOSFETs and JFETs, but with a dual gate MOSFET, both inputs are amplified in one stage.
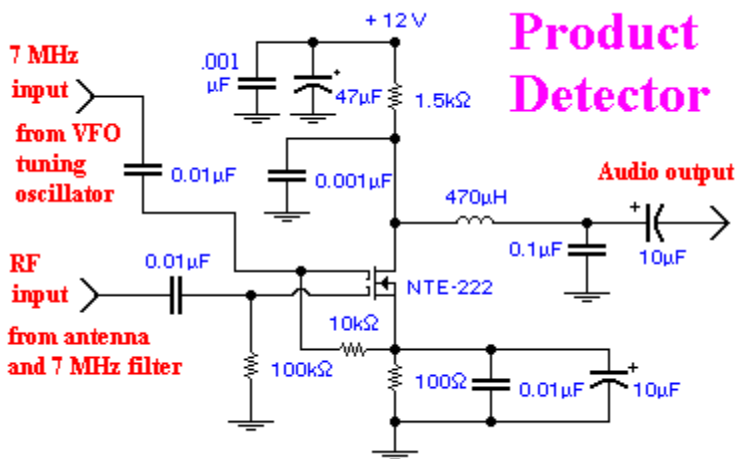
The gates of the MOSFET are tiny capacitors and therefore have extremely high impedance. The amplifier design is a "***common source***" design, which implies that the source is essentially at ground. This also means the load resistance, 1.5 K ohms, is on the drain side (+12 volt side) of the transistor. Because the desired output is an audio frequency signal, the load impedance is a resistor, not an inductor. In order to work at audio frequencies, an inductor would have to be huge and for this application would have little advantage over a resistor. The 470 microhenry RF choke (inductor) and the 0.001 and 0.1 microfarad capacitors serve as a filter to remove the RF from the audio output. Without the filter, the audio amplifier would be more likely to rectify, (i.e. detect), strong RF signals that managed to get into the product detector and were not within the desired audio frequency difference from the VFO.

Modern designs often use integrated circuit mixer modules for product detectors. Personally, I prefer the dual gate MOSFET design simply because I know what's in there. It isn't just another mysterious integrated circuit. In this application any of the following dual gate MOSFET transistor types will work fine. I have successfully used the NTE221, NTE222, NTE454 or NTE 455. These are all "replacement" transistor types. So far as I know, any of the original 3N-series dual gates such as the 3N140 will also work. Unfortunately, they are hard to find in modern catalogs.

The AF amplifier

The output from the product detector is an audio signal that needs to be amplified before it goes to the earphones or speaker. Once again, most designs seen in ham magazines use integrated circuits marked "audio amplifier." For example, the LM386 is a typical one-chip audio amplifier. I've used these and they usually work well. Of course I didn't learn anything from the experience.
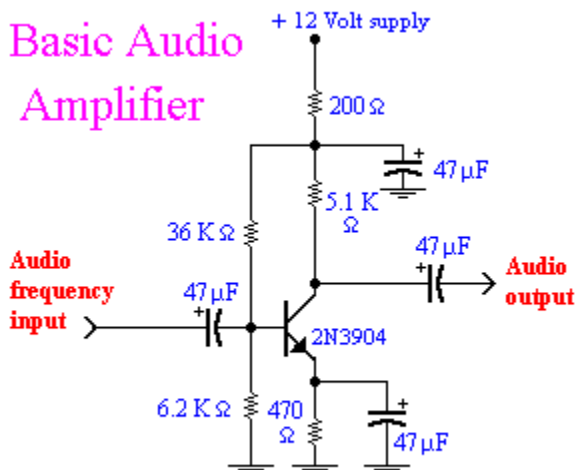
The diagram above shows a basic audio frequency *"RC coupled"* linear amplifier. If you look closely at the component values, you'll see it is similar to the class A RF amplifier we used as a buffer amplifier in the QRP transmitter in chapter 6. The differences are the large sizes of the capacitors and the absence of inductors. A 5.1 K Ω resistor is used as a load where you would expect to find an inductor in an RF amplifier. Notice that the 36 K Ω resistor turns the amplifier partly on so that an audio sinewave will "fit" between zero volts and 12 volts. Otherwise the amplifier would only amplify positive signals larger than about 0.6 volts. Without the forward bias, the negative half of the sinewaves would be clipped off and the sound would be badly distorted. Because of the 0.6 volt base voltage offset, small signals wouldn't be heard at all.

The 200 ohm resistor and its 47 μF capacitor serve to isolate the power supply from the amplifier and thereby make oscillation less likely. If you leave out these parts, it will probably work OK and you may not notice the difference.

My complete audio amplifier is an extensively modified version of an example in the ARRL 1986 handbook. It looks like three straight-forward R-C coupled amplifiers in series. But the original design had extra filter components I didn't quite understand. Every part that I didn't understand, I left out. That was my education. The audio amplifier was dead as a doornail when I first turned it on.

+ 12 volts

Aluminum electrolytic

1kΩ

2.2µF

5.6kΩ

220 µF

5.1kΩ

100kΩ

2.2µF

Input from product detector

100kΩ

2.2µF

10µF

1kΩ

Audio gain

5kΩ

2N3904

2.2µF

0.1µF

10kΩ

560Ω

10µF

10kΩ

220Ω

10µF

2N3904

2N2222

8 ohm headphones

100kΩ

10kΩ

82Ω

10µF

C1 10µF

22kΩ

R1

4.7kΩ

R2

Audio Amplifier

XFMR is Radio Shack # 273-1380.

Diodes across headphones are 1N914 or equiv.

An audio Automatic Gain Control (AGC)

I was particularly puzzled by the low frequency feedback link, R1, R2 and C1. I couldn't understand what sort of "low frequency filtering" the designer was trying to accomplish. But, when the amplifier seemed completely dead, I put these mysterious components back in the circuit. Voila! The earphones came to life. It turns out that this loop biases the amplifier "on" for weak signals and biases it "off" for loud signals. It's a sort of audio Automatic Gain Control (AGC) circuit.

Remember that for a bipolar transistor to turn on, the input signal must be greater than 0.6 volts or no current will flow into the base. In a "Class A" amplifier a DC signal is added to the base. This increases the base voltage above 0.6 volts so that it's always turned on. The low frequency feedback adjusts the bias for weak and strong signals. When the signals are weak, the second transistor is turned off, so it's collector voltage is high (+12 volts) and unchanging. This big collector voltage is leaked into C1 through R2. The voltage on C1 biases the base through R1 to provide a forward bias for the transistor, biasing it on and raising its sensitivity. Conversely, when the signals are strong, the collector has a big current flowing but a low average voltage from the collector to ground. This lower voltage biases the transistor more "off."

Protecting your ears from strong signals

This audio amplifier is able to blow your ears off when you encounter a strong signal. Therefore it's essential to add a clamp circuit to limit the voltage to the headphones to less than about one volt. I first did this with back-to-back 5 volt Zener diodes across the headphone jack. In practice, with sensitive, modern 8 ohm headphones, I found that less than one volt peak is plenty of volume for me. Eventually I put in two ordinary silicon 1N914 diodes "shorted" across the headphones. This limits the positive and negative sound peaks to just 0.6 volts and my ears have been adequately protected.

How Hi-Fi should it be?

The original circuit was also sprinkled with 0.1 microfarad bypass capacitors as if the designer were trying to kill all higher frequency sounds and shunt most of the audio to ground. Since I was worried about having enough gain, I left out the bypasses. The amplifier worked well without them, but the sound of the static had an obnoxious, piercing, high pitch that irritated my ears. I put the bypasses in and, as I expected, the audio sounded more "base" and became somewhat weaker. However, getting rid of that piercing, hissing static was well worth the loss of gain. Experiment!

The original design also had no emitter bypass capacitor, the 10 µF capacitor across the 220 ohm resistor. Not having this bypass capacitor reduces the gain because some of the audio voltage signal is wasted across the 220 ohm emitter resistor. Since I didn't want to waste any gain, I put in the capacitor and my gain jumped up noticeably. This bypass has no disadvantage that I could detect.

Mechanical construction

I built my receiver in a box made from soldering pieces of two-sided PC board together. This is the same construction described for the QRP transmitter described in chapter 6. The black coax RG-174 cables running around the inside of the box connect the optional 700 Hz filter module described later in this chapter. The coax shields the wires from stray RF that might be present. Only one end of the coax should be grounded.

The tuning knob ideally should be a mechanical, vernier planetary-gear type to spread out the 40 meter CW band and make the signals easier to tune in. Alternatively, one can use a smaller variable capacitor, say 1 to 5 or 10 picofarads (pF). In this way, out of the 180 degrees of useful knob rotation, more degrees can be devoted to the CW band and less to the nearby broadcast stations. Another approach is to use two variable capacitors in parallel. A big capacitor can tune the whole frequency spectrum around 40 meters. Then, a small capacitor in parallel, called an *electrical bandspread*, can do the fine-tuning.

The receiver power supply

The receiver will work well on 9 volts at about 10 milliamperes. However, when the voltage drops below about 8 volts, the volume and sensitivity will fall off dramatically. So, if you use a small alkaline "transistor radio" battery, it will only work well for about 1/3 of the

energy stored in the battery. To get the most from alkaline batteries, you need to be able to run them down to 2/3 of their original voltage. Therefore, in this case the receiver would have to work well down to 6 volts. I recommend making up a 12 volt battery out of AA cells. Radio Shack and other companies sell battery holders that carry 6 or 8 cells to give you 9 or 12 volts. Or if you are using the receiver with the QRP transmitter described in the last chapter, the receiver can share the QRP power supply.

Hearing the VFO

When I was trying to use the DCR with my transmitter, I found I couldn't hear my own transmitter VFO over the stations I wanted to call. To fix that, I ran a coax cable over to the QRP and imported a weakly-coupled transmitter VFO signal into the receiver box. The center connector on the right side of the receiver is for that purpose. The receiver has is no direct connection to the VFO. The connector merely projects a small piece of wire into the receiver box like an antenna to broadcast the weak VFO signal.

****

FIXING THE LIMITATIONS OF DIRECT CONVERSION

One DCR limitation I had read about didn't need to be fixed. Because a DCR has nearly all its gain in the audio amplifiers, these amplifiers are supposed to be prone to *microphonics*. In other words, DC receivers are supposed to be sensitive to vibration. When you touch a knob or bump the table, you are likely to hear that sound amplified in the earphones. I observed no microphonics at all.

A DCR detects both sidebands at once

Unfortunately, the product detector mixer detects both the upper and lower sidebands simultaneously. This is OK for listening to AM radio stations, but has poor selectivity on a crowded CW band. A good CW receiver can select a bandwidth as small as 500 Hz or less. A simple direct conversion receiver will have a bandwidth of 10,000 Hz or more, depending on the audio filtering.

Although audio filtering is helpful, the big problem is that you'll still be listening to audio from both sidebands at once. For example, suppose you build a sharp audio filter to select audio tones between 600 and 700 Hz. Yes, you'll hear your 650 Hz CW station just fine. But you're likely to be confused by an "*image*" signal that might be 1.3 KHz away on the opposite sideband. That is, 2 X 650 Hz = 1.3 KHz. When you answer a CQ, this confusion will make it hard to know which sideband your contact will be listening on.

Modern Image-Rejecting
Direct Conversion Receiver
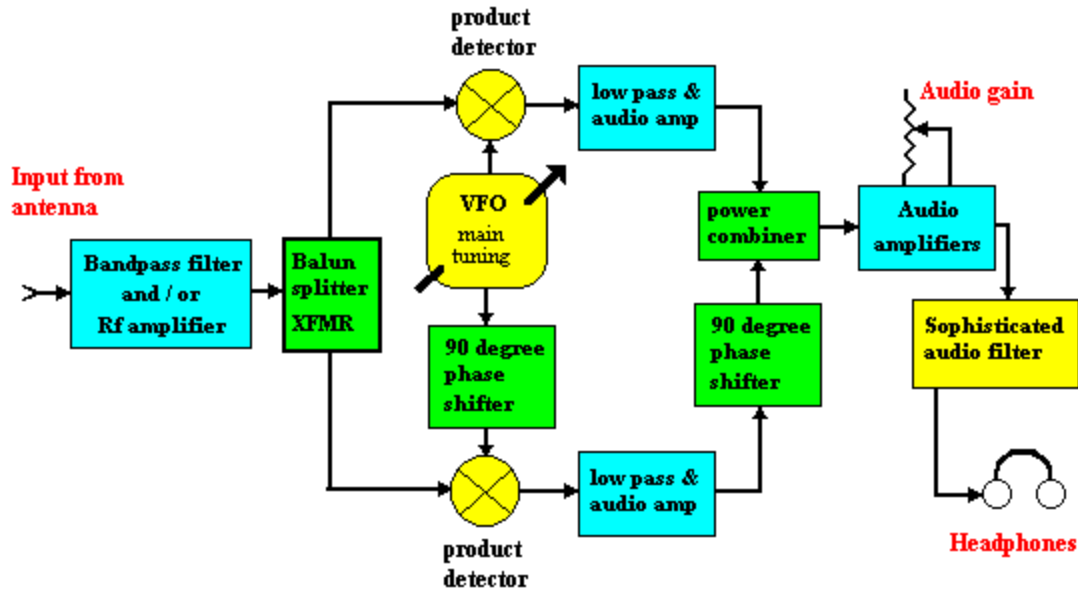
A sophisticated direct conversion receiver eliminates one sideband by essentially building two DC receivers. One sideband is cancelled out by phase shifting the input VFO RF signal and also phase shifting the resulting audio signal to remove one sideband. So, although DC is "simple," you might need to build two of them, plus a sophisticated audio filter. Personally, I decided that a dual conversion superhetrodyne was the best way to go.

AM broadcast interference

In my city there is a powerful AM radio station that broadcasts at high power during the day. When I put an oscilloscope on my 40 meter dipole lead in, I see a 1.75 peak volts RF signal on the wire even with a 50 ohm resistor connected to the antenna! This represents 31 milliwatts of power! No wonder my crystal set was so loud.

Power = Voltage (RMS) squared ÷ load resistance = V_{RMS}^2 /R

RMS voltage = Voltage peak x (0.707)

Power = [(1.75 volts peak) x (0.707)]^2 ÷ 50 ohms   =   31 milliwatts

The ham signals I was trying to listen to were buried in the voltage storms from the local AM rap station. The input filter for the DC receiver described earlier in this chapter was apparently inadequate to get rid of such a large signal. So, although I could hear ham stations, in the background I could always hear the rap music leaking through like a crystal set. I needed a better filter! The good old '86 ARRL handbook had such a filter design. It worked the first time without tweaking and knocked the RF voltage coming in on my antenna down to about 0.15 volts peak without affecting the strength of the 40 meter signals.
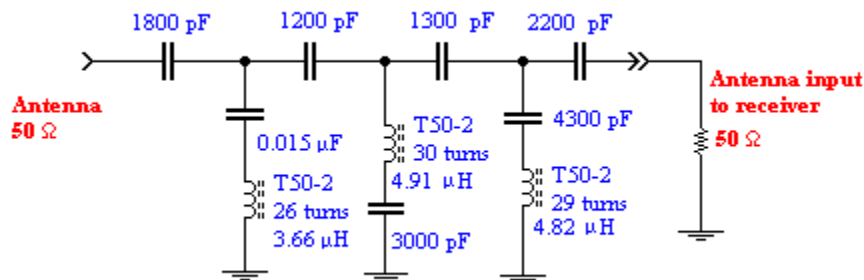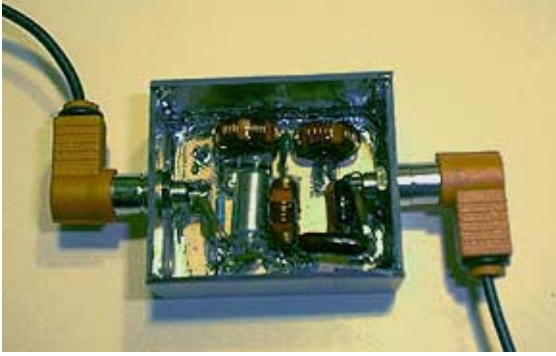
An AM broadcast filter

A 700 Hz audio filter – why you need one

Most modern hams are using transceivers that automatically listen about 700 Hz above or below their transmitting frequency. This offset frequency is adjustable, but is nearly always set between 500 to 1000 Hz. By convention, on HF bands on or above 30 meters, today's hams listen ABOVE the transmitting frequency. *On 40 meters and below, the offset is conventionally BELOW the transmitting frequency.* This convention has its origin in the method for generating single sideband phone that used to be common 40 years ago. The old SSB design isn't used anymore, but the convention lives on. The new 60 meter band is specified for upper sideband only and is an exception.

The lesson about sidebands is, that if you intend to answer a fellow calling CQ, you must be sure you are listening on the same side of his transmitter frequency that he is. Because your direct conversion receiver has no image canceling, you will hear his Morse code both above and below his actual transmitting frequency. If you zero in your transmitter on the wrong side of his signal, your transmitter will be 1.4 KHz (2 X 700 Hz) away from where he is listening and he'll never hear you.

For example, on 40 meters, as you tune *UP* the band you'll first hear his Morse code on the low side of his actual frequency. That is the lower sideband. If you continue tuning *VERY* carefully, the tone you hear will fall to a low pitch, then zero, then rise back up to the same musical tone again. That is the upper sideband.

If you wish to answer the fellow's CQ, listen on the lower sideband. Now set your transmitter to "spot" and tune your transmitter crystal-pulling capacitor *DOWN*-frequency until

you first hear an equal tone. If you have a little musical talent, you should be able to match the tones pretty well. ***In summary, when <u>listening</u> for CQs, tune UP the 40 meter band. When <u>spotting</u> your transmitter oscillator on top of the station you wish to call, tune the transmitter DOWN the band.***

Those darn modern hams are listening with exquisitely narrow audio filters. They will usually only hear you if your signal is making a tone within a couple hundred Hz above or below their listening frequency. When they switch in the <u>really</u> sharp digital filters, they only hear stations within a few Hz of their listening frequency.

An analog audio filter

If we had ideal, small, cheap components, the easy way to build analog audio filters would be to use inductors and capacitors the same way we build radio frequency filters. We might even imagine that there would be audio frequency crystals for building super precise audio filters.

Unfortunately, in the real world those parts don't exist. In order to work at such low frequencies, the inductors would have to be huge and expensive. Since that approach isn't practical, we use resistor/ capacitor networks. ***These RC networks don't resonate, but rather they just attenuate some frequencies more than others.*** A large capacitor charges more slowly than a small one. When combined with a resistor, the frequency of the sinewave across either the capacitor or the resistor will be attenuated at either the high frequencies or the low frequencies, respectively.
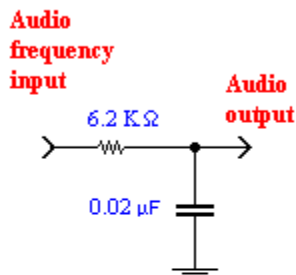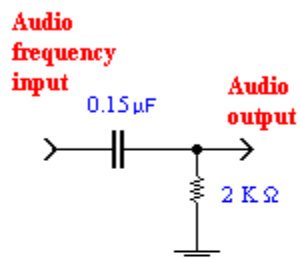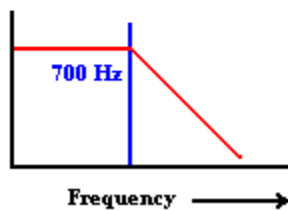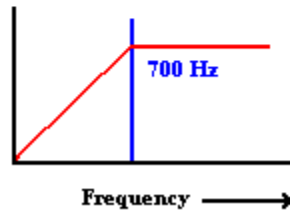
Low pass filter

As shown above, a simple resistor and capacitor makes a low pass filter when the output is taken off the capacitor. If the capacitor is large, relatively high frequency sinewaves will be "shorted out" to ground. Remember, ***the voltage across a capacitor can't change instantly***. In

contrast, smaller capacitors will be negligible to low frequency sinewaves that have plenty to time to charge the capacitor during each half cycle. The resistor loads down the circuit and draws current into the capacitor. Similarly, during the next half cycle, the resistor has sufficiently low resistance to fully discharge the charged capacitor and get ready for the next half cycle.

High pass filter

When the R and C are reversed and the output is taken off the resistor, then the RC filter becomes a high pass filter. High frequencies pass right through a capacitor to the output as if it weren't even there. Remember, *the voltage across a capacitor cannot change instantly.* Therefore, the capacitor looks like a wire with zero voltage drop across it. At high frequencies there isn't time to change. At low frequencies, the capacitor charges up completely and the voltage drop across the capacitor approaches the entire voltage of the input sinewave. These *RC coupled filters* all have a particular frequency called the *break point* where the capacitor becomes insignificant in the circuit. A simple RC filter attenuates the sinewave voltage ten times (20 decibels) for a tenfold change in frequency away from its break point.

Compensating for attenuation

A problem with RC filters is that the resistors attenuate ALL the frequencies, not just the ones we don't want. However, if an RC network is combined with an audio frequency linear amplifier, we can compensate for the attenuation. By amplifying the output, we can restore the signal strength of the desired frequencies back to its original strength.

Bandpass filter = RC networks plus amplifier

To make a bandpass filter we need to combine a low pass filter with a high pass filter and then amplify the result. The circuit below is a one-stage R-C (resistor/ capacitor) audio filter/ amplifier that accentuates 700 Hz tones and attenuates tones above and below roughly 600 and 800 Hz.
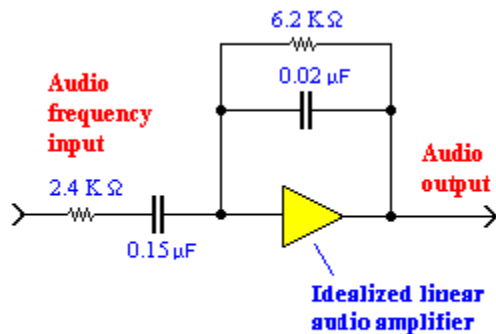
Single Stage 700 Hz Bandpass Filter

In this filter the Rs and Cs are not arranged as you might expect. However, if you carefully analyze how they affect signals passing through the circuit, they work the same as the separate circuits described earlier. That is, low frequencies and high frequencies are attenuated and the desired 700 Hz frequency range is relatively unaffected. The input RC, the 2K Ω and 0.15 μF capacitor, attenuate low frequencies because low frequencies, (like 60 Hz and direct

current), can't get through the capacitor. Therefore the input network is a <u>high pass filter</u>.

Note that the 6.2K Ω ohm and 0.02 μF capacitors are wired between the input and output of the linear amplifier. This feedback network is the <u>low pass filter</u>. This combination of components tends to "short out" the amplifier and attenuate everything above about 700 Hz. Note that the small 0.02 μF capacitor has little effect on low frequencies because it charges essentially immediately. Because the capacitor charges almost instantly, its voltage follows the low frequency sinewave curve without significantly attenuating it. However, at high frequencies a 0.02 μF capacitor becomes charged more slowly than the high frequency sinewave is changing. Between half cycles, the 6.2K Ω ohm resistor has low enough resistance to be able to discharge the 0.02 μF capacitor significantly so that the network is restored to block the next half cycle.
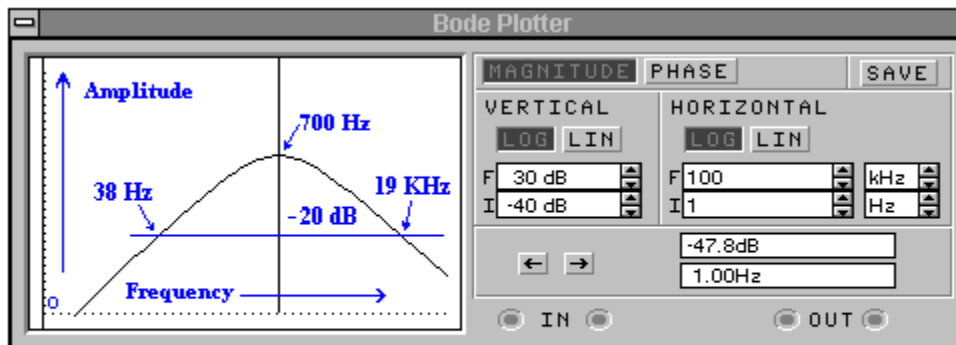
Single Stage 700 Hz Audio Filter

The frequency plot above shows the response of the single stage filter. As you can see, this filter is pretty crude. In order for the voltage of a sinewave to be attenuated more than 10 times (20 decibels), the frequency must be at or below 38 Hz or at or above 19 KHz. To be blunt, this won't help much. It will decrease some of the unpleasant high frequency noise from static, but won't be particularly helpful in relieving the QRM (interference from other stations).

More precise filtering can be achieved by putting multiple audio filters in series. The plot below shows four of the same filters in series. This is a big improvement and makes it easier to listen to just one station at a time. It also eliminates the high frequency noise and makes listening
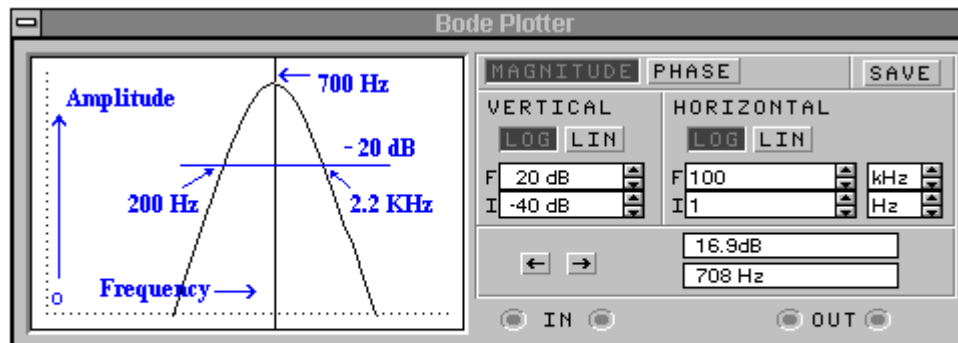
Four Stage 700 Hz Audio Filter

less tiring.

Implementing the filter

We can build filters that work just like the graphs above using transistor linear AF amplifiers made from discrete components. Here is what a single stage 700 Hz filter would look like:
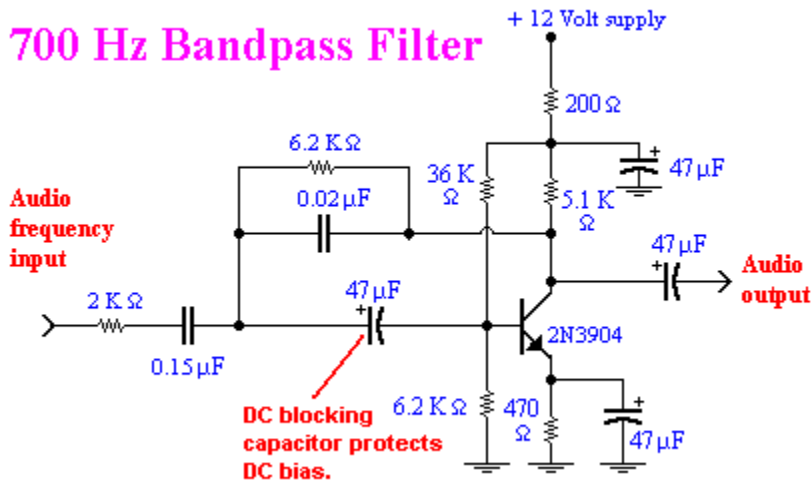
Operational amplifiers – "perfect" amplifiers

Notice the big blocking capacitor needed to prevent the DC bias for the class A amplifier from being changed by the 6.2 K ohm resistor. In any case, normal, non-eccentric hams do not make audio filters using linear amplifiers made from discrete parts. Instead, they use integrated circuit operational amplifiers. Being obsessive-compulsive, I thought about wiring all those bias resistors and 47 µF capacitors. Then I decided, "What the heck! I'm checked out on audio amplifiers. I'm going to use a quadruple op-amp integrated circuit!"

Op-amps are integrated circuits containing 12 to 30 transistors and resistors in a network that produces a "perfect" or idealized amplifier. How much gain should a "perfect" amplifier have? The best answer is that the gain should be infinite and then feedback can be used to produce any gain you like. Therefore real operational amplifiers have *near infinite gain*, and *near infinite input impedance* and a *voltage source output*.

Typically there are two or four operational amplifiers on a single chip. The symbol for an operational amplifier is a triangle. The typical op-amp has an output pin and two input pins. For example, look at pins #1, # 2 and #3 below. A *positive* voltage on the *positive input* pin makes the output pin voltage rise, that is, go positive. In contrast a *positive* voltage on the *negative* input pin makes the output pin go down. *Because of the feedback, the op-amp will "attempt" to drive its output pin up or down until feedback from the external circuit components cause the two inputs to be equal in voltage.* If the feedback is insufficient to produce equilibrium, the output will bump into either ground or the voltage supply, whichever happens first.

To bias an operational amplifier so that a large sinewave will "fit" between zero volts and 12 volts output, the amplifier must have a baseline about halfway between the supply voltage and zero. In this case the resting level will be about 6 volts. In the filter below, the positive input is connected to a 6 volt sample level made from a voltage divider connected between 12 volts and ground.
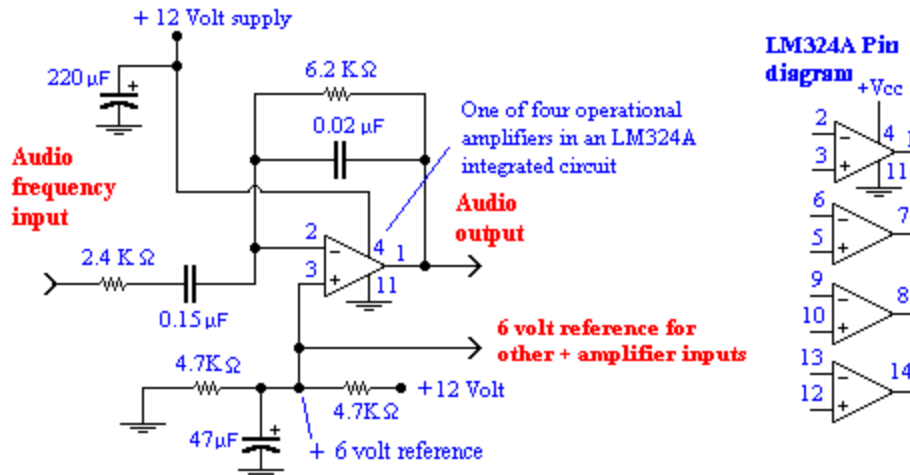
Single Stage 700 Hz Bandpass Filter

Homebrewing with integrated circuits

Homemade "gouge boards" described in chapter 6 are usually much too crude to use with integrated circuits. Therefore when I build with ICs, I use perf-boards. These are plain, 1/16 inch thick fiberglass boards. They have no copper layers but have a grid of tiny holes drilled on 1/10 inch centers. The older ICs have their pins spaced 1/10 inch apart and the two rows of pins are spaced apart in even multiples of one-tenth inch. Modern ICs are often available either as old-style, through-hole or modern surface-mount. To use through-hole, you just push them through the perf-board and then solder your components and wiring on the pins on the other side.

I prefer to use IC sockets. If you accidentally damage an IC, with an IC socket it can be instantly replaced. Without a socket, you'll seriously damage your wiring when you tear it apart to solder in a new one. The IC socket also has pins lined up just like an IC, so you push it through the board and solder your wires to the socket pins on the bottom.

For homebrew work you need the big, old time ICs with 1/10 inch spacing. Modern surface mount ICs have pin spacing as tiny as 20 thousands of an inch. They are designed to be installed with mass production robots and are extremely tricky to solder in your basement. One practical (but extremely time-consuming) home-brew approach is to make little etched circuit boards that accept the surface mount IC. The little adapter boards have traces that serve to expand the pin lead spacing radially out to large pads that human fingers can work with directly. Using hemostat clamps, tweezers and a microscope, you solder the IC onto the miniature board. After you have inspected your pin connections under a microscope, you can then solder these adapter boards onto a normal size perf-board.
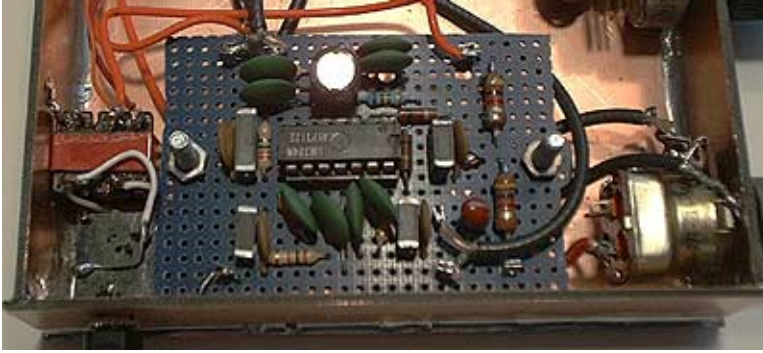
A four-stage 700 Hz bandpass filter built on a perf-board.

Using the diagram for the single stage filter shown earlier, simply feed one output into the next input until you have four stages in series. All four op-amps can share the same 6 volt resting level reference.

Label your pins!

Keeping track of the pin numbers isn't easy unless you label them. I cut out a thin strip of sticky white label paper and paste it between the pins. I write the pin numbers on the paper adjacent to the respective pins. ***Pin # 1 is at the end of the integrated circuit that has the notch.*** Sometimes pin # 1 is indicated with a little number or indentation in the black plastic. In any case, the pin numbers seen from the top are numbered counterclockwise. However, <u>as seen from the bottom of the IC socket where you do your soldering</u>, ***the pin numbers go around clockwise starting from the end with the notch in plastic case.***

There are two kinds of IC sockets suitable for ham work - *solder tail* and *wire wrap*. Wire wrap sockets have big tall pins that allow thin wires to be wrapped around them with a special tool. I prefer the solder-tail type. They are harder to work with, but aren't so tall, are less messy and don't take up so much room. Just to cover the subject of IC sockets, large complex computer ICs use grid sockets and solderball sockets with hundreds of contact points. Unfortunately, working with these is nearly impossible at home because that would involve extreme precision and building multi-layer PC boards.

Wiring the 700 Hz filter into the circuit

I designed the op-amp filter to have a slight amount of amplification. Unfortunately, by the time I put four in series, I had as much gain as one of the audio amplifier stages. Therefore, the output of my filter goes to the input of the <u>second</u> AF amplifier stage and bypasses the first stage. When I returned the signal to the input of the 1st stage, it was much too loud and unstable. You could bypass the 2nd stage, but you would lose your AGC. A block diagram of my receiver is shown below.   A double-pole, double-throw DPDT switch substitutes the filter for the 1st stage AF amplifier.

Direct Conversion Receiver with Optional Filters
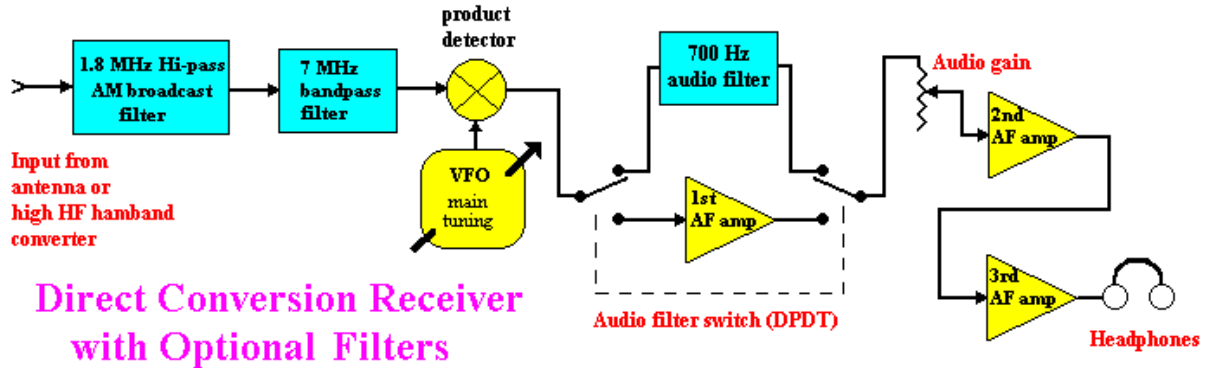
The digital solution to audio filtering

Actually, op-amp filters are also old-fashioned. The modern way to build audio filters is to use digital filtering. Basically, a microcomputer program measures the width of individual sinewaves with a counter-like algorithm. For example, a 700 Hz sinewave cycle is 1.43 milliseconds long. The digital filter measures the height and widths of the sinewave humps. If the widths are the desired frequency, then it just recreates waveforms of that length and amplitude. Sinewaves that are longer or shorter are ignored. Averaging and integrating math algorithms are used to massage the data and arrive at the most accurate and useful representation of the original spectral content of the signal. In practice, a digitally filtered passband of just one Hz is easy to build but is very hard to tune in with your VFO tuning knob. Therefore the passband of a digital filter is usually adjustable. When the passband is fairly wide, say 200 Hz, tuning isn't so difficult. However, the precision of a digital filter can be as selective as you please.

In conclusion,

The block diagram above shows the receiver I built. I packaged the AM broadcast band filter outside the receiver so I could use it with other receivers. A switch allows me to put in the 700 Hz filter when I need it. If you use it with single sideband phone, it will get rid of much of the noise, but voice quality will suffer. To tune in single sideband, you have to tune your VFO to exactly the right spot to make the modulation intelligible. AM voice stations must also be tuned in perfectly, otherwise they make an obnoxious whistle. The whistle occurs because the AM broadcast includes a fixed carrier wave that is comparable to a Morse code signal with the key held down. To get rid of the whistle, you must "zero beat" the VFO so that there is no audio frequency difference between the carrier wave and your local VFO. When you do that, the whistle vanishes and you will just hear the audio sidebands.

So? How well does the direct conversion receiver work? If this were the year 1935, all your ham friends would probably be insanely jealous of its terrific performance. Unfortunately, by modern standards it is a bit of a toy. It's adequate for shortwave listening and an experienced CW operator can use it to talk to people. I managed to use it in conjunction with the QRP transmitter in chapter 6 to talk to hams in other states. I guess that makes me an experienced operator. Novice hams could easily use it for communications whenever the band isn't crowded. It has plenty of sensitivity, just not much selectivity.

CRYSTAL SETS TO SIDEBAND
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Chapter 8
POWER SUPPLIES

Once you progress past crystal sets, electronic projects almost always need a power supply. Low power projects, like a small receiver, can be powered with flashlight batteries or even a little 9 volt "transistor" battery. Other convenient sources of low power DC are *adapter plugs*. These are the black cubes a few inches square that plug into the wall and have a long, skinny cord that plugs into your recorder or small appliance. They deliver 6, 12 or other DC voltage at a few watts. Adapter plugs have the safety of a battery with the convenience of wall power.

Unfortunately, if you plan to power your QRP with household power, you'll need more than a few watts. When you decide to plug a homebuilt circuit into the wall, you must confront some significant safety issues. Line-powered power supplies convert 120 volts AC into DC voltage at the required levels of voltage and current. Actually, a transmitter can also be thought of as an energy conversion device. It converts direct current into radio frequency current. In this chapter I'll describe some power supplies you could use for your QRP transmitter. A 5-watt transmitter needs at least 10 watts of power with good voltage regulation.

Line-powered power supplies

The ideal power supply is called a *"voltage source."* A voltage source is a power supply that can supply infinite amounts of current without the slightest waver in the voltage. For example: As every northern resident knows, starting a car can be difficult when it's below zero. A cold battery does not supply as much current as a warm battery. So, when you turn the ignition key on a frigid morning, the battery voltage crashes.
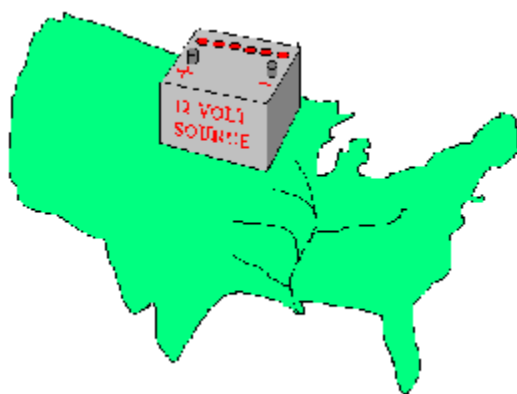
On the other hand, if you had a battery the size of North Dakota, the voltage would not drop a microvolt when you started the engine. Moreover, you could start all the other cars in Minnesota simultaneously without voltage drop. Of course, there are also other practical issues here. For example, your battery would need zero resistance battery cables, zero resistance connectors, etc. Well, you get the idea: The ideal voltage source should not lose any voltage, no

matter how much power it supplies. Using ham radio vernacular, a good power supply is a "stiff" supply.

Lab power supplies

A reliable, line-powered laboratory power supply is useful for checking circuit boards. No lab should be without one. A big advantage of commercial lab supplies is that the voltage is adjustable from zero to some high level like 20 volts. Meters show you the current and voltage at every moment, so you know what is happening. Variable voltage allows you to power up a new circuit CAREFULLY. You can start with a few tenths of a volt and see what happens. If the circuit is shorted, you can find out with one volt applied to the circuit board, rather than blasting it with 12 volts right away. This way you can avoid burning up expensive transistors. Many lab supplies put out two or even three separate supply voltages at once. Another feature of some lab power supplies is that they automatically limit the available current to some maximum that you select.

Bench power supplies are quite generic and there are many modern ones that will serve you well. Remember, to power your QRP you need about 1.0 ampere at 12 volts DC. A typical modern, transistor QRP transmitter runs on a 12 volt power supply. That is,

$$10 \text{ watts} = 12 \text{ volts} \times 800 \text{ milliamperes}$$

Homebuilt power supplies for use with rechargeable batteries or line power are described below. If you aren't familiar with power supply design, a discussion of the basic principles follows.

Simple wall-powered supplies

Choke decreases ripple & prevents transformer saturation.

Isolation transformer

ON/OFF

SPST

120 volts AC

Fuse

Line cord

12 Volts AC RMS

Silicon rectifier diode. for example, IN4001 200 volt @ 1 ampere.

> 5 H
Big AC Choke
150 mA

100K Ω

"Bleeder" resistor drains capacitor when supply shut off.

+ 12 Volts DC

DC

Big capacitor, say 4700 µF @ 25 Working Volts
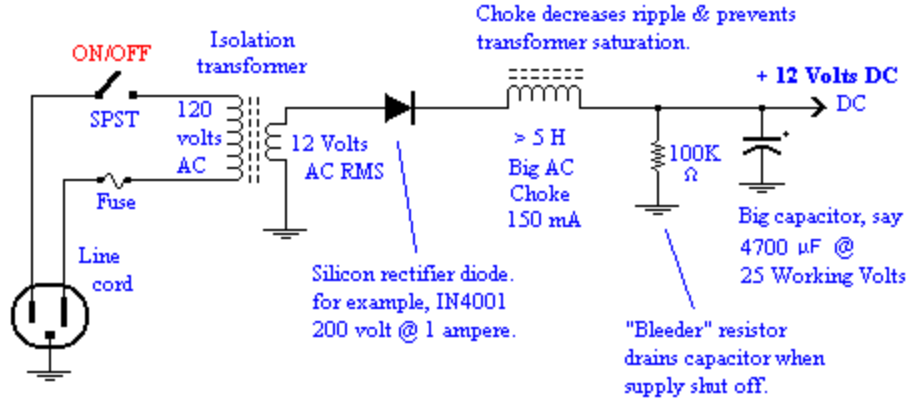
SIMPLE LINE-POWERED
12 VOLT POWER SUPPLY.
(NOT SUFFICIENT FOR QRP)

The diagram above illustrates the simplest, safe, generic, line-powered power supply you can build. Unfortunately, this supply is too poorly regulated to power a transmitter. However, it illustrates the minimum safety features and it's easy to explain.

Power supply safety

The supply should be enclosed in a box to insure that children (and you) won't get fingers across the 120 volts AC. Ideally the box should be made of <u>metal</u> so that, in case of a short circuit, a fire is highly unlikely.

Another safety design philosophy is called ***double insulation.*** In this scheme the electronics are housed in a <u>plastic</u> box and extra effort is made to insure that the internal wires are properly protected so that shorts and loose wires are highly unlikely. A double insulated plastic box does not necessarily need a ground wire in the line cord. However, in ham work, metal boxes shield circuitry from stray radio waves and are usually the best choice.

Line cord. The line cord should be the modern, three-wire type with the (green) ground wire securely connected to the metal box. In case a loose wire in the box causes the hot side of the AC line to touch the metal box, the ground wire will safely shunt the AC current to ground.

The line cord should pass into the metal box through a ***rubber grommet*** so that the metal edge can't cut through the insulation on the wire and cause a short circuit. Once inside the box, the cord should be held captive by a clamp, properly known as a ***strain relief.*** The strain relief insures that if the power supply is ever yanked by its cord, the live wires will not be ripped loose and short out.

The wires in a line cord are usually color-coded. The "hot" wire usually has black insulation while the "neutral" or return wire is white. The neutral wire is supposed to be connected to the house ground buss out in the circuit breaker box. Looking at a household three-prong socket, the round pin is the "ground." The wider, flat pin is the hot side and the narrower flat pin is neutral. Unfortunately, sometimes wall sockets are wired wrong, so it's better not to

bet your life on the orientation of the flat pins.

Fuse. The first destination of one of the two power wires should be a *fuse*. As you probably know, fuses are little pieces of solder-like lead mounted in a glass case. When the current exceeds some calibrated level, like one ampere, the lead melts and the circuit opens. Fuses, of course, can only be blown once and can't be reused. A fuse is represented on the diagram by the squiggle in the diagram labeled "1A," meaning "one ampere." The electrical standards allow a fuse to be considerably larger than necessary, like 5 amperes and still give adequate protection against shorts.

Switch. The power switch can switch just one side of the line.   Or, it is even safer to switch both sides of the power line at once. The switch should be rated for at least 125 volts AC and 3 amperes.

The transformer

      After the power switch, the line current usually goes to the primary winding of a transformer. The transformer has two functions: first, it isolates your power supply from the household supply and from ground. This makes electrocuting yourself much less likely. As explained earlier, the AC lines supply 120 volts AC referenced to ground. The transformer secondary delivers AC power that has no relation to ground at all.

      For example, I don't recommend actually trying this, but suppose you were to plug a well-designed transformer into a wall socket. And suppose that this transformer has high voltage secondary wires left dangling open circuit: Because of the isolation, you could touch either secondary wire without being shocked, even if your other hand were hanging onto a grounded water pipe. Of course if you touch both high voltage wires simultaneously, they will blast you.
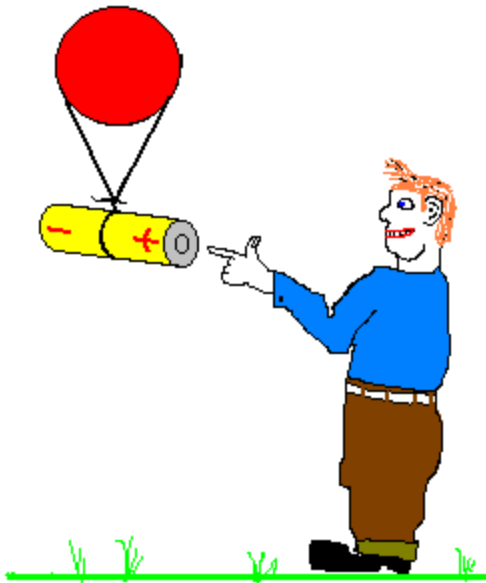
A secondary winding is isolated from ground - like a battery floating in mid-air

      Think of isolation as a battery hanging from a balloon. Electric circuits require a closed loop in order for current to flow. For the dangling battery, the current can only flow from one

end of the battery to the other. There is no relationship to ground. If a person standing on the ground reaches up and touches the battery, no circuit loops are completed, so no current flows.
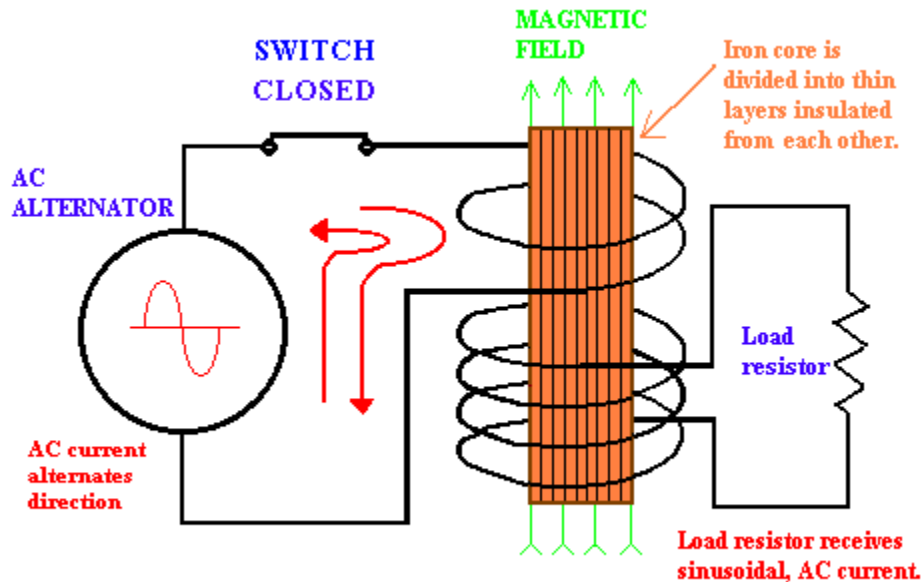
As explained in Chapter 2, transformers can change the ratio of current to voltage in proportion to the number of turns of wire around the core. Transformers are not 100 % efficient. They are made from copper wire that has a significant resistance and iron that dissipates a small amount of energy as heat every time a magnetic field is generated. In general, the larger the transformer, the larger the diameter wire used on the windings, the higher the efficiency will be.

Iron has a severe and abrupt limit on how much magnetic field it can support. Once all the iron has been magnetized, the iron will contribute no more magnetic field, no matter how much more current flows through the primary. Obviously, the larger the iron core, the more energy the iron can pass on to the secondary before the iron saturates. As a general rule, the larger the transformer, the more power it can pass through its windings.

Diode only conducts current in one direction.
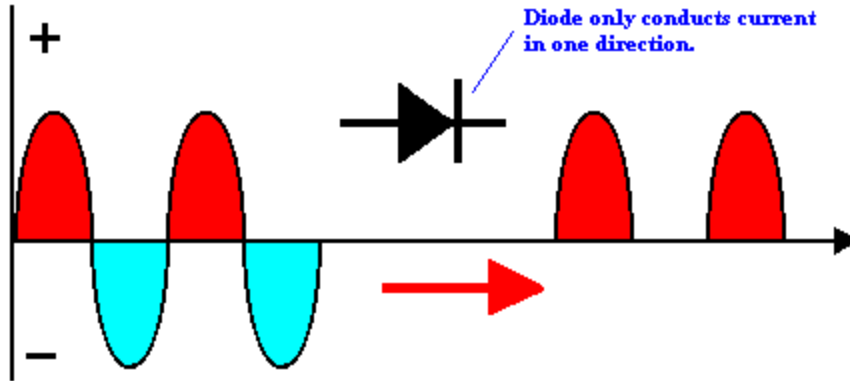
HALF-WAVE RECTIFICATION
(Only one half of wave is exploited.)

Rectification

Most electronic devices require DC voltage to work properly. AC is converted to DC by means of rectifier diodes. Rectifiers are high-power, high-current, high-voltage versions of the diodes used in crystal sets. Referring to the simple power supply shown earlier, the transformer is followed by a rectifier diode. ***The diode only passes positive current flow in the direction of the arrow.*** This means that current leaving the diode is in the form of "humps," or half sine waves. Only half of the sinewave is passed through, so a single diode rectifier is called a "half-wave rectifier." By definition these humps are "DC" since they have only one polarity. Unfortunately, for most electronics applications bumpy, intermittent, sine-wave halves are grossly inadequate. For example, if you use them to power a CW transmitter, your signal will sound like an unpleasant buzz and it will take up 120 Hertz of bandwidth. If you try to run a computer microprocessor on these humps without filtering, the processor will reset 60 times per second.

Peak Volts and RMS volts and DC volts

You may have noticed that sinewaves don't remain at any one voltage, so how are they measured?   If the sinewave reaches peaks of plus 12 volts and minus 12 volts, most of the time the output from the rectifier will be much less than 12 volts. Also, the arithmetic average of any sinewave voltage is zero. Obviously that measurement isn't useful either.

Rules are needed to name sinewave voltage and current. As you might expect, ***peak voltage*** is the voltage difference between zero and the most positive extreme of the waveform. ***Peak-to-peak*** or ***PP*** voltage means the voltage difference between the most negative peak and the highest positive peak.

As you may know, the voltage that comes out of our wall sockets is officially ***120 volts AC RMS***. During my lifetime this same voltage has also been nominally called "110 volts AC," "115 volts AC" and "117 volts AC." Confusing, no? Anyway, the two power wires coming into your house from the power pole out in the alley nominally have 240 volts AC across them. Of course it was formerly called two times 110 volts AC or 220 volts AC. Some people still call it

220 volts. Line voltage is designed so that each of the two wires from the power pole is at 120 volts AC with respect to ground.

As explained in chapter 2, inside your circuit breaker box these two wires are connected to two big metal "buss" bars. There is a third, grounded metal bar that runs down between the two hot buss bars. The individual circuit breakers snap onto these bars like cars on a railroad track. Heavy power circuits for your electric stove and clothes drier clip clear across the tracks to engage both 240 volt lines. Little circuit breakers just clip from one side to the ground bar to give you 120 volts for ordinary, low current circuits.

The **RMS** or **Root Mean Square** of a sinewave voltage (or sinewave current) is the peak voltage divided by the square root of two. Therefore 120 volts RMS is a sinewave with a peak voltage of 1.414 times the RMS voltage. In other words,

120 V RMS x $\sqrt{2}$ = 120 x 1.414 = 169.7 Volts Peak. Therefore, household line voltage could be expressed as *120 Volts RMS, 170 Volts Peak* or *340 Volts Peak-to-Peak*.

Measuring transmitter power with an oscilloscope

To measure the power output of your transmitter into an antenna or a dummy load, you can look at the RF voltage across the load with an oscilloscope. Since RMS power is what we usually use, we need to measure the RMS voltage of a sinewave. You can measure the peak voltage by counting the grid squares on the screen.   Then, to get the RMS voltage, you divide by the square root of two. For example, suppose the RF sinewave on the screen has a peak voltage of 100 volts:

100 volts Peak / $\sqrt{2}$ =   100 volts / 1.414 = 100 volts x 0.707 = 70.7 volts RMS .

Rather than calculating the square root of 2 or its inverse each time, you can save time by remembering the factors 1.414 and 0.707. For example, suppose the RF voltage seen on the oscilloscope screen is 100 volts peak, then the RF power delivered to a 50 ohm antenna or dummy load resistor would be:

Power = I_{RMS} x V_{RMS} = (V_{RMS} / Resistance) x V_{RMS} = (V_{RMS})^2 / Resistance.

In this case, Power output = (70.7 volts RMS)^2 / 50 ohms = 100 watts.

Filter capacitors - filtering out the ripple

The half sinewave bumps, which are properly known as "ripple" must be smoothed out into a continuous DC voltage. This is accomplished by means of a *low pass filter.* In this case low pass means that the filter only passes frequencies well below 60 Hz. DC is of course zero Hertz, which is the lowest frequency there can be. The half-wave rectified supply illustrated earlier is equipped with an L-C "L" filter. "L" filters are simply two-element filters that represent the two legs of the letter "L."

Capacitors conduct AC and prevent the flow of DC. And inductors conduct DC, but resist the flow of AC current. In an effective DC filter, the component values will be huge, like 10 henries and 5,000 microfarads. This is because the frequency we want to filter out, 60 Hz, is extremely low and big components are needed to have an effect on such a slowly changing sinewave.

Bleeder resistor across the capacitor

The purpose of the bleeder resistor across the filter capacitor is to discharge it when the supply is not in use. Remember that high quality capacitors will hold their charge for many hours, sometimes days. Bleeders usually aren't important with a low voltage supply like 12 volts. But if this were a 500 volt supply, a person could get a nasty jolt or burn if they were to touch the capacitor. This can happen even though the supply is no longer turned on or plugged in.

If you were to build the half-wave supply shown earlier and put a l0 watt load on it, with an excellent transformer and a really huge capacitor, perhaps the DC voltage will at least be continuous. However, there will still be a 60 Hz sinewave ripple or waves impressed on top of it. If you used it to power a transmitter, the tone of the Morse code would have a distinct rough sound as the DC level varies at 60 times per second. When hams gave you a signal report they would say that your signal tone was a number much less than 9. For example, they might send "UR RST 595." (RST means Readability, Strength Tone. Hams use a scale of 1 to 5 for readability, and 1 to 9 for both strength and tone.) Because of the harsh note of your tone, you might only rate a "5." For this reason, transmitter power supplies always use dual rectifiers to produce "full wave rectification."

Full wave rectification
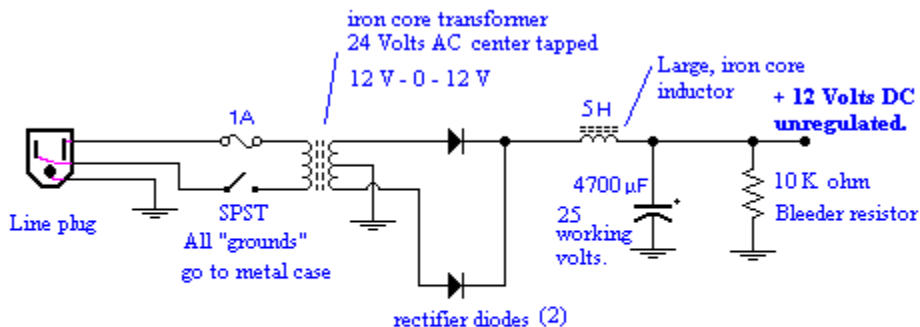
**FULL - WAVE RETIFICATION USING
A TAPPED POWER TRANSFORMER**

Full wave rectifiers convert both halves of the sinewave into useful DC current. The DC voltage is now a succession of "humps" with no "off" intervals. With twice as many "humps" per second, the voltage is much easier to filter. Full wave rectification is a big step toward producing a DC source that resembles the smooth continuous voltage available from a battery.

There are two ways to achieve full wave rectification. The circuit above uses two diodes. What you probably didn't notice at first is that the secondary of the transformer has *TWO* 12 volt RMS AC windings. By having two separate windings, and wiring them in series, one of the windings can be positive at all times. This allows positive current to flow through one of the two diodes at all times and greatly decreases the ripple. Notice that, if we wanted, we could reverse the polarity of the diodes and produce the same waveform with the opposite polarity. That is, if we wanted a *NEGATIVE voltage source* referenced to ground, reversing the diodes would do that.

Bridge rectifiers

Bridge rectifier

AC

Bridge rectifier array vectors current to positive side.

Now all current pulses flow in one direction.
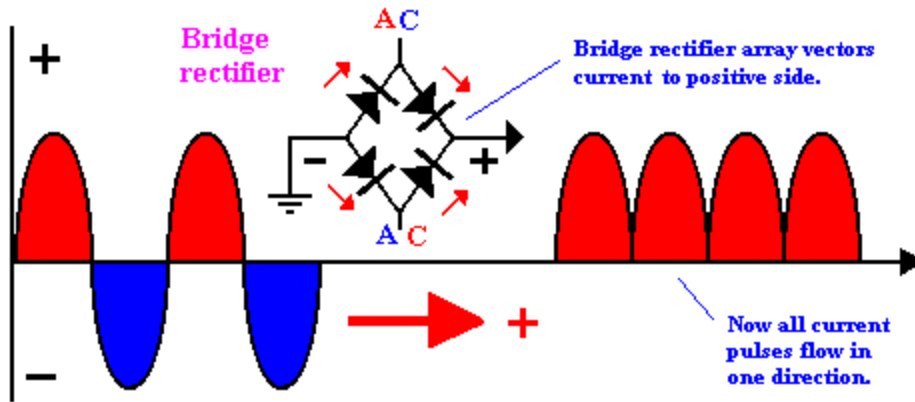
FULL WAVE RECTIFICATION
(Both polarities of sinewave are exploited.)

The second way to achieve full wave rectification is to use a bridge rectifier made from four individual diodes. This configuration allows us to get full wave rectification from a single secondary winding. The four diodes are soldered in a diamond pattern as shown above. The AC voltage source is applied across the top and bottom of the diamond. The two diodes on the right are pointed so that the positive current will always flow to the positive side. The left side is wired to ground and the diodes point in such a way the negative current is always vectored toward ground. To say it another way, the positive current always flows "UP" from ground.

No load = No ripple

Moderate load = moderate ripple

High load = big ripple

Voltage to Capacitor from full wave rectifier.
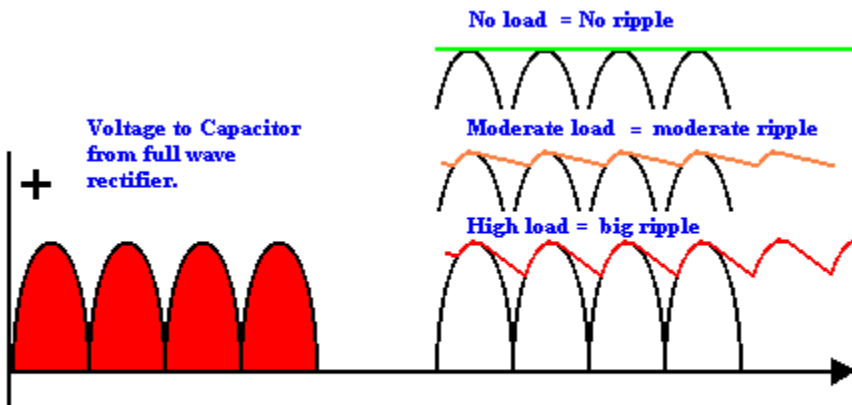
Effect of Load Current on Power Supply Ripple.

Ripple

Because the rectifier is supplying current in the form of "humps," the voltage output across the capacitor will also vary up and down. The capacitance is large, so the voltage doesn't drop to zero during the "valleys," but it can drop fairly low if the current drain from the supply is large. The more current that is sucked out of the capacitor, the lower the voltage "valleys." This variation in voltage is called "ripple." This is illustrated in the drawing above. If the choke is large enough, it will work with the capacitor to smooth out the height of the voltage peaks and

raise the level of the valleys dramatically.

With no load current, output voltage charges to the peak voltage

Notice that, if the power supply is not connected to an external load, the output voltage will rise up to the maximum voltage that comes through the rectifiers. For a 12 volt RMS transformer output winding, this is approximately the square root of two (1.414) multiplied times 12 volt RMS volts, or about 18 volts. Referring to the diagram, with no external load the only load on the capacitor is the tiny one milliampere current passing through the bleeder resistor. This means that the variation in voltage between the humps will be extremely small. In summary, if there is no load on the power supply, to a voltmeter it looks like a "regulated" 18 volt power supply with essentially no ripple. If your 12 volt circuit might be damaged by 18 volts, you must not connect a supply like this to your circuit.

When you first turn it on, the voltage will be 18 volts for a moment before the load current flow is established and the choke and capacitor pull the peak voltage down. RMS (Root Mean Square) refers to the *AVERAGE* voltage of the rectified sine wave "humps." If the output from the big capacitor were fed directly into your QRP without the regulator, the capacitor would charge toward the peak voltage of the "humps." Depending on how much current your QRP was drawing, 18 volts might destroy some of the components in your QRP. As the load on the power supply is increased, the output voltage would drop down toward the rated RMS voltage, 12 volts. As the rated transformer load, say 3 amps, is exceeded, the DC voltage will probably drop below 12 volts.

Power transformer saturation

A second purpose of the choke is to prevent the peak current from the transformer from exceeding the current rating of the transformer. If the choke were not located between the rectifier and the capacitor, the current from the "humps" would only flow into capacitor when the voltage from the rectifiers is higher than the voltage already stored in the capacitor. It is like a tidal pool alongside the ocean. The pool can only fill with water when the tide rises higher than the level of the pool. The result of these pulses of charging current is that the power transformer must provide much more peak current than it may be rated for. If a transformer is rated for, say 10 amperes RMS, and these surges of current are drawn in bursts just a few microseconds long, then the peak current might be 100 amperes. Since the transformer doesn't have enough iron for that, the iron saturates and the transformer inductance collapses. Suddenly, the transformer will act like a few turns of copper wire shorting out the AC source. This causes the windings and the transformer to heat rapidly and perform poorly.

Substituting big chokes with small, cheap resistors

In the real world, most low voltage power supplies like this solve the problem with a cheap resistor instead of a large, expensive iron core inductor. Resistors waste energy, but what the heck! You can use the resistor with an extra-large filter capacitor that costs less and weighs less than a choke with equivalent filter value. Or, as we'll see shortly, a linear voltage regulator can put a load on the capacitor all the time so that the current flow is not just in short bursts.

Regulators

To provide pure DC at a constant voltage over a wide range of load current, you need a

regulated power supply. The regulator's first task is to "trim off" unwanted peak voltage and provide a DC voltage equal to (or similar to) the transformer RMS voltage. Regulators solve the 18 volt over-voltage problem described above. Its second purpose is to maintain constant voltage even when the load resistance is changing continuously or during a line voltage brown out. A regulator circuit is usually added to a power supply like the one above. There are two basic designs for regulators, *linear regulators* and *switching regulators*.

Linear regulators are a sort of automatic variable resistor placed in series with the output of a simple supply like the one we have been discussing. The regulator uses feedback from the load voltage to change the size of the "automatic resistor" and hold the load voltage constant. For example, in the above power supply the regulator input voltage might vary from say 15 to 18 volts, but the regulator would change its resistance to hold the output constant at 12 volts DC. *A linear regulator not only insures that the load voltage is always the same, it also "trims" off the ripple.*

Switching regulators are more complex circuits that usually involve inductors (or transformers) and switching transistors. They start with unregulated DC and turn it back into AC power. This AC power is then passed through a transformer to generate whatever voltage is needed above or below the original DC voltage. In an equivalent method, the unregulated DC is pulsed through an inductor to generate higher or lower voltages. For amateur radio work, switchers usually make radio noise that you will hear in your receiver. Yes, commercial radio equipment often have switchers in their designs, but in my experience, getting rid of the noise is extremely difficult.

In contrast to switching regulators, some switchers just boost the voltage, but don't regulate the output voltage. These are often called "*charge pumps*." The noise from these unregulated charge pumps can be insignificant because they only switch at one frequency and they don't "dither" back and forth trying to hold the output voltage constant. In summary, *regulated switchers are noisy* and I have pretty well given up trying to use them inside ham equipment.

Zener diode regulators

The simplest regulator is a linear regulator made from *Zener diode*. It is "linear" because there are no AC signals involved during the regulation and it works entirely with DC. It dissipates the unwanted voltage as heat. A Zener diode is a modified silicon diode subtly different from the rectifiers used in the power supplies above. Zener diodes are made from silicon that has been doped with extra ions. The extra ions cause the diode to break down at a specific lower reverse voltage when a high reverse voltage is applied. Zener diodes are inferior rectifiers, but when used as regulators, they are quite useful.
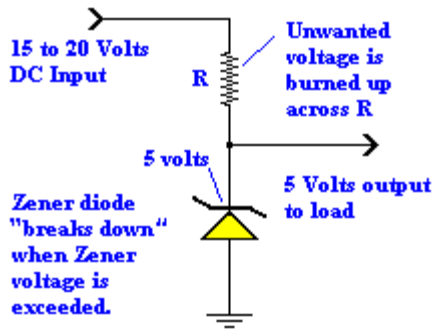
Why ordinary rectifiers don't behave like Zeners

Diodes rectify because the reverse voltage is insufficient to force electrons through the P side of the P-N junction that has no free electrons. However, when enough voltage or "electrical force" is applied, the P-N barrier breaks down in an *avalanche breakdown*. When this breakdown happens at high voltage and high current, the diode (or bipolar transistor) is instantly ruined by the heat. You may remember the homemade crystal diode discussed in chapter 4. When this crude diode was reversed biased, it broke down abruptly at about one volt. At any voltage above 1 volt, it acted like a short circuit and "regulated" the load voltage to one volt. At low voltage levels, such a breakdown doesn't necessarily destroy the diode if the diode doesn't overheat. This *Zener voltage* level can be used as voltage reference.

Doping silicon diodes makes Zeners

When big, tough, modern 400 volt silicon diodes are "doped" with extra ions mixed into the semiconductor, the avalanche can happen at lower voltages anywhere below 400 down to as little as 3 volts. Now because the voltage is low, and presumably the load resistance radically limits the current, the heating in the silicon is low and the diode survives the breakdown. In practice, Zener diodes are available from about 3 to 50 volts. 100 volt Zeners would have to be capable of dissipating a great deal of heat or they would be easily destroyed.

In the circuit above the Zener diode breaks down at 5 volts. If one of these diodes is placed across a load, the Zener diode will clamp the voltage to 5 volts so the voltage across the load never rises above 5 volts. Of course the input voltage must always be higher than 5 volts and the unwanted voltage will be dissipated across the resistor in series with the power supply.

Real versus ideal Zeners

If a Zener diode behaved "perfectly," the voltage across it would be the Zener voltage, no matter how many amperes flowed through the diode. This is illustrated by the green curve in the graph below. Unfortunately, the Zener voltage rises with large currents as shown below on the red curve. Notice that when the Zener diode is wired backwards, it acts like a normal, forward-biased silicon diode. Conduction starts at about 0.6 volts. Real Zeners look like ordinary forward biased silicon diodes. What is called "forward" conduction for a normal diode is called "reverse" conduction for a Zener.

Positive diode current

"Reverse" Zener conducts at -.6 volts like a normal silicon diode.

Zener voltage = + 5 volts.

V input (-)

V input (+)

7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8

Ideal Zener diode would not break down in reverse and would conduct at Zener voltage, regardless of current.

ZENER DIODE VOLTAGE / CURRENT BEHAVIOR

Negative Diode current.
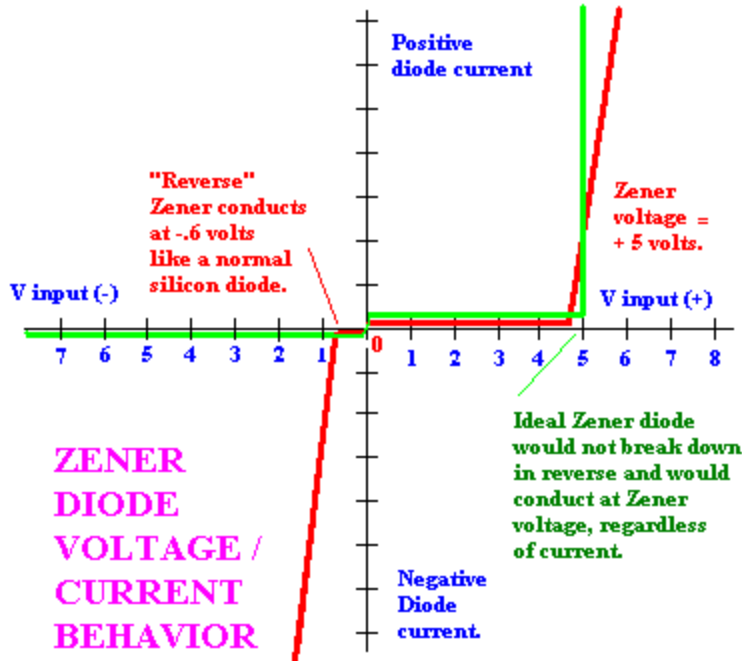
Zener diodes are impractical for heavy current regulation. They not only dissipate energy in the series resistor R, they also burn up energy in the diode. Moreover, as the diode current rises, the Zener voltage can be significantly different from its nominal value. In practice Zener regulation is used for light loads over a narrow range of input voltage. As you will see later, Zeners can be used as **VOLTAGE REFERENCES** to run a transistor regulator. In this way, the regulation can be fairly good and energy isn't wasted. This will be illustrated in an application later in this chapter.

A homebuilt, line-powered power supply for a QRP

Now let's get practical: The 12 volt supply below worked well for me and can be assembled entirely from parts at your local Radio Shack.
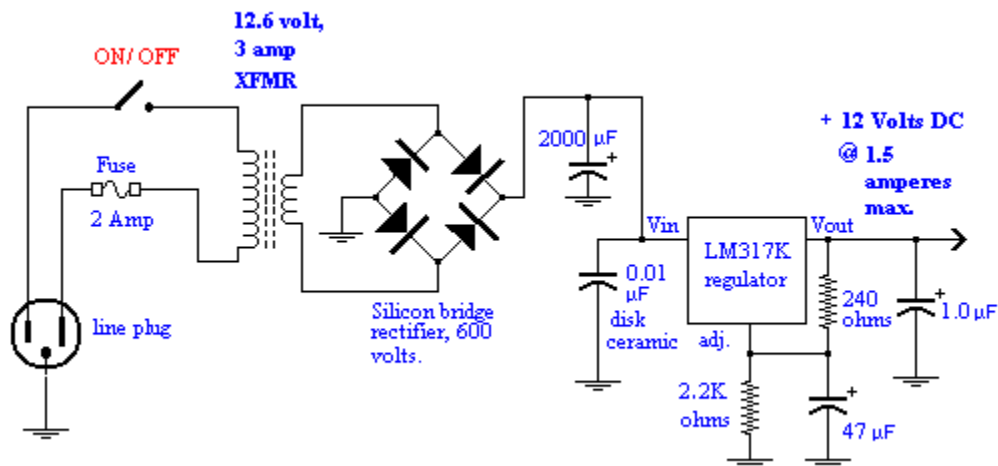
This 18 watt regulated line-powered supply should be built in a metal chassis. The round ground pin from the line cord should be connected to the chassis. In that way, if the "hot" black wire should break and touch the chassis, the metal would not become dangerous to touch. The supply is protected by a 2 to 5 ampere fuse in series with the line input. The ON/OFF switch should be rated for 250 volts DC and at least 1 ampere. The line cord should pass through a grommet on the way into the chassis. Once inside, the line cord should be clamped to the chassis so that, if the power supply is picked up by the cord, the force will be on the clamp and not on the solder joint where the line cord is fastened to the fuse and switch.

The transformer is rated at 12.6 volts RMS at 3 amperes. I used Radio Shack part # 273-1511. The rectifier is a generic silicon bridge rectifier rated for at least 400 volts @ 1 ampere. Alternatively you could use 4 individual rectifiers arranged as shown above. The filter capacitor following the rectifier just needs to be large and greater than about 25 working volts. The other three capacitors serve to stabilize the output and prevent oscillations and ripple.

The LM317K programmable voltage regulator

The LM317K regulator chip is packaged in a TO-3 metal case and can deliver 1.5 amperes. To dissipate the heat, the TO-3 case should be bolted to the metal chassis and insulated by means of a mica washer and silicon grease. Mounting kits for this purpose are also available at Radio Shack. This regulator chip works by regulating the voltage between the V_{out} and the "adjustment" lead on the regulator. The regulator regulates this voltage difference to 1.2 volts. This low voltage allows the designer to regulate voltages equal to or higher than 1.2 volts. In this 12 volt application, the regulator passes current through a 240 ohm resistor and regulates the voltage across the 240 ohm resistor to 1.2 volts. This results in a "current source" that drives a regulated current through the 2.2K resistor to ground. This increases the total regulated output voltage from 1.2 up to 12 volts. That is, 240 ohms is about 10% of the sum of 240 ohms plus 2200 ohms. Because you can "program" the total regulated voltage, this same regulator can be used to regulate voltages from 1.2 volts up to about 20 volts.

Another reason you need good voltage regulation is that the tuned stages in your QRP don't take kindly to changing the supply voltage. If you tune up the antenna using 12 volts, and the voltage later goes up or down, the tuning of some stages may change slightly and your signal might crash in the middle of a QSO (conversation).

The LM317K "clips off" any voltage above 12 volts so your QRP will never see a higher voltage. Notice that the LM317K is a *linear regulator*. This means that it turns any input voltage that is above the regulation voltage into heat. This seems wasteful, but linear regulation makes no radio noise and produces a flat output voltage with practically no ripple. Notice that the choke is not necessary here because the regulator is drawing current from the capacitor nearly all the time. This means that the current is flowing from the transformer nearly all of the time and will not be saturated by high current pulses.

This power supply violates my goal to never use integrated circuits. If there are purists who share my aversion to integrated circuits, the "low dropout" regulator shown below can be substituted for the LM317K regulator. A larger power supply than this would be more versatile and could power a bigger transmitter. Obviously, the higher the power level, the more cumbersome the regulation becomes. Running a 100 watt transmitter requires a 300 watt regulated power supply. I sidestepped this project by running my entire ham station on a solar-

charged 12 volt battery which is described later in this chapter.

A low dropout voltage regulator for use with a battery

As you will read shortly, a lead-acid golf-cart battery makes a fine, high-current 12 volt power supply. Unfortunately, running your transmitter on batteries means that, when the battery is ready to be recharged, its voltage will drop down to 11 or even 10.5 volts. This means that (ideally) your QRP must be tuned up to run on 10.5 or 11 volts and then regulated to that level. Remember that *a linear regulator can only deliver LESS than its input voltage*. So if you're running on a 12 volt battery, you need a regulator that wastes as little voltage as possible. This waste voltage is called *dropout.* The regulator shown below receives nominal 12 volts from a battery. The active regulation element is a big P-channel MOSFET transistor. This transistor can be arbitrarily large. The bigger it is, the less voltage it will waste and the lower the "drop out."
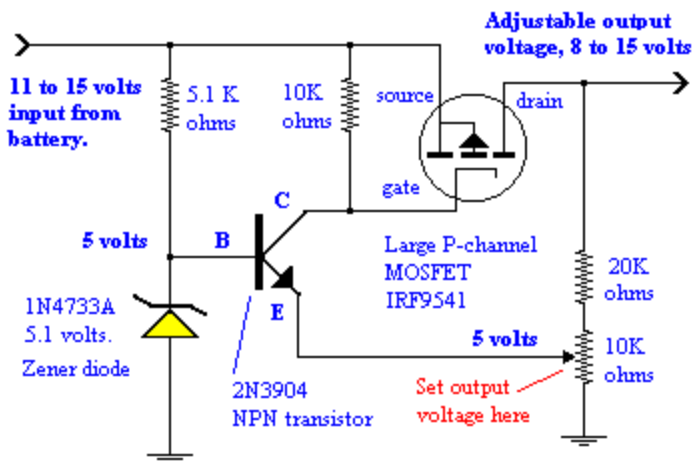
Low Dropout 12 Volt Power Supply

The P-channel MOSFET transistor turns on (conducts current) when its gate voltage is pulled downward toward ground. So when the battery voltage drops, the gate voltage must be pulled down (toward zero volts) to turn the MOSFET more on. When the battery input voltage rises, the gate voltage must be raised to turn the transistor more off and restore the output set voltage.

The gate voltage control is done with an NPN bipolar transistor. The transistor compares the reference voltage across a 5 volt Zener with a fraction of the output voltage across the sense resistor pot on the lower right. The slider on the sense resistor contacts the resistance at a level that produces about 0.6 volts less than 5 volts. As the output voltage rises, the voltage on the sense resistor rises. This in turn increases the transistor emitter voltage. The difference in voltage between the base and emitter drops, causing the drive to the NPN transistor to drop. As the NPN transistor turns more off, the gate voltage on the MOSFET rises toward the battery voltage and turns off the MOSFET and lowers the regulated output voltage.

Regulator Performance

Regulation set to 9 volts @ 300 mA load.
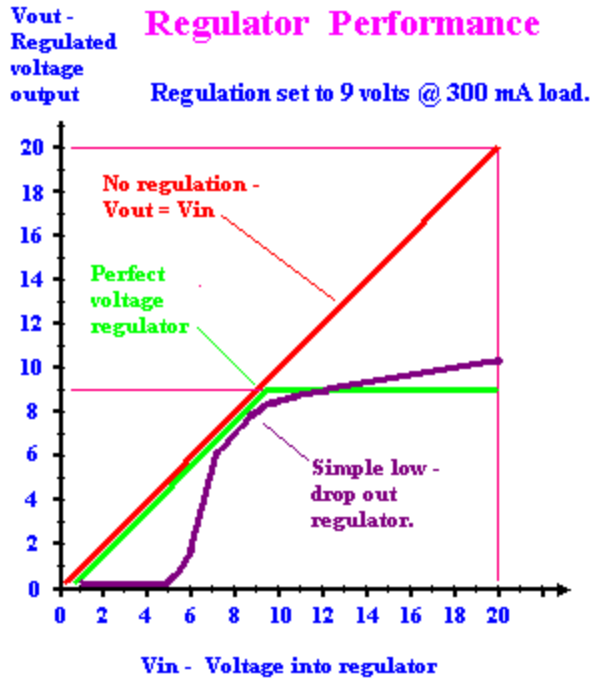
The purple plot above shows the performance of this simple power supply when it has been set to 9 volts with a 300 milliampere load. The red line shows the voltage the load would receive if there were no regulation. That is, Vin = Vout. The green line illustrates the performance of an ideal or perfect linear regulator. If the transistors had infinite gain and the Zener diode always produced precisely the same reference output voltage, then the green curve is what you would get. As soon as the regulator is given 9 volts input, it would deliver exactly nine volts, no matter what the load was. As you can see, the simple regulator isn't radically different from ideal, but it is much less then perfect.

A precision, temperature-compensated, low-dropout regulator

Near perfect regulation can be achieved by replacing the NPN transistor with an operational amplifier. Operation amplifiers, op-amps, are integrated circuits composed of many or even dozens of transistors. Op-amps perform as though they were nearly perfect transistors. Similarly the LM336 voltage reference is an integrated circuit made from bunches of transistors that perform as though they were a nearly "perfect" Zener diode. As the voltage across the regulator is varied, the voltage across the Zener remains constant within a couple thousandths of a volt.
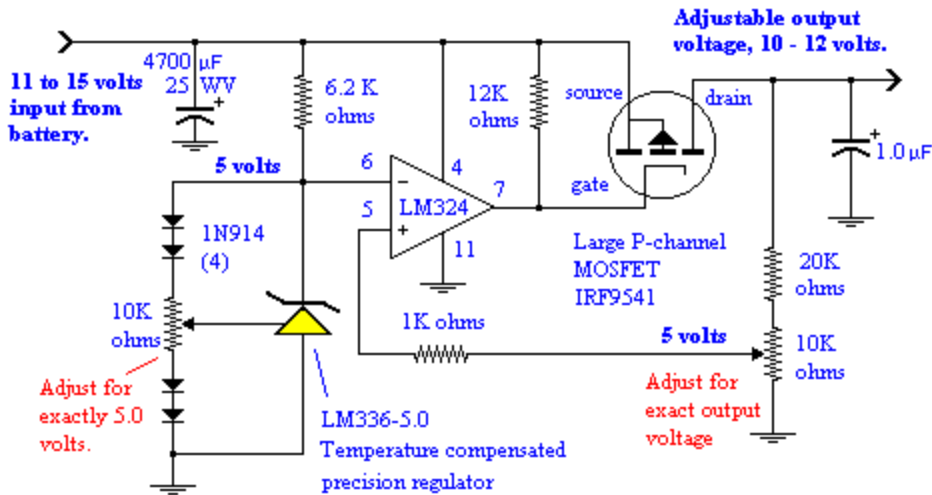
The op-amp is the triangle in the center. This op-amp has 14 pins and the numbers shown are the pin numbers. This particular chip contains four op-amps. Only one is used in this circuit. Pins 6 and 5 are the inputs. The function of the input pins is that the op-amp changes the output voltage (pin 7) to "try" to keep the two input pins at the same voltage. That is, so long as the voltage on pin 6 is identical to the voltage on pin 5, the output remains constant. When the **positive** pin 5 has a higher voltage than the **negative** pin 6, the output pin will shoot positive as high as it can go. When the negative pin 6 is higher than pin 5, the output pin will zoom negative as low as it can go.

Unlike simple transistors, the op-amp has nearly infinite current gain. Gains like 100,000 or a million are common. Also, the inputs draw no current. They have nearly infinitely high input resistance. This means that op-amps are ideal to "monitor" some condition, like the output voltage from the power supply and then change the OP-AMP output pin voltage in order to restore the supply to equilibrium. Looking at the diagram, pin 6, the negative input, always rests at 5.00 volts, so long as the battery voltage input is at least 5 volts. The output voltage pot at the lower right is adjusted to produce the desired output voltage. The big MOSFET transistor will remain turned on to the exact degree to deliver the voltage you set. This set point is the place where 5 volts appears on the pot. As soon as the op-amp "sees" that pins 5 and 6 have the same voltage, the output voltage on pin 7 holds still and stops changing.

A precision Zener diode

The LM336 precision Zener diode is not only extremely accurate, it will maintain its accuracy over a wide temperature range. Speaking of temperature change, don't forget to bolt your MOSFET to a big heat sink. At high input voltages and big load currents, you may expect the MOSFET to get boiling hot without a heat sink. Keeping it cool improves its regulation. The metal flange on the transistor should be insulated from the heat sink and metal chassis with a mica insulator and silicon grease.

As we shall see in chapter 10, building a variable frequency oscillator that reaches modern standards of frequency drift requires the use of a super-regulated power supply. This in turn requires regulators made from integrated circuits. Sigh. Of course you could prove me wrong by building one with discrete parts.

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BATTERIES AS A POWER SUPPLY

The beauty of batteries

As I mentioned earlier, I run my whole station on solar power stored in a 12 volt battery. You're probably thinking, "Yeah. And I'll bet he voted for Ralph Nader." Now I know this sounds like pinko, tree-hugging, liberal silliness, but my solar powered station came about quite logically and has many advantages for a homebuilt station. There are lots of hams who do this - and no wonder! A lead acid storage battery is a wonderful power supply. It puts out huge currents whenever you need them and the voltage regulation is excellent. The best advantages are that batteries make no switching power supply RF noise and there's no waste heat from a big linear regulator.

My return to ham radio began 5 years ago when I hauled my 1967 homebuilt mobile ham rig down from the attic and blew off the dust. Since my old mobile rig runs on 12 volts, I couldn't even try out the receiver without a heavy-duty 12 volt power supply. I considered building or buying a supply but after 10 seconds I decided that was ridiculous. I happened to have some 6 volt golf cart batteries in the garage. I hauled two of them down to the basement and put on an automotive 12 volt trickle charger. After a day, the batteries recovered and I could fire up the rig. AM phone was extinct, but there was nothing to stop me from getting on CW, which I did with good success. Well, that's not quite true. My adventures included a drifting VFO and a blown 200 watt charge-pump switcher, but those problems had nothing to do with the power source.

My old vacuum tube rig was a power hog. The receiver drew 3.5 amperes at 12 volts. That's 42 watts just to listen! The transmitter was much worse, of course, but it isn't dramatically worse than a transistorized rig. After all, a transmitter can't radiate big power if it doesn't draw big power. Moreover, a modern, linear, class A transistor rig can be even more inefficient than an old Class C vacuum tube transmitter. Either way, my transmitters draw 6 to 18 amperes.

Compared to a golf cart or an automobile starter motor, a ham rig is a low power device. 20 amperes should be plenty of current. A deep discharge storage battery is best, but there's no reason you can't use an old car battery. We all routinely discard car batteries when they can no longer supply 400 amperes on a January morning. But even an old car battery will usually supply 20 amperes for five minutes without appreciable voltage drop. All you need to do is keep a small, one-ampere charger on it continuously. For anyone on a budget, a free used battery is a darn cheap high current regulated supply.

**Requirements of a line-powered 20 ampere, 12 volt supply**

I don't plan to build an equivalent line-powered power supply. But if I did, I believe the

best way to get rid of the AC ripple in a high current supply is an optimum combination of a big, linear regulator and a bunch of capacitors. Come to think of it, the battery behaves just like a giant linear regulator with huge capacitors.

I've had zero luck running ham equipment on switching regulated power supplies. If the switcher isn't just functioning as an asynchronous charge pump, but actually regulates the output voltage, then the switcher will make RF noise which you'll hear in your receiver. When powering transmitters, I found that the switcher and the RF amplifier stages "talked to each other." That is, when the load increased, the supply increased the pulse width modulation to compensate, but not without a slight delay. This subtle ripple or "jitter" was hard to see on a scope, but no matter how much I filtered it, the jitter appeared as a slightly rough note on a CW signal. In practical terms, I kept getting 598 RST reports. There was an elaborate 12 volt switcher in QEX magazine a few years ago that solved the "talking problem." I was delighted to see that I wasn't the only one who has noticed "talking." The problem is real, but after seeing the Rube Goldberg solutions, my desire to build one has vanished.

Going solar

Because my trickle charger was feeble, I was charging non-stop. Even then, I was having trouble keeping the battery charged for a couple hours of daily operating. However, I already owned a 12 watt, 12 volt solar panel which I installed on the roof.
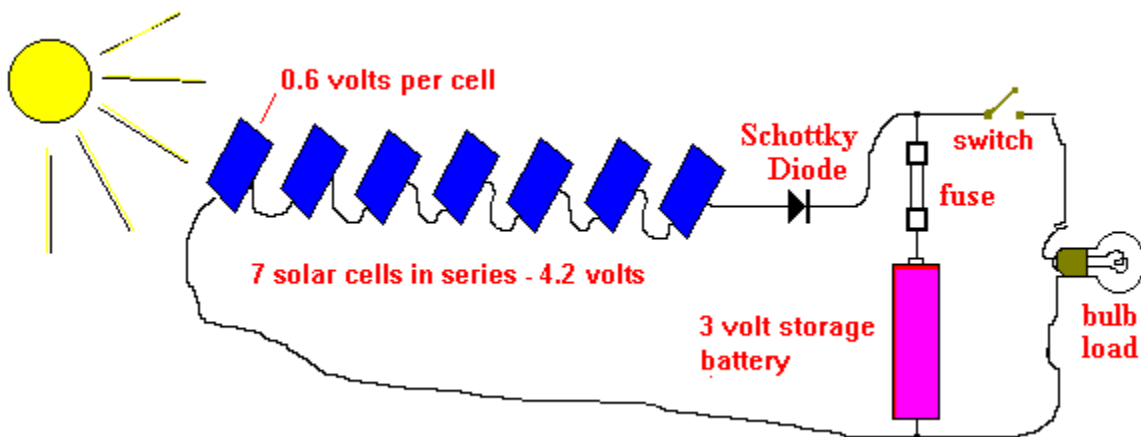
A simple solar charger circuit

Solar cells are a kind of silicon diode. They are arranged in series so that the forward voltage drop of each diode adds up to some voltage greater than the voltage of the storage battery. For example, at 0.6 volts per solar cell, we need at least 20 cells in series to raise the panel voltage higher than the 12 volt battery. Typically, an open circuited panel puts out 20 volts in bright sunshine. This extra capability insures that it will continue to charge a 12 volt battery all day and implies that there are roughly thirty 0.6 volt cells in series. Solar cells are interesting to play with. I was surprised to discover that if you put your hand over just one of the series cells, it turns off the whole string, something like Christmas tree lights wired in series. This means that just one wet leaf stuck on your panel can turn off the whole array.

The panel output current is proportional to the sine of the angle the sunlight makes with

the panel. If your object is to produce the maximum kilowatt-hours averaged over the entire year, then the angle should equal the latitude. I mounted my panel at 45°, which at 40° latitude, gives me better performance during the winter. Optimizing for winter is smart because the days are short and the panel is often covered with snow. Actually 50° may be better here in Boulder. Snow slides off a steep incline and higher angles are more resistant to hail damage. On the other hand, mounting them on a steep frame may make them subject to wind damage. There is no way to win. Many people just mount the panels flat on whatever roof they happen to have. If you want to sacrifice some percentage of the output for beauty or mounting convenience, that's your decision.

The "lunar discharger"

It's bad form to connect a solar panel directly to a storage battery. The solar cells are forward biased diodes with respect to the battery. Therefore, whenever the sunlight quits, the panel voltage may drop below the battery voltage and battery current will reverse and flow through the solar panel. In other words, at night, the solar charger becomes a "lunar discharger." (Never mind.) If there are enough extra solar cells, then the night-time voltage drop may still exceed the battery voltage. Anyway, the discharge problem is typically prevented by a silicon diode in series with the panel to insure that current is never allowed to flow from the battery back into the panel. Since this check valve diode has a forward voltage drop that wastes energy, you may as well use a big Schottky diode that will only penalize you with 0.2 volts instead of 0.6 volts loss.

Another wise precaution is a fuse in series with battery string. This will limit the current to some practical limit such as 30 amperes. Without a fuse, a short circuit could draw literally hundreds of amps and cause melted wires or even light fires.

Another small issue is lightning protection. My panel is on the roof where, in theory, it might attract a bolt. I'm not really worried, but I have a connector on the lead from the panel so I can disconnect it from my shack when I go away on trips or when a storm is particularly frightening.

Solar panel on the roof

Conservation helps too

My solar panel charges about as much as the line-powered trickle charger, about 1 ampere. Consequently I still had to use line power to charge occasionally whenever I stayed on the air too long. A breakthrough came when I built a new transistorized receiver. The new receiver draws 120 mA. That sure beats 3,500 mA. Since then, I haven't needed my line-powered charger.

12 Volt power distribution

A storage battery can deliver hundreds of amperes, so it's wise to isolate the battery from your rig and solar panel with an appropriate fuse. 30 amperes should be about right. I have a master switch to isolate the battery from the ham rig when I'm not using it. A little LED pilot light tells me when it's connected and a voltmeter warns me if the battery is not fit for use. I also have charging and discharging ammeters (ampere meters) so I know the status of my supply at all times. I find the discharge meter helpful for monitoring my transmitters. You can even tune the antenna while watching the battery current. For fun I also have a small 12 volt lamp for emergency lighting.

Maintaining clean battery contacts is critical to keeping the supply voltage constant under load. Every few months, I clean the contacts and top off the batteries with distilled water. I can tell that the battery contacts need cleaning whenever the pilot light on my transmitter begins to dim significantly while I'm transmitting. A gel-cell battery shouldn't have these corrosion and fluid loss problems.

In summary, I get a kick out of operating like a fully solar-powered field day station. Because the whole station runs on 12 volts, in theory I'm always ready for field day and there's nothing to stop me from going mobile. One of my back-to-nature dreams is that, during a power failure, I can go right on operating and thumb my nose at the evil corporate power monopoly.

Twice during power failures I have galloped downstairs in the dark to make my first 100% truly independent radio contact. But before I could even tune the transmitter, the *#@%!$ lights came back on. Oh, curse those efficient fellows at Public Service!

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LED THERE BE LIGHT

Emergency Station Lighting

As I explained above, I run my whole station on solar energy stored in a 12 volt battery. An advantage of battery power is that I operate free from the power grid. This saves very little money, but it's quite romantic. Of course at night, even on batteries I need to keep a log and throw the correct switches. Using candles or a flashlight clenched in my teeth didn't seem very sophisticated.

My first idea was to dangle a 12 volt automotive light bulb over my shack. My buddy Bob, NØRN, uses such a light in his tent on Field Day. This solution is completely practical, but it seemed old-tech and boring. It also draws about 10 watts of power. If I am going to all the trouble to build a custom 12 volt light, I figured it should at least be **_an interesting light_**. Modern lighting methods produce more light per watt than tungsten bulbs. Also, energy conservation is important if your station is powered by a battery charged with a small solar panel.

A homebrew LED and flourescent station lamp

White LEDs – a modern marvel.

I happened to notice some "white LEDs" for sale down at Radio Shack. (Part # 276-320) I thought cynically, "I'll bet they're really dim and not really white." I bought one and hooked it to a variable power supply. I slowly turned up the voltage until I obtained the rated 20 mA DC current. Hey! Not bad! The beam of white light has a slightly bluish cast, but otherwise, it

throws a spot of light out to a couple feet. It's rated at 1100 mcd. That's impressive brightness when you consider its beam angle is 100°. One LED makes a perfect key chain light and many tiny LED flashlights are on the market.
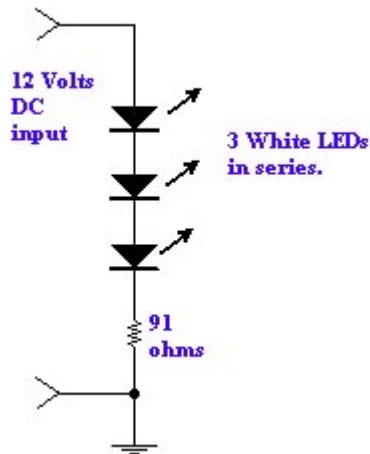
I'm told these white LEDs are made from sophisticated layers consisting of yellow and blue LEDs and a phosphorous that glows white. As LEDs go, it has a rather high voltage drop, 3.6 volts. I figured if I put three in series plus a single dropping resistor, it could run on 12 volts. The current is limited with just one 91 ohm resistor. The resulting triple light consumes just 0.25 watts and is adequate for keeping a log and operating the station. That's amazing when you think about it. We routinely squander hundreds of watts to illuminate entire rooms when all we really need is ¼ watt to read our newspaper or book.

Flourescent lighting

Unfortunately, "adequate" isn't the same as "comfortably bright." So my next project was to build a 12 volt powered compact fluorescent. I fiddled for a couple hours trying to build a power oscillator capable of producing the required 800 Volts AC needed to ignite the miniature fluorescent bulb. I had several transformer and switching transistor problems and solutions did not present themselves. I also fried my voltmeter because I forgot to change the range when I put it on the high voltage. There's nothing like dead test gear to make you think differently!

I remembered that I had still a 6 volt fluorescent lamp that I used to use for lighting my pup tent while camping. One day I rolled up the tent while the light was still hanging from the tent ceiling. Oops! The plastic housing was splintered and the remains of the light assembly were now in my junk box. I found the parts of the light and resoldered the broken wires. I connected it to a 6 volt power supply and it still worked fine. Next I built a shiny reflector/lampshade out of sheet aluminum and it produced loads of light. Unfortunately, I need a 12 volt light, not a 6 volt light. I didn't have a second light to put in series with the first, so I used a big dropping resistor to run the light on 12 volts. That worked OK, but it seemed pretty crude. Besides, I was already "cheating" because I hadn't built the fluorescent high voltage supply and I pride myself on claiming to have a "100% homebrew station."

Nifty "buck-type" switching power supply

I replaced the dropping resistor with a switching power supply to reduce 12 volts DC down to 6 volts. I got the design from the National Semiconductor data book. Using the switcher the fluorescent light draws about 2.5 watts at 12 volts. The switcher is about 80% efficient. That is, it dissipates 20% of the total energy. In contrast a resistor would have dissipated 50% of my energy. I have used this little supply design for several home projects so far and found it thoroughly reliable. If you're a homebuilder, this simple, buck-switcher belongs in your bag of tricks. If you're bored with building a 12 volt light, maybe this little switcher will turn you on.

STEPDOWN SWITCHING POWER SUPPLY

(12 Volt DC to 6 Volt DC Converter)
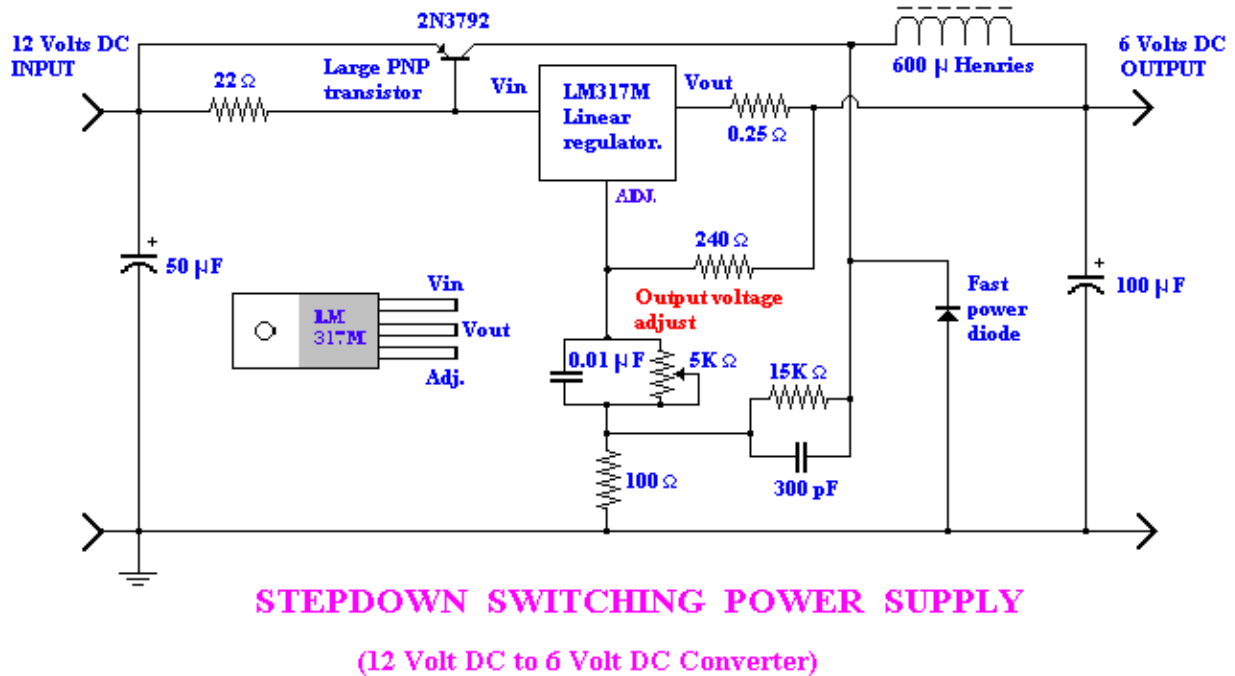
Switching power supply made from a linear regulator.

How can this work?

This switcher uses a LINEAR regulator to generate the pulsewidth modulation needed to implement a switching power supply. This is the same linear regulator used in the suggested line-powered QRP power supply. I'll bet if I had invented this concept, it wouldn't have worked worth a hoot. But, when you put a scope probe on the inductor, sure enough! The linear regulator is switching full on and off in rectangular pulses. Apparently the 15K Ω resistor and 300 pF capacitor are coupling a feedback pulse into the regulator to cause it to switch full on and full off. The pulse width varies with load and responds just like a real switcher. Aside from my amazement that linear regulators can work as switchers, I was also surprised that I hear very little switcher noise in my receiver. The RF noise it produces is apparently sufficiently isolated from the receiver that I rarely hear hash in the receiver. On the rare occasions when I do hear it, I just turn off the fluorescent.

Subjectively, the fluorescent produces roughly twice as much light as the LEDs. In other words, for ten times as much power the light seems to be twice as bright. On the other hand, it

illuminates a much wider area than the LEDs, so I just run both of them simultaneously. The LEDs illuminate my log and scratch pad while the fluorescent lights up the station as a whole. I've used this light for hours at a time. It's bright enough that I'm content with it and I don't think about running across the room to turn on "the real lights." In summary, battery power and energy conservation are fun games. And, if we're really unlucky, someday our hobbies might even be useful in a community crisis.

CRYSTAL SETS TO SIDEBAND
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Chapter 9
ACCESSORIES

A MORSE CODE KEY

"Straight keys"

A simple telegraph key.

A telegraph key for sending Morse code is an easy mechanical project. All that's needed is a reliable spring-loaded switch. The fingers contact a simple knob on a lever. The operator rests his wrist and forearm on the table and grips the knob with two fingers and a thumb. The operator pushes down on the knob, closing the switch contacts. A "straight" key like this is used to send both dots and dashes. The timing of the dots and dashes is totally dependent on the operator. No timers or computer chips are used to form the dots and dashes.

Commercial straight keys, especially the old ones, are made from elegant machined brass parts and springs on engraved Bakelite plates. The exact tension and gap width can be adjusted to each operator's preference. This sophistication is nice, but not essential for a beginner sending at low speeds. A straight key is good for code speed up to about 15 words per minute. Faster speeds are tiring and hard to send well.

The straight key shown above was made from two pieces of single-sided printed circuit board. The upper sender lever board serves as the spring and its underside is the conductive surface. The switch contact consists of a machine screw that touches the grounded lower board when the lever is pushed down. Two nuts on the screw adjust the contact distance. Most operators like to adjust the switch contacts so that the travel is about 1/32 inch. The spring action of the lever should be strong enough so that it breaks the contact sharply when the lever is released, but not so much force that it is tiring to use. The two pieces of circuit board are insulated from each other by a small block of plywood. The knob is a plastic pull knob from a

drawer.

Several articles in QST have appeared in recent years describing how to make keys out of household junk. Most of these keys are really "paddles," rather than straight keys. Paddles are keys that they are pressed side-to-side instead of just downward. Paddles have two switch contacts and are used to control automatic keyers of the type found in modern transceivers. When the paddle is pushed left, the keyer automatically generates perfect dots. When the paddle is pushed right, the keyer pauses the exact length of time, then automatically makes perfect dashes. It would not be hard to adapt the mechanisms described in those magazine articles to make a "straight," up-and-down key.

Mechanical bugs

No, we're not talking about a mechanical glitch, we're talking about a type of telegraph key. The next step up in sophistication from a straight key is a mechanical ***"bug."*** This telegraph key is activated with a paddle. When pushed left, it automatically makes dots, so long as the operator deflects the paddle. Mechanical bugs make the dots with a spring-loaded, weighted beam that swings back and forth. A dot occurs whenever the swinging lever closes the "dot switch." When the bug paddle is pushed to the right, it closes the "dash switch." The operator must make each dash manually. So unlike a modern keyer, the operator provides the timing for dashes. Mechanical bugs like this were standard among commercial radio-telegraph operators and hams for many years. Even railroad telegraph operators often used them.

You can still buy commercial mechanical bugs. At one time there were even versions that generated both dots and dashes automatically. A mechanical bug is a difficult basement project without a machine shop. It requires a great deal of patience to make a reliable mechanical bug, but it can be done.

Homebrew electronic keyers with automatic dots and dashes are a common homebrew project. Most hams just buy a keyer kit that has a tiny, pre-programmed "PIC" microcomputer chip that does all the difficult timing chores. Since a pre-programmed chip didn't fit my rules for "homebuilt," I built a homebuilt electronic bug that makes automatic dots but requires manual dashes.

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A HOMEBREW ELECTRONIC BUG

No matter how I adjusted the screws and cleaned the burned contacts on my 40 year old mechanical bug, the dots sounded more like static. Of course, if I had bought a quality bug in the first place, it would still be working. While I was trying to get the old bug working, it occurred to me that my key was the only part of my rig that wasn't homebrew. Ah ha! - a challenge!

I didn't see how I could build a decent mechanical bug with my limited tools. However, I figured that an all-electronic key that generated both dots and dashes automatically couldn't be too hard. I began prototyping a logic circuit based key on a large plug-in board. I quickly discovered that implementing automatic dashes wasn't so simple. The dashes had to be timed with respect to the dots and there could be no overlap. Moreover, the spaces between dots and dashes should be enforced regardless of how inept the operator might be. I soon had about 20 CMOS ICs wired in a complex mess of logic circuits that nearly worked. But no matter how

many more gates I added, I always seemed to have glitches. This was getting frustrating. Also, my new key was going to end up as a foot-long circuit board. I lowered my sights to building a simple electronic bug built with op-amp oscillators. The new key would have automatic dots, but manual dashes. In other words, it would the electronic equivalent of a mechanical bug.


A homebrew electronic bug.

The mechanical parts

The mechanical requirement was to make two momentary-contact, spring-loaded switches controlled by a single paddle. I suppose I could have used printed circuit board switches like the straight key discussed earlier. However, my solution was to use two miniature, push-button momentary switches. The switches can provide both the switching and spring action. I mounted them on opposite sides of a piece of aluminum channel so that the buttons face each other. The back of the plastic paddle arm rests between the two buttons and pushes one or the other as needed. I cut out the paddle from a plastic sheet that I bought at a local plastics shop. By the way, scrap plastic is a great resource for material to make antenna insulators, stand-offs, boxes, etc.

The bug is packaged in a commercial aluminum box and mounted on a thick aluminum plate. I glued a piece of sticky rubber from an old mouse pad onto the bottom to prevent sliding from side to side.

After I got my bug working, I had trouble sending accurately. That is, I kept sending extra dots or half-formed dots. The biggest problem turned out to be insufficient return spring force. I supplemented the spring force of my button switches with coil springs that I stuffed into the aluminum channel on both sides of the plastic paddle. Afterwards I was surprised how much easier it was to send good code. Also, the key kept sliding on the table so I screwed metal "railings" to my tabletop to confine the key. The key continued to creep away from me so finally I just screwed it down to the table. Now I can bang away and the key stays put. Good sending is just plain hard. Any advantage you can give yourself is worth doing.

The electronic parts
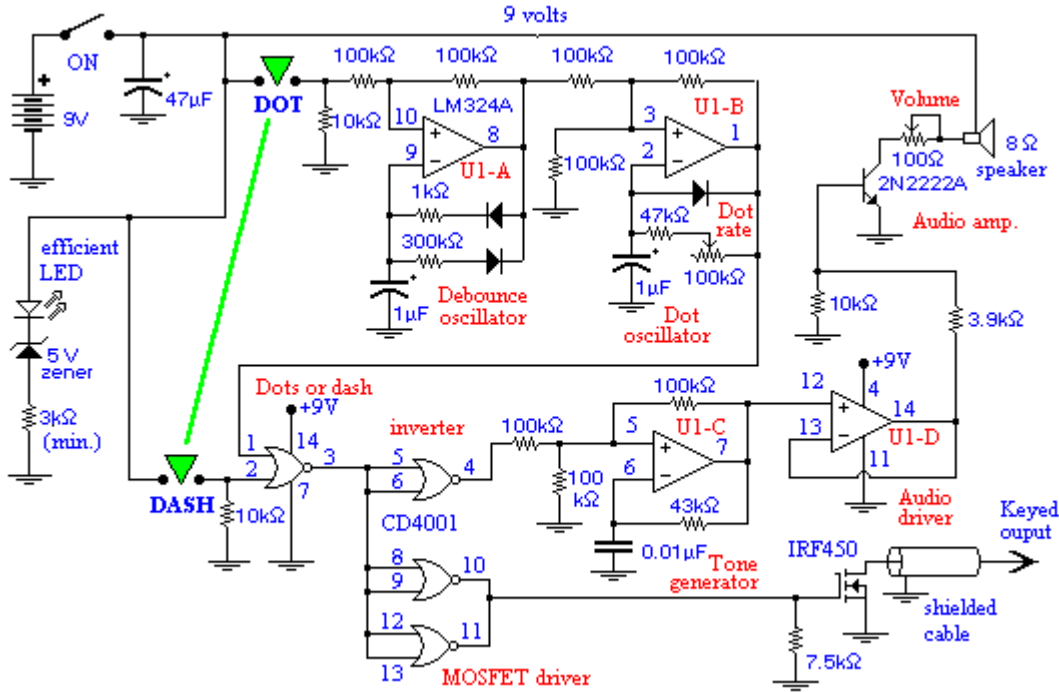
Circuit Diagram for the Bug.

My bug has two unusual features. It has a **built-in sounder** and it can **key any positive voltage to ground up to 400 volts.** The transistor that does the actual keying is a 400 volt N-channel MOSFET power transistor. I built the bug while I was still using a vacuum tube transmitter with a 6146 final. There was positive 300 volts cathode voltage on the key, so I needed high voltage capability. A keying relay would have worked, but I wanted to escape from mechanical contacts. The IRF450 N-channel MOSFET transistor handles any positive signal from 5 volt logic up to several amperes at high voltage. Of course you may use whatever size MOSFET is appropriate for your transmitter.

The built-in sounder consists of a small speaker and an audio oscillator. When I was on the air, I used to listen to my own signal in the receiver. Unfortunately the sound from my receiver was distorted from the transmitter being so close. The distortion led to poor sending. Too much coffee may have been another reason. Anyway, by listening to clean tones from the sounder, my "fist" is likely to be as good as it can be. The sounder can also be used as a stand-alone code practice sender.

My rig is more primitive than commercial transceivers. I still have to turn on the transmitter and mute the receiver manually. To do this more quickly, I installed a small toggle switch on the bug just to the right of the key paddle. The switch is just a contact to ground. Shielded leads connect the switch to both the transmitter and receiver. The ground lead triggers the Transmit-Receive relay in the transmitter and sets the receiver power supply to standby. It isn't exactly "break-in keying," but it's OK for the time being.

Circuit Description

The bug runs on a 9 volt alkaline battery turned on by a small toggle switch. A red LED reminds me to turn it off. When it's time to change the battery, a 5 volt Zener diode in series

with the LED makes the LED dim when the voltage gets down to about 6 volts. When not sending, the bug draws 1.2 milliamperes. This means the 550 milliampere-hour alkaline 9 volt battery will last over two weeks if I forget to turn it off.

All oscillators in the circuit are implemented with an LM324 quad op-amp. The LM324 is a great old component. It doesn't work at high frequencies like modern op-amps, but that can be a good thing because it doesn't oscillate unexpectedly. And unlike nearly all the old op-amps, such as LM458, LM741 or LM301, the LM324 almost always acts like an "ideal op-amp." It only needs one supply voltage and it rarely surprises you with "practical limitations."

It's necessary to "debounce" the dot key. First I just tried turning on the dot-generating oscillator with the dot switch. Because my timing wasn't always matched to the oscillator speed, and because the contacts didn't always close solidly, the dots often sputtered like my old bug. Referring to the circuit diagram, the dot switch now keys a multivibrator (U1-A). This generates a narrow, repeating pulse that sets the maximum dot rate. The actual dots are formed by a second op-amp multivibrator, (U1-B). The pulses from (U1-A) start a new dot, provided that the second oscillator, (U1-B), is ready to start one. The dot rate is adjustable over a wide range using the 100K pot.

The logic circuitry is implemented with 1970s era CMOS 4000 series logic gates. These old parts are immune to interference from RF and tolerate up to 18 volts peak. Modern CMOS is limited to lower voltages and is designed for performing logic at high speed. High speed isn't needed here and just makes the chips vulnerable to interference and self-oscillation.

The dots and dashes are combined with a CMOS 4001 NOR gate to make a single keying signal. That is, the NOR gate puts out an output if either a "dot" or a "dash" is present. Two more NOR gates serve as a signal polarity inverter and driver for the keying transistor and for the audio oscillator. The NOR gate output turns on the audio oscillator (U1-C) by pulling up the hysteresis 100K feedback resistor. The audio oscillator in turn drives an op-amp voltage follower (U1-D) and the 2N2222 speaker driver. The audio volume control is simply a 100 ohm pot in series with the 8 ohm speaker.

I've used my bug for three years. I've had hundreds of QSO's with it and replaced the battery about twice a year. Once the paddle began to stick "on," so I had to oil the machine screw pivot on the paddle. Otherwise, the bug has given me good service and little trouble. This is an easy home project because it doesn't involve RF and is almost guaranteed to work.

DUMMY LOADS

A checkout of a homebrew transmitter begins with a low inductance dummy load. Once you are able to deliver a pure, stable sinewave into your dummy load, then you may graduate to an antenna.
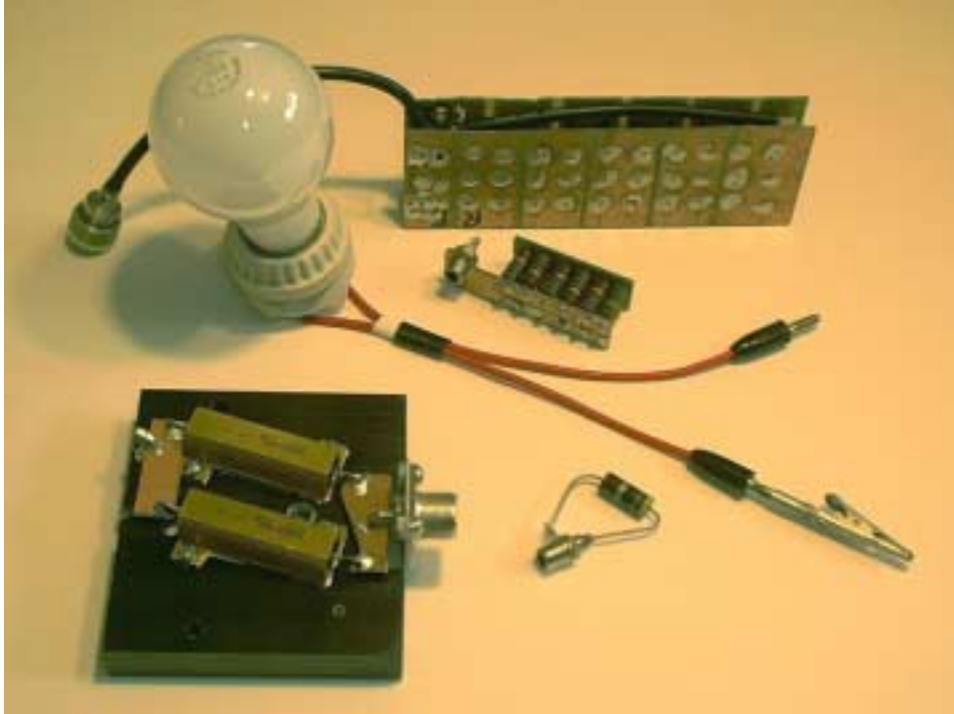
Homebrew dummy loads ranging from 2 to 100 watts.

A dummy load is just a big resistor that can stand the power from your transmitter without smoking or catching fire. In order that it resemble a well-designed antenna, the dummy load should be a pure resistance with little accidental inductance or capacitance.   Big, non-inductive resistors are pricey and must be specially ordered. That's why most hams buy commercial dummy loads rated for power equal to their transmitter's maximum power. Dummy loads are almost always designed for 50 ohms because that is the standard design impedance for most transmitter amplifiers and many antennas.

For a QRP, a dummy load can be as simple as a 47 or 51 ohm 2 watt carbon composition resistor. If you don't drive it continuously, five watts won't hurt it. Be careful, though. The heat may not damage the resistor, but it can melt oscilloscope probe tips clipped onto the resistor leads. For higher powers, you can build a good dummy load out of arrays of carbon composition or other low inductance resistors.

A dummy load is one of the few simple quality homebrew test instruments that a guy can make himself in a few hours. A big dummy load resistor can be made from an array of low power, low inductance resistors. Metal film resistors and carbon composition resistors usually have low inductance and make good dummy loads. For example, I happened to have a whole package of old 1 watt, 150 ohm carbon composition resistors. By placing them in the appropriate series/ parallel arrangement I made a 10 watt, 50 ohm dummy load. If you need a 50 watt dummy load, it can be made from an array of 25 two watt resistors.   You will have to be clever selecting the resistance and arranging them so that the final resistance is 50 ohms.

For high frequencies, like the 10 meter band and above, it is important to use a low inductance connection with the resistance. Therefore, the leads into the dummy load should be coaxial cable. I used circuit boards with wide traces to connect the individual resistors in an

array.

Light bulbs as dummy loads

       An ordinary filament light bulb can work as dummy load. They are far from ideal and should not be your only dummy load. However, they do have advantages: They are fun to use and great show-and-tell devices. However, at less than 100 watts, their impedances are much higher than 50 ohms and the impedance rises as they get hot. On the other hand, if you need a dummy load that simulates a high impedance antenna, then a light bulb is useful. Also, if you're checking out a power meter, a light bulb gives an obvious indication of when the power output is maximum.

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BUILDING A "T" MATCH ANTENNA COUPLER

       Modern transmitters are usually designed for 50 ohm antennas. The Chebyshev output filters found in modern transmitters only work at this design impedance. When you load them with a mismatch, you won't believe the scrambled waveform that comes out. In other words, they only filter properly at 50 ohms. Unfortunately, real antennas are usually higher or lower impedance and need some form of impedance transformer to make them appear as a 50 ohm load to the transmitter.

       Old vacuum tube transmitters usually had built-in antenna couplers, but none of the transistorized designs in the ARRL annual handbooks have couplers. So after I built a transistorized transmitter, I needed an antenna coupler. The coupler designs in the handbooks were complicated with all-band capability and built-in power / SWR meters. They're nice, but I wanted to get on the air fast. I consulted Bob, NØRN, for advice. Bob had built several couplers and he thought a simple "T" match was best. It just consists of two variable capacitors and a

variable inductor.

A Simple "T" Match Antenna Coupler
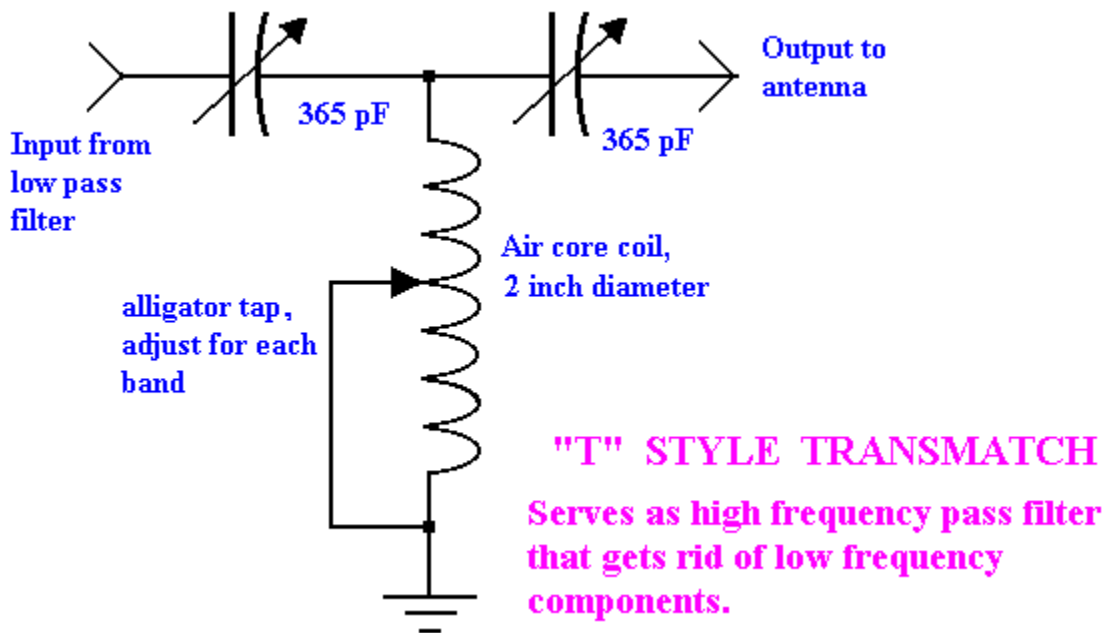
Diagram of the "T" style transmatch.

How it works

The idea behind the T match is resonate the variable capacitor on the left with the inductor to ground. When tuned to resonance the oscillation produces sinewave voltages across the L and C that can be much larger than the sinewave voltage that arrives on the input. Because the voltage across the inductor can be huge, the coupler can "match" the impedance of a high impedance antenna. For example, transistorized transmitters are nearly always designed to match a 50 ohm load. In fact, the output Chebyshev filters will work poorly if not driving a 50 ohm

load. On the other hand, a 300 ohm antenna will need six times more voltage to deliver the current needed for a given power level. The oscillating L and C work like a transformer, stepping up the voltage.

The variable capacitor on the right is not nearly so critical. You will find that for most situations, keeping the capacitor at full capacitance, 365 pF produces the best signal. Sometimes I can get a little better sinewave output or slightly more amplitude by adjusting this capacitor. But usually, I just leave it alone. For the lower bands, 80 and 160 meters, you may want to add some more capacitance in parallel with both capacitors using switches. My variable capacitors are dual section types from old broadcast radios. I use small toggle switches to add the capacitance from the second sections. In addition, the right hand capacitor has a fixed 1000 volt, 200 pF mica capacitor across the second section so I have plenty of coupling capacitance for 160 meters.

Packaging

My friend Bob showed me a "T" match he had built in a wood and plastic box.

"Why didn't you use a metal box?" I asked.

"Oh, wood was easier and it doesn't matter," explained Bob. "Maybe I get more RF radiation here in the shack, but otherwise, there's no need for a metal cabinet."

I was anxious to get on the air, so I rummaged through my junk and came up with two dual 365 pF broadcast radio variable capacitors. One of them was out of a 1935 radio. I thought using an ancient component had a nostalgic charm. I also found a big piece of open "Air Dux" coil I could use for the inductor. I made the inductor "variable" by using an alligator clip to short out the unwanted length of coil. For RF connectors, I used SO-239 "UHF" connectors from Radio Shack. After an hour's work I had screwed all the parts down onto a pine board and I had a "T" match.

Improving performance on the higher bands

I originally used a simple 12 gauge wire connecting the grounds on the input and output connectors. This simple "wire" looks like a significant inductor on 17 meters and above. This small inductance can occasionally make loading difficult or impossible with some antennas. I replaced the wire with a low inductance, 3 inch wide sheet of metal and the difficulty largely disappeared. Try to maintain at least a half an inch of spacing between this ground sheet and your coil. Another modification that was helpful was mounting the coil vertically. This minimized the capacitive coupling between the coil and the sheet metal ground plane. I used clear plastic and epoxy to build brackets and insulate the bottom of the coil.

I tested the coupler by using a few ordinary light bulbs as dummy loads. Bulbs have a wide range of resistance, depending on the wattage and how hot the filament happens to be. The "T" match worked great and the bulbs burned brightly. It worked just as well on my real antennas, so I went on the air and began working folks right and left. So, if you just want a coupler that works, the story is over now. If you like, you may stop reading.

The "T" match as an aid for receiving on 80 and 160 meters

One surprise from this project was that my "T" match was vital for receiving weak signals on 80 and 160 meter ham bands. These lower bands are quite close to the standard

broadcast AM band, (550 – 1700 KHz).   As you probably know, these stations are extremely powerful – as much as 50,000 watts. If you have such a station within 50 miles, or a less powerful station close to your house, there will be big RF voltages riding on your antenna at all times. In fact, a few years ago there was an article in QST about a fellow who used a crystal set tuned to a local station as a power supply just as though it were solar cell.

With these AM elephants bellowing in your neighborhood, your little home-built receiver may have trouble filtering them out and hearing puny ham stations whispering hundreds of miles away. The front end of the receiver can easily be overwhelmed. Even though you probably won't hear the AM broadcasts in your headphones, you'll hear static on the ham bands and you may believe there are no ham signals there.

When your receiver uses the same antenna as the transmitter, the signal strength of weak signals on the low bands peaks dramatically when the "T" match is properly tuned to the transmitter. The "T" match serves as a "high pass" filter that reduces the signal strength of the broadcast stations dramatically. In my station, operation on those two low HF bands is impractical without using my "T" match on receive. Not only was I suddenly hearing dozens of CW stations on 80 meters, I found myself working QRP stations halfway across the country. I didn't know that was even practical.

Using the "T" match on receive has another benefit. Assuming your receiver is designed for a 50 ohm input, when you peak the received signal strength using the "T" match, you'll find that the 50 ohm transmitter is also (nearly) perfectly matched. So on any band, before I try to load the antenna with my transmitter, I peak the received signals with the "T" match.

Adding the whistles and bells

The interesting part of the "T" match story is what happens when you add the refinements - you know, the metal case, the power meter and all that. After I had used my primitive coupler for a while, I wanted something more impressive. I already owned a metal enclosure that was about the right size. It took me considerably longer than an hour to build another coupler, but eventually I had a professional-looking "T" match in a metal box. I tried it out and .... it didn't work worth a darn. It couldn't match much of anything. It seemed to be a wonderful standing wave generator, but a poor antenna coupler.

I consulted Bob about my problem. He nodded knowingly. "Oh, yeah. It doesn't work in metal cabinets. That's why I used wood and plastic." Now he tells me. "However," he went on, "you could convert the coupler to a 'π ' match. That should work in a metal box since the capacitors go directly to ground and the accidental capacitance to the metal case will become part of the circuit. Also, you could use a powdered iron core inductor. The magnetic flux is confined to the core, so powdered iron cores work well in small metal enclosures."

Air core coil, 2 inch diameter

Input from low pass filter

Output to antenna.

alligator tap, adjust for each band

365 pF

365 pF

Pi (π) STYLE TRANSMATCH
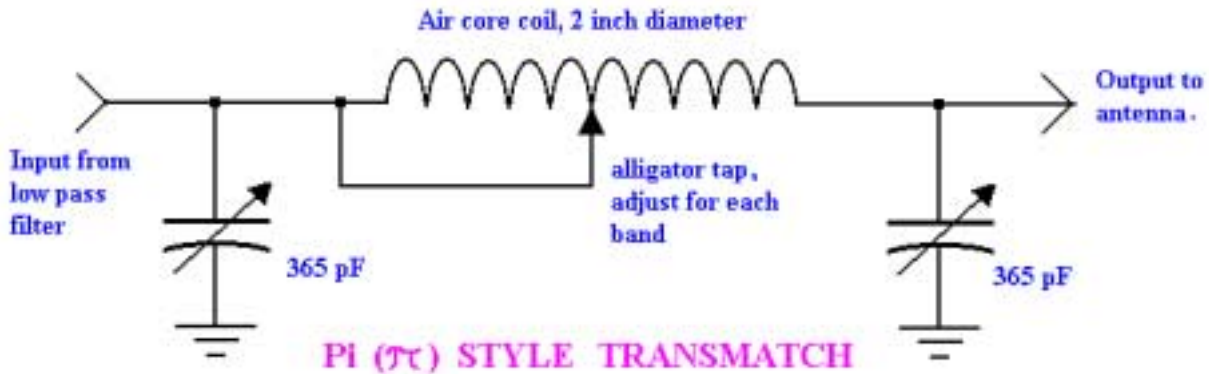
The "π" Match

I tried out these ideas. Yes, I got the "π" to work, but I found out that the "T" match was better. If you examine the "π " match circuit, you'll see it is a low pass filter. That is, the high frequency noise gets shunted to ground through the capacitors, while low frequency components pass through the inductor. I was already using a low pass filter to suppress TVI, so the "π " match was redundant. With the "π" match I noticed the output waveform usually had low frequency, "roller coaster" distortion and sub-harmonic modulation on it that resembled AM modulation. In contrast, the "T" match serves as a high pass filter that removes these distortions. In fact, the low pass filter and the "T" match work together as a band pass filter to maintain a pure sinewave.

I found a powdered iron core in my junk box large enough to handle 100 watts and I wound a multiple tap winding on it. Yes, the powdered iron core inductor worked, but it got hot and was clearly inferior to the air core. Since I didn't have any data on the core I was using, I ordered a big new core from CWS Bytemark with known properties. I bought a CWS (Amidon) T200-6. Sure enough, it heated up too! Long live air- core inductors!

My other experiment was built-in power meters. I installed dual meters for forward and reverse power. Cool, huh? Too bad they worked so poorly. The meters were voltage sensitive rather than power sensitive. For example, they read twice as much "power" into a 100 ohm load as into a 50 ohm load. I knew the meters weren't correct because all the other data I had from my oscilloscope, DC power input to the final, etc., all told me that the power into 50 ohms and 100 ohms should have been equal. I discovered I could compensate for this error by placing the power meters on the transmitter side, the 50 ohm side, of the antenna coupler. That way the voltage was constant for the same power level.

Eventually I retired the fancy coupler to the junk pile and I'm still using the piece of wood with the 1935 capacitor. (Now you know why I have so much junk.) In order to monitor my output power and frequency purity, I monitor the input to the antenna with scope probes going to a frequency counter and to an oscilloscope. The picture on the scope and the frequency counter readout are far more sensitive to the problems of a home-brew rig than an SWR meter will ever be. In summary, build a "T" match and get on the air fast!

The "T" Match monitored by oscilloscope and counter probes.

The low pass filter is on the left. The antenna coaxial cable goes out on the right. The oscilloscope probes monitor frequency and waveform shape.

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BUILDING A LOWPASS FILTER

I carried my old vacuum tube HF transmitters down from the attic and looked at them critically. Hmmm..... Class C output stages. Class C equals harmonics. I hadn't been on the air in 30 years, but I knew from studying for my new license that spectrum purity standards were higher than they used to be. At the very least, if I used my ancient transmitters, I would be risking TV interference (**TVI**) complaints from the neighbors. Consequently a transmitter lowpass filter became my first project.

I'm told that today hardly anyone with a modern transceiver needs or uses lowpass filters. However, if you do any homebrewing, especially with Class C or Class B output stages, a lowpass is a good idea. When placed directly on the transmitter output, I've found that the filter doesn't reduce power output and it doesn't make the antenna hard to tune, even when operating QRP. I think of my lowpass filter as "insurance" against angry neighbors and pink slips. So why not use one?

Your first question probably is," Do I need one for my puny little 5 watt QRP?" The answer is, "Probably not." However, as soon as you get complaints, your neighbors will eternally label you as the cause of every bit of snow on their screens or virtually any problem with their TV sets. Once the complaint syndrome begins, being "legal" and "meeting FCC requirements" isn't enough. It is much better to do everything you can to be sure the neighbors never realize that you might be interfering with their TVs.

Electrical Design of the Filter.
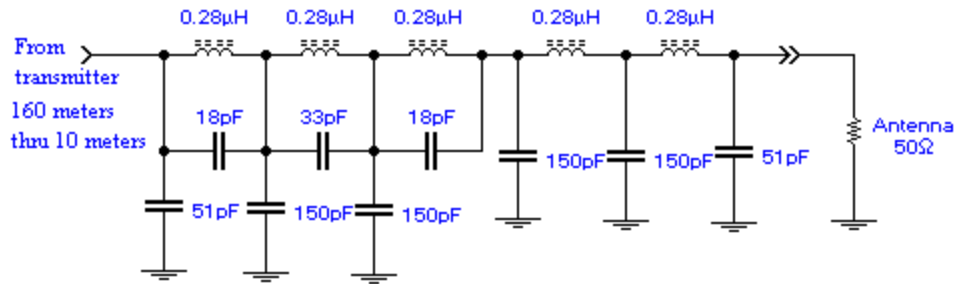
A five-stage lowpass filter.

I started with a three stage elliptic lowpass filter from the good-ol' ARRL handbook. Later, I acquired a "Spice" program for analyzing circuits, Electronics Workbench. I turned it loose on my lowpass and settled on the circuit shown above. The capacitors to ground tell us this is a lowpass filter. In other words, the capacitors shunt high frequencies to ground that might otherwise radiate in the TV bands, while lower HF frequencies will pass through the filter via the inductors. This filter is designed to pass all the ham HF bands from 10 meters (30 MHz) and below. As you will see shortly, it attenuates all frequencies above 10 meters.

Notice that there are 33 pF and 18 pF capacitors across three of the inductors. Each inductor is part of an LC resonant trap that appears as a high, series impedance to TV channels 2 and 4. However, the higher channels are also attenuated at least 105 dB. The main lesson I learned from Spice was that component values are surprisingly tolerant. I had used Chebyshev filter tables that have values to 4 decimal points and sophisticated "bell curves" for the different component values. That elegance made me think filters had to be precise. Wrong! Well, that's what Spice and my experience tells me. Notice that I made all the inductors identical and use only two values of capacitors to ground.

Like all complex reactive filters, this one is designed for specific impedances, in this case 50 ohms. That means that the filter only works correctly when the input and output impedances are 50 ohms. For that reason, it's inserted into the antenna line right after the transmitter and just before the power meter and antenna coupler. The antenna can have any impedance from near zero to hundreds of ohms, so the coupler serves as a transformer to match 50 ohms to whatever is needed.
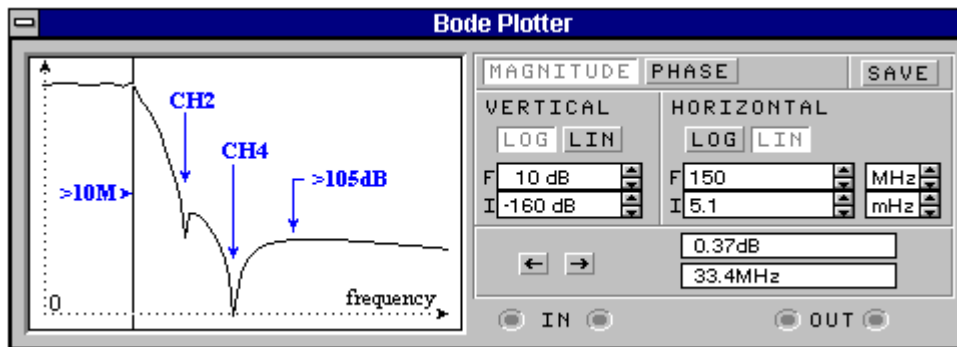
Lowpass filter Bode plot.

Construction Details.

The filter is housed in a long, skinny aluminum box. Capacitance to ground is part of the design. Therefore, provided the leakage capacitance between the coils and the metal box isn't extreme, this stray capacitance won't degrade the performance. Just keep the coils at least 1/2 inch away from the grounded metal walls and the filter will work well. I used air core inductors, which meant that I had to rivet four pairs of overlapping metal partitions into my box to prevent coupling between the five coils. Without the metal shields, air core inductors would couple to each other like transformer windings. I prefer air core because simple coils don't dissipate significant energy. I'm also cheap.

Inside view of the filter. Each coil is isolated from its neighbors by notched partitions.

I wound my coils out of 12 gauge insulated copper wire stripped from Romex household three-conductor wiring cable. If you follow the dimensions in Table 1 exactly, you should get about the same resonant frequencies I did. Depending on the shape of your box, you may use either large coils with 2 turns or smaller diameter coils with 3 turns. The inductance will be about the same. The important issues are that the three LC traps should resonate well above the 10 meter band and there should be no significant attenuation below 30 MHz.

Table 1. **Air core inductor specifications**.

	turns	**diameter**	**length**	**inductance**
	2 turns	1.25 inches	0.5 inch	0.28 microhenries
or,	3 turns	1 inch	0.75 inch	0.28 microhenries.

The inductors could also be wound on powdered iron cores. An advantage of powdered iron is that the magnetic flux is confined in the cores and you can cram the filter into a smaller

metal box without metal shields between filter sections.   However, iron core inductors will still have stray capacitance to ground.

All capacitors should be mica and capable of handling voltages consistent with your power level. If you're running more than 100 watts, it would be prudent to use capacitors with working voltages of 1000 volts or more. I used 500 volt caps with my 100 watts and so far haven't had any capacitor failures. Two identical 500 volt caps in series will give a working voltage approaching 1000 volts, but of course the effective capacitance will be half the value of each. Use real RF connectors on your filter, UHF SO-239 or equivalent.

Testing the filter

I tested my filter by terminating it with a 50 ohm load then running an RF signal generator through it. There was no significant attenuation or distortion of the sinewave from 160 to 10 meters. Above 10 meters the output signal dropped to almost nothing. Similarly, when I loaded lightbulbs and 50 ohm dummy loads on all HF bands, 80 through 10 meters, I could see no differences with or without the filter.

So far, my only TVI complaints have been from my own family. On 15 meters, they see minor flickering on the picture. Not surprisingly, 17 Meters bothers channel 4 (4 x 18 MHz = 72 MHz) and 30 meters tears up channel 6 (8 x 10.1 MHz = 80.8 MHz.) I believe my biggest remaining TVI problem is my open-chassis transmitter with the PC boards exposed to the breezes. Obviously I need a cabinet.

When we bought a modern TV, all my interference problems vanished. Fortunately, modern TV designs and the increasing use of cable TV, Direct TV satellites and 2.4 gigahertz digital cell phones, makes annoying the neighbors less and less likely. Considering that we are entering "The Wireless Age," the future of our TVI problems looks surprisingly bright.

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STAYING LEGAL WITH HOMEBREW TRANSMITTERS

On Field Day I watched while up-to-date hams tuned up their rigs. I was amazed by how casually they assumed their signals were matched to the antennas and not suffering from rough CW tone, harmonics or drifting frequency. They plugged beam antennas and dipoles directly into sophisticated transceivers and were instantly in business. I didn't see any antenna couplers, power meters, low pass filters, dummy loads, oscilloscopes, frequency counters or any of the tools we homebuilders use to stay legal.

Investigate before you radiate

Many hams these days are building QRP transmitters. Before they go on the air with a homebrew transmitter, they should learn how to check it out. Out there on the bands are Official Observers who send out little white SWL (Short Wave Listener) cards. Four years ago when I got back on the air with my homebrew, vacuum tube antique, I quickly got an OO card from New Jersey. OO cards are *NOT* suitable for framing. Very embarrassing! Don't just go on the air and hope everything is OK. ***Investigate before you radiate!***

Listen to your own signal

A good way to find out how your signal would sound to another station is to load a

dummy load then listen to it with your receiver. I routinely use my old Collins receiver for this purpose. The tricky part is desensitizing the receiver so that the signal strength simulates a signal on the air. I did this by shorting a coax connector and plugging it into the antenna jack on the back of the receiver. I also clamped ferrite blocks on the line cord and speaker wires to help keep RF out of the receiver cabinet. After I made these changes, key-clicks, rough note and "warble" instabilities became obvious. Now I could understand what my contacts were complaining about.

My 1967 transmitter was a mobile unit with a switching power supply. No matter how I filtered the supply, I couldn't get rid of the switching hash. The hash was extremely hard to see on the oscilloscope, but in the receiver, I could hear a distinctly rough note. No wonder I kept getting those 598 reports!

Oscilloscopes

In my opinion, an HF transmitter would be hard to build without a quality RF oscilloscope. Looking at the waveforms on a scope makes it easy to tune up a stage, or at least to get the tuning approximately right. When I operate, I keep a 10:1 scope probe right on the antenna feedline. That way, there's no question about what's being transmitted. A typical probe is rated for several hundred volts and has one megohm load resistance and five picofarads capacitance. This shouldn't bother your tuning and your transmatch can compensate for any slight mismatch.
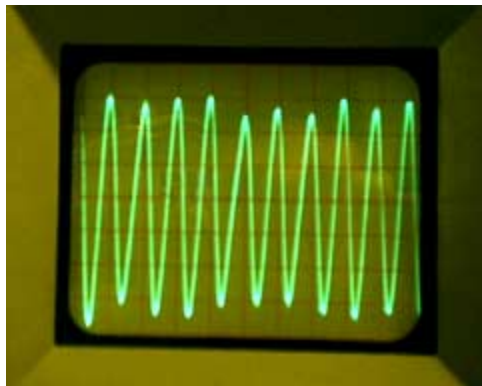
A well-tuned 30 meter CW signal on the antenna lead.

Usually on the lowest HF bands, like 80 and 40, you'll see a truly perfect sinewave on your antenna. But the higher the frequency, the less perfect the waveform will probably be. The 30 meter signal above is sharply focused, but it has a bit of low frequency modulation. This is quite all right.

Beware of blurs
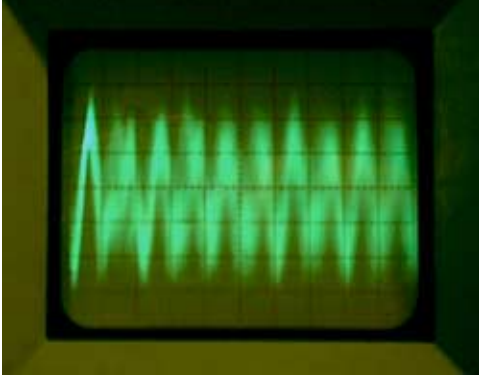
A poorly tuned 30 meter CW signal.

On the other hand, the 30 meter signal shown directly above is mistuned. Notice how only the first half sinewave is synchronized. After that, the waves are a blur of different, overlapping frequencies. Also, the reading on your frequency counter will usually be low and out of the desired band. Usually tuning the transmatch instantly corrects this.

Look for the zero crossings

At even higher frequencies, like 15 and 10 meters, your sinewave may have more low frequency modulation and be slightly blurry as illustrated below. The higher the frequency, the more difficult purity becomes. Also, above 20 meters it becomes increasingly hard to know what's artifact from the oscilloscope and probe and what's actually going out the antenna. *A reliable indication that all is well is when the picture focuses sharply enough to see the zero crossings clearly.*

An adequate signal on 10 meters.

In contrast, the signal shown below is too blurry. Tune your transmatch!

This 10 meter signal needs to be tuned.

Tuning for maximum power out.

I tune my transmatch for maximum amplitude of a sharply focused sinewave at my antenna lead. This gives me an approximate measurement of antenna impedance. For example, suppose I first I load my dummy load on 80 meters and get about 50 watts. Next I try to load my 40-meter dipole on 80 meters. Using the transmatch, it loads up and produces a sharp sinewave. Unfortunately, the 300 volts peak on the coax with a 50-watt signal suggests really high antenna impedance, about 900 ohms. If the antenna looked like 50 ohms, I would see about 70 volts peak. In my experience, with a match that poor, it may be safe for the transmitter, but nobody will hear me.

An oscilloscope for HF ham work should be rated for at least 50 MHz. A brand new oscilloscope like this will cost at least $2000, but is not a good value. My Tektronics 5441 scope originally sold for $11,000 in 1976. Today that scope or equivalent ones can be found used in electronic surplus stores or mail-order catalogs for $400 or less.

An FM radio will detect serious frequency impurity

A serious splatter problem will make a roar of static in your FM radio. On the other hand, sometimes the FM radio just cuts out and goes silent. That may not be a transmitter problem. I could be that the radio's IF is just overwhelmed by your signal. Alternatively a harmonic of your transmitter frequency might happen to line up with your FM station and obliterate it. Again, the FM radio just goes silent.

DC power supply ampere meter

It is always nice to know how much current the transmitter is drawing. Moreover, DC current is another indication of the SWR (Standing Wave Ratio). That is, how well your antenna is tuned. When operating correctly, 50 watts output should draw about 8 to 10 amperes. If it reads 15 or 20 amperes, it means you are way out of tune and the final amplifier is heating rapidly.

A typical HF frequency counter

Frequency counters

       The most persistent problem a homebrewer faces is frequency drift. Commercial transceivers use frequency synthesizer chips slaved to unusually stable crystal oscillators. They also have built-in displays that read frequency to a fraction of a Hertz. This amount of precision is almost never justified by the specifications, but hey! The guy you're working hasn't read the specs on his transceiver and he believes his readout is gospel. Since we homebrewers just use simple, free-running oscillators, we drift and our contacts notice.

       When I operate, I have two scope probes on the antenna line. One goes to the scope and the other goes to a frequency counter. A good counter is vital because most of the frequencies you must measure are too close to each other to simply count squares on the oscilloscope screen. When the transmitter is operating properly, the counter display is solid to within 10 Hz and doesn't dance around. The same conditions that cause blurry sinewaves on the scope cause the counter to read low and jump about. For example, if you are loading up on 15 meters and the counter reads something like "20.68XXX with the last few digits changing every second, you are mistuned. Don't be satisfied until the counter reads what it should and stays there. That is, you should see a solid reading of a legal frequency, like "21.12089." Counters can be a bargain if you buy them used. My used Hewlett-Packard originally sold for about $2000, but I paid $60 for it.

Lowpass filters

       When operating homebrew equipment, it's a safe bet you will occasionally generate out-of-band harmonics, especially while loading your antenna. A lowpass filter is simple insurance against generating interference above some design frequency. Another way I minimize the out-of-band noise problem is to keep a chart of the transmatch settings for each band tacked up on the wall. So when I switch bands, the transmatch is already fairly well adjusted before I key the transmitter.

Not so useful instruments

Power meters   I have not found power meters particularly useful. I have a commercial one that gives readings that correspond well with the light produced by a light bulb dummy load. My homemade power meter isn't quite that good. The point is that power meters only tell you the power delivered to the antenna. I need to know more than that to avoid bad signal reports and

OO cards.

Grid dip meters   In the old days we used "grid dip meters" for frequency measurement. A grid dip meter measures the frequency of a resonating coil by placing a secondary coil next to the target coil. RF currents induced into the coil produce a drop or "dip" in the meter reading when the tuning knob on the meter is tuned to the resonating frequency. The approximate frequency is then read off the dial. Grid dip meters aren't at all accurate, but they got us onto the right ham band. Today's inductors are usually wound on powdered iron toroids. Grid dip meters don't work well on toroids because the magnetic field is trapped in the closed loop. There is practically no leakage outside the toroid for the grid dip meter to tap into.

Spectrum analyzers   A spectrum analyzer would be great for a homebuider. They measure the purity of transmitter signals and are often referenced in homebrew transmitter articles. Unfortunately, even a used spectrum analyzer with sufficient precision is pricey - many thousands. Since I can't afford one, they don't do me a bit of good. Without this tool, I have to "interpret" what I see on the oscilloscope and the frequency counter. Fortunately, that isn't hard.

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ANTENNA RELAYS

Switching from transmit to receive

If you simultaneously connect both your receiver and your transmitter to the antenna, you may burn up the front-end stages of your receiver when you transmit. When you first go on the air with your QRP transmitter, you will no doubt be irritated by the need to use a separate antenna for the receiver. A clumsy solution would be to rig up a manual switch to move the antenna back and forth from transmitter to receiver every time you stop sending. That's inefficient, to say the least. If you have to throw more than one switch to go between send and receive, you will be at a huge disadvantage when trying to work DX or in contests. Actually, even one switch is not up to modern standards.

Modern transceivers have "break-in keying."   When they stop sending, the receiver instantly comes back on automatically. Non-homebuilders aren't even aware that switching antennas is a problem. I haven't yet mastered building break-in keying and still use one switch to go from send to receive. Even so, by the time my receiver comes back up after transmitting, I usually only hear the last three or four characters of my call sign from my contact, "…IYE". The other guy has already switched over and sent "KØ" before my receiver was back on the air. As you can see, one switch operation is the bare minimum.

Requirements for an antenna relay

An antenna relay is usually a ***single-pole, double-throw*** switch, sometimes called ***SPDT***. The external antenna line is connected to the moving contact. This contact is normally resting against the receiver contact. When the relay is activated, the moving contact switches over to the transmitter contact.
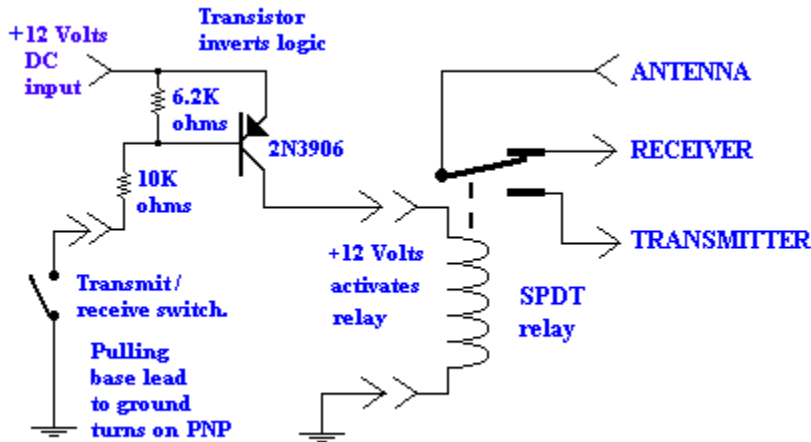
Schematic of antenna relay   The optional transistor inverter turns on the relay with a high impedance line switched to ground.

Unfortunately, ordinary relays have too much inductance on 10 meters. Inside the relay RF current must travel through a length of wire perhaps one or two inches long. This wire is not a coaxial transmission line or a wide, low inductance strip. The result is that ordinary relays often work poorly on 10, 12 and 15 meters. By "poor" I mean that no matter how you adjust the antenna coupler, you can't quite deliver a sharply focused sinewave to the antenna. (See the above article on checking out homebrew transmitters.) In fact, the final amplifier may remain in "noise mode" and not produce a sinewave at all. You can demonstrate that the problem is the relay by bypassing it and connecting the final amplifier directly to the lowpass or to the antenna coupler. Once the relay is out of the circuit, you will often find that the problem is cured and the antenna coupler will load the antenna just fine.
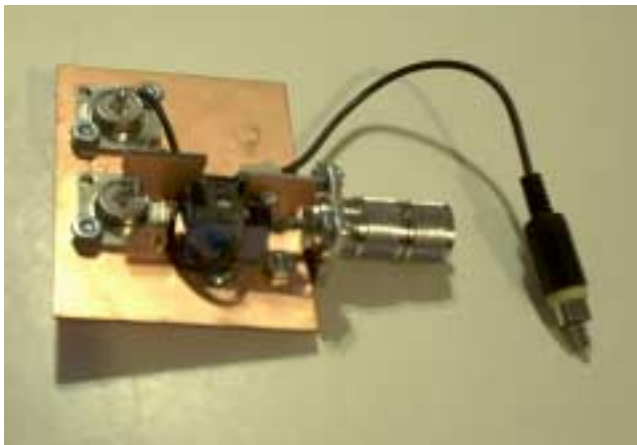
Homebuilt antenna relay

There are, of course, commercial coaxial cable relays to solve this problem. I built a usable antenna relay out of a _TINY_ 10 amp relay rated at 120 volts AC (Radio Shack Part # 275-248A). The important specification is the "tiny" part. Since the relay is miniature, the wires inside the relay are very short. I kept the external transmitter RF leads as short as possible by implementing the "wires" with little rectangles of PC board. The connections only have to travel

about 5/8 inch from the center conductors of the SO-239 RF connectors to the relay pins.

The receiver antenna connection is not nearly so critical. Therefore it was implemented with a three-inch length of RG-174 coaxial cable. The cable shield is only grounded at one end. These precautions reduced the inductance of the relay leads sufficiently. Now when I load my 10 meter vertical antenna, it works as well with or without the relay in the pathway. The relay coil was energized with another short length of RG-174 going to the phono plug on the right. I shielded the 12 volt signal wire because I was trying to keep RF out of my power supply. This goal was easier for me using the logic inverter to drive the relay coil. Don't bother building the inverter if you don't need it.

Turning on the transmitter power supply
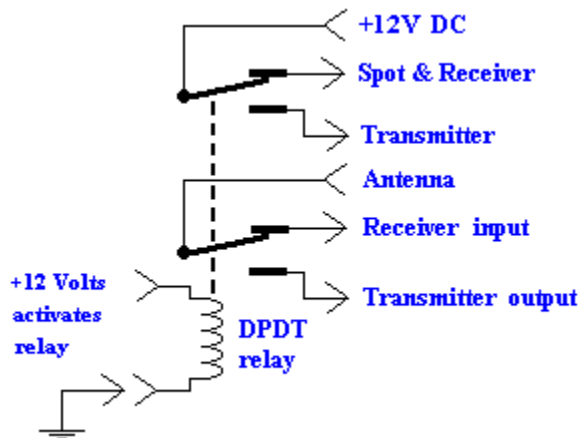
In many homebuilt transmitter designs the antenna relay has another set of contacts to turn on the DC power supply for the transmitter. A VFO-controlled transmitter is much more complex than a crystal controlled QRP. There are usually one or more oscillators running during transmit that must be turned off during receive. Otherwise you will hear them as whistles in the receiver. The "double" relay above in older ham transmitters is usually a ***Double Pole, Double Throw***, a ***DPDT***. In other words, this relay is a dual SPDT. The DC supply line goes to a moving contact. At rest this contact energizes the "spot" circuit and perhaps also the receiver. The "spot switch" allows you to turn on the transmitter crystal oscillator or VFO to figure out where your signal will be in relation to the fellow you're listening to.

Grounding one side of the relay coil activates both the antenna relay and the DC supply relay. In other words, this control line always has 12 volts on it. When the line is grounded by means of the send-receive switch, this line activates the transmitter. This same signal can also be used to "mute" or inactivate the receiver. Alternatively, the DC supply relay in the transmitter could turn the power to the receiver off and transfer it to the transmitter.

I have built three transmitters that used a DPDT relay to perform both the antenna switching and the DC power switching. Except for the 10 meter problem explained earlier, these big relays all worked well, at first. But eventually, the DC power side always became intermittent. For this reason, if you are going to run a 50 or 100 watt transmitter, plan on switching at least 20 amperes. I recommend using a 30 ampere relay and maybe yours won't become intermittent. Of course, the bigger the relay, the more difficult it will be to use one

section of the relay as an antenna relay. I finally gave up and used separate relays for the power and antenna. When I push the little send/receive toggle switch on my bug box, it activates the coils of both relays.

Avoid power relays

Yet another problem with relays is that, the larger the relay, the more DC current it takes to activate it. A big 20 or 30 ampere relay coil can draw 100 to 200 milliamperes of current just to turn it on. Better yet, don't use a DC power relay! Using the QRP keyer described in Chapter 6 as a model to follow, you may use P-channel MOSFET power transistors to turn on the transmitter and/ or receiver. A heavy duty P-channel MOSFET power switch is illustrated below
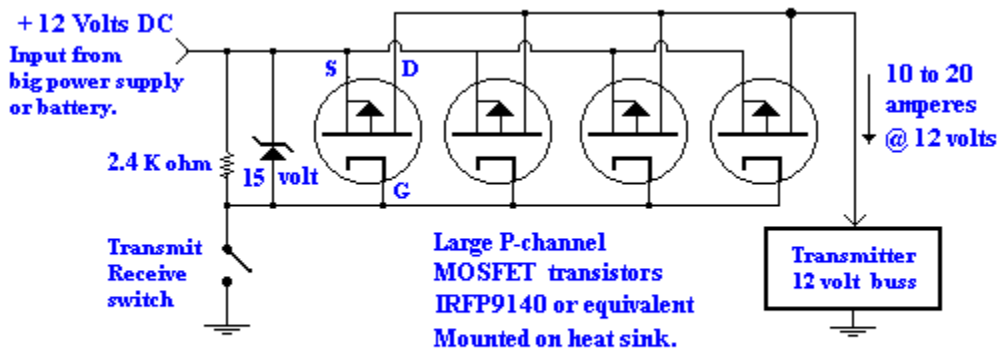
TRANSMITTER POWER SWITCH

The MOSFET power switch above uses four P-channel MOSFETs in parallel. When they are turned on, MOSFETs look like low resistances, 0.15 ohms or less. This means that little voltage is wasted across the switch. The larger the MOSFET, the lower the resistance. By putting several in parallel, the resistance can be lower still. Large TO-3 type MOSFETs can be bolted to a heat sink to keep the transistor temperature as low as possible. Otherwise, as the temperature rises, the internal resistance of the transistors will rise.

P-channel MOSFETs are the easiest to use because you can turn them on by pulling their gates down to ground. In my first transmitter I used two big TO-3 case MOSFETs. Their heating was negligible when bolted to a large heat sink,. In my second transmitter I used four smaller TO-220 case MOSFETS, type RFP30P05 p-channel MOSFETS. (Notice that you can decode the type number: 30 = 30 amperes, P = p-channel and 05 stands for 50 volts.)

Actually, for a given size and voltage rating of a transistor, N-channels are superior to P-channels. N-channels usually have about 1/3 of the on-resistance. Unfortunately, to turn on N-channel MOSFETs, you would need a 24 volt power supply to pull the gates up to about 12 volts above 12 volts. Every decision is a trade-off.

The 2.4 K ohm gate-to-source resistor insures that the transistors turn off when the switch opens. The 15 volt Zener diode on the gates is advisable because, in my transmitter, the gates of the transistor are in parallel with the antenna relay coil. When the transmit/ receive switch is opened, a big voltage can appear across the coil and may damage the transistor gates.

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HOMEMADE QSL CARDS

I do not miss the QSL cards from the old days. Forty years ago the most common cards were bought from World Radio Labs. They had a map of the US with one's call letters printed in red. It seemed like practically everyone else had Allied Radio cards. Allied cards were just white cards with big orange call letters and a couple of orange stripes. These designs were quite attractive, but since that was most of what you received, QSL cards were pretty monotonous. Back then, if you bought QSL cards that would have been competitive with today's commercial cards, they would have cost a fortune. Hand-drawing my own cards was fun, but only for the first 2 or 3 cards. After that, it was much too time consuming to be practical. I managed to make a crude template and print some rough black and white cards that were barely acceptable, but they sure looked primitive.

Since the age of Xerox, computers, digital cameras and the color printers, making your own color QSLs has become a breeze. Other than knowing how to run an ordinary computer, it is totally non-technical. I dare say that typical 12 year olds can make great cards, even if their parents can't. Considering how easy it is, I'm disappointed that so few guys make their own cards. These cards have much more "soul" than mass-produced commercial cards.

Here are a few examples of homebrew cards. The two on the left were made using Microsoft Paint, Mac Draw or a similar, standard drawing program. The ones on the right were made using hand drawings that were later Xeroxed. They were printed onto plain 5 by 8 inch index cards and then trimmed to postcard size. Not much to it, really!

My buddy Jack, KØHEH, used his digital camera to take a picture of a nearby mountain. Then he used a free QSL software program to overlay his call letters on the scenic picture and ended up with a beautiful card. The cards can be printed on a color printer using photo quality paper. The result is very classy.

Four more examples are shown above. The Boulder Amateur Radio Club card at the upper left, WØDK, could be made with a digital camera as was just described. Alternatively, one could begin with a regular color photo and a scanner. The photo card on the lower left, is from Paul, WAØNXZ. This card could have been done with a scanner or digital camera, but this particular card happens to be a commercial postcard with hand-lettered call sign at the top. It's a beautiful card, but buying postcards is pretty expensive. The guy with the surfboard holding the walkie-talkie at the upper right, is Tom, KQ6DV.   He did his the same way, but he kept the cost down by not using color and photo quality paper. The card at the lower right, is from John, KB2JKS. He made a complex hand-drawing and then Xeroxed it onto cards.

There are loads of ways to make QSL cards today. And all of these cards are more interesting than commercial ones. Yes, printing cards a few at a time is expensive. But most of us don't send out zillions of cards anyway. Making them yourself lets you modify them as often as you like. You aren't stuck with some error on the card for the next two hundred copies. Even if it's just QSL cards, long live homebrew!

CRYSTAL SETS TO SIDEBAND
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Chapter 10

Variable Frequency Oscillators (VFOs)

It won't be long before you become frustrated with being stuck on one crystal controlled frequency. You would like to have a frequency-tuning knob that covers the entire band and not just a few kilohertz. This sounds simple, but isn't. It's hard because, without the stability of a crystal, an ordinary RF oscillator will drift hundreds of hertz while you're sending. The fellow you're talking to probably has a modern transceiver with a narrow, stable passband. From his perspective your signal quickly drifts out of his passband. His digital readout is calibrated to tenths of a Hertz and he will take great delight in telling you about *YOUR PROBLEM*.

Drift is a big deal today

In the old days, like 1950, receiver passbands were usually huge, like 10 or 20 kilohertz. So you could drift quite a distance before your contact even noticed, let alone could no longer hear you. Besides, everyone drifted a little back then, so it wasn't worth mentioning. In the really old days, like 1930, the signals drifted so much, that hams often tuned their receivers with one hand while they copied down the Morse code with the other.
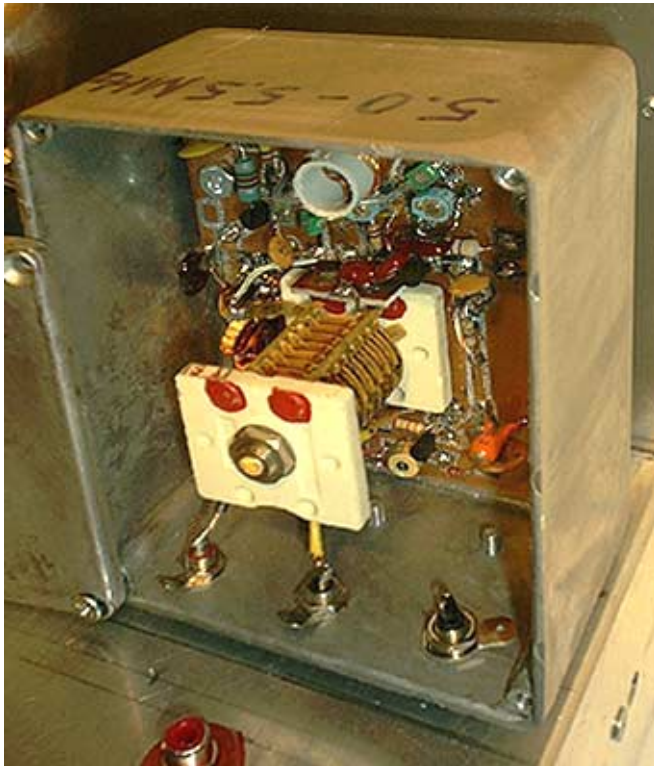
A 5 MHz VFO tuned by a mechanical variable capacitor

A stable variable frequency oscillator can replace a crystal oscillator. This chapter summarizes what I learned in my odyssey through six VFO prototypes. My early VFOs drifted

hundreds of Hz and I got loads of complaints. After I added temperature compensation, I got the instability down to 20 Hz drift per minute. Some stations notice 20 Hz drift and a few even told me about it. Eventually I built a super-regulated power supply for the VFO and got the drift down to about 5 Hz. I suggest you avoid embarrassment and work directly toward 5 Hz. According to the ARRL handbook, +/- 5 Hz is about as good as you can do without phase lock loop technology.

The test equipment needed to build a VFO are a precision multi-meter for measuring voltage down to millivolts and a frequency standard. A super-accurate, modern receiver is OK, but a frequency counter is better for this application. The hardest part about building a stable VFO is following all the detailed instructions on how to do it. If you're like me, you'll have trouble believing that all that trivia is really necessary. Yes, you can cut a few corners, but the more compromises you make, the more your VFO will drift.

Low frequency VFOs drift less than high frequency VFOs

For HF transmitters running on 160 meters (1.8 to 2.0 MHz) or on 80 meters (3.5 to 4.0 MHz), it's practical to build a VFO for those frequencies. Then you may amplify the VFO signal directly. For example, if you had a crystal controlled QRP designed for 80 meters, an 80 meter VFO could be plugged directly into the crystal socket. You might want to attenuate the signal somewhat before directly substituting a crystal, but the VFO can replace the crystal and allow you to tune all over the band. If you can build a really first rate VFO for 40 meters, that band would also be practical. Unfortunately, for a given level of sophistication and precision, frequency drift is directly proportional to frequency. You will probably find that somewhere above 5 MHz, there is too much instability to keep the drift under 5 Hz per minute. In order to build a low drift VFO for 40 meters or above, a low frequency VFO is "converted" up to the desired high frequency. This is done by adding the VFO to a high frequency crystal oscillator signal and then filtering out the sum frequency. Frequency conversion is covered in chapter 11.

Considering the size of most ham bands, a VFO needs a tuning range of at least 0.5 MHz. The higher the basic frequency of the VFO, the wider the tuning range you can achieve. ARRL handbook VFO projects have various frequencies ranging from 1.75 to 9 MHz. My CW transmitter VFO ranges from 3.5 to 4.0 MHz. My receiver VFO tunes from 5.0 to 5.5 MHz. In retrospect, if I were starting over I would have built the 5 MHz VFO first, since that frequency turns out to be more versatile. The disadvantage of a 5 MHz VFO is that it can't be used on any hamband directly and every ham band needs a frequency converter circuit.

JFET transistors

Junction Field Effect Transistors (JFETs) are ideal for building VFOs. Unlike bipolar transistors, the main current from the drain to the source does not pass through any PN junctions. PN junctions change their characteristics with temperature. Therefore, VFOs made from bipolar transistors tend to drift more than JFETs. JFETs work on the same principle as a MOSFET, but the control gate is a P-N junction diode rather than a capacitor. JFETs were explained and used in the VFO oscillator in the direct conversion receiver in chapter 7.

THE VFO CIRCUIT

The basic oscillator

In principle the VFO is almost the same as a quartz crystal oscillator. The crystal is electrically equivalent to an LC resonant circuit. Therefore, to tune a VFO we use either a variable capacitor or a variable inductor to change the resonant frequency. So far as I know, suitable variable inductors can't be bought or built in a basement. That means that the tuning element will have to be a variable capacitor, much like the one you used to adjust the crystal frequency in your QRP.
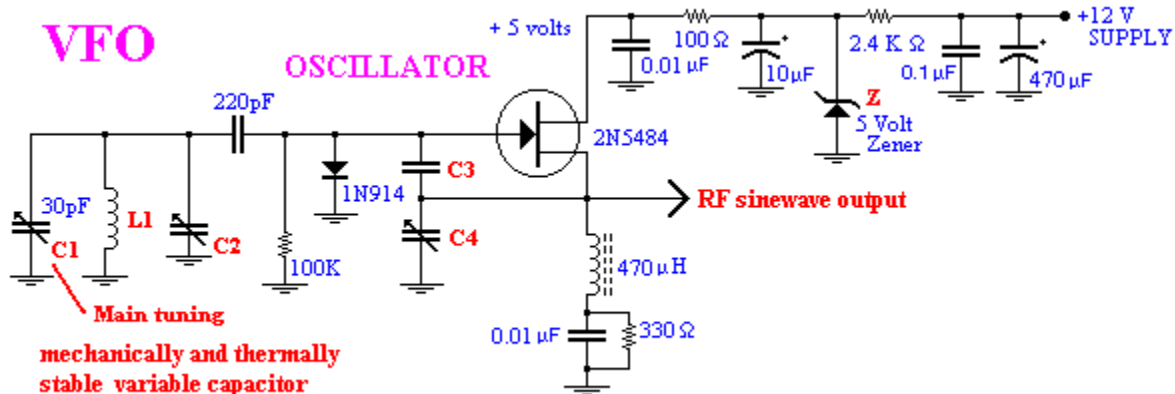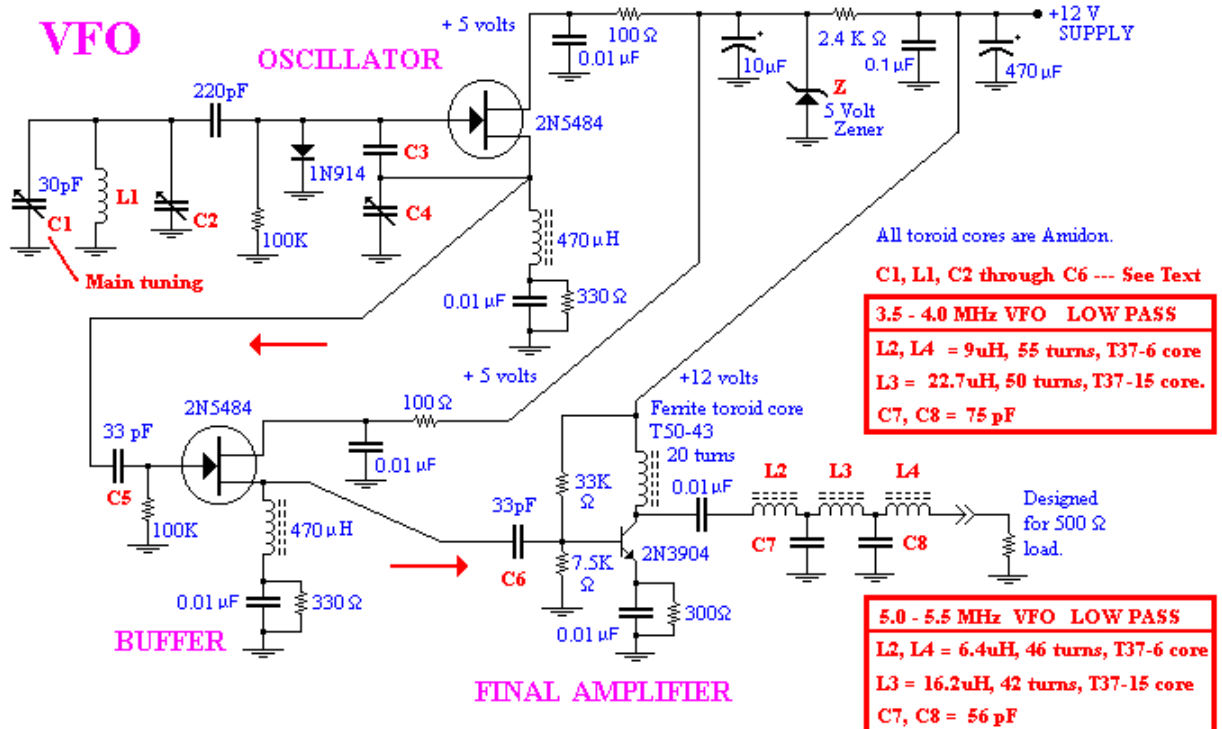

The circuit above is essentially what you will find in your ARRL handbook. It uses a JFET transistor. The oscillator is a *Colpitts* and can be recognized by the capacitive divider feedback, C3 and C4. Whenever the source voltage goes up, some of this change is coupled to the gate through C3. This turns the JFET more ON. That is, the feedback is <u>positive</u> which sustains the oscillation. The basic LC resonant circuit that determines the frequency is C1 and L1. C2 is a trimmer capacitor to help adjust the desired tuning range.

So what are the values of C1, L1, C2, etc.? The answer isn't simple. We start with a quality variable capacitor for C1 as described below. For various reasons, **C1 will probably be about 30 pF.**   Starting with this capacitor and the need for a 0.5 MHz tuning range, the other values must be determined by trial and error. The values are extremely hard to calculate because C3, C4 and even the 1N914 diode are part of the capacitance. Don't try too hard to get the values right until you have studied this entire chapter and formulated a plan for your VFO. As you will see later, C2, C3 and C4 are part of the temperature compensation strategy and will need to be determined by those considerations first. When you have decided what to do about C3 and C4, then you can work on L1 and C2.

The 1N914 diode on the gate seems counter-productive, but it is used as a clamp to keep the base of the JFET transistor out of the forward conduction region. That is, when the oscillation gets too vigorous and the gate P-N junction begins to turn on at 0.6 volts, the diode will help prevent operation in this range. The VFO as a whole is powered by 12 volts. However, 5 volts derived from a Zener diode regulator (Z) power the oscillator stage and its buffer. This is done to dissipate as little energy as possible in the oscillator and prevent the components from heating.

The entire VFO circuit

VFO

OSCILLATOR

+ 5 volts

220pF

30pF L1
C1 C2

Main tuning

1N914 C3
C4
100K
2N5484

100 Ω
0.01 µF

10µF

2.4 K Ω
0.1 µF

+12 V
SUPPLY

470 µF

Z
5 Volt
Zener

470 µH

0.01 µF 330 Ω

All toroid cores are Amidon.

C1, L1, C2 through C6 --- See Text

3.5 - 4.0 MHz VFO LOW PASS
L2, L4 = 9uH, 55 turns, T37-6 core
L3 = 22.7uH, 50 turns, T37-15 core.
C7, C8 = 75 pF

2N5484

33 pF
C5
100K
470 µH
0.01 µF 330 Ω

BUFFER

+ 5 volts

100 Ω
0.01 µF

33pF
C6
7.5K Ω

+12 volts

Ferrite toroid core
T50-43
20 turns
33K Ω
0.01 µF
2N3904
300Ω
0.01 µF

L2 L3 L4

C7 C8

Designed
for 500 Ω
load.

FINAL AMPLIFIER

5.0 - 5.5 MHz VFO LOW PASS
L2, L4 = 6.4uH, 46 turns, T37-6 core
L3 = 16.2uH, 42 turns, T37-15 core
C7, C8 = 56 pF

Here is the entire VFO circuit, excluding the temperature compensation. As you can see, the VFO also contains a buffer stage and a final amplifier. Temperature compensation consists of special circuits that replace either C2 or C4.

Buffer

The buffer stage separates the oscillator from the final amplifier. Otherwise there would be a subtle connection between the load on the VFO output and the oscillator. Believe it or not, without the buffer, if you change the load slightly, the frequency will change too. The buffer is connected to the other stages by C5 and C6. These capacitors should be as small as possible to reduce the connection between the oscillator and final amplifier.

Final amplifier

The final amplifier raises the VFO output up to the level needed to drive the transmitter. The stage being driven in the transmitter is usually a "mixer" which we shall discuss in the next chapter. But, if the VFO is designed for the 80 meter ham band, then the next stage after the VFO could be a string of class C amplifiers to increase the output power to the final level, say 5 or 50 watts. The VFO final stage will need to deliver at least two volts peak sine wave. Since we have deliberately kept the oscillator and buffer signals tiny, the final amplifier must be a linear or Class A amplifier to get the signal level up to 2 to 5 volts peak. The drive to this transistor is biased with a 33K resistor so that this stage is always turned on.

Low pass filter

The drive to the transmitter should be as pure a sinewave as possible avoid radiating harmonics outside the hamband. A low pass filter on the output attenuates most of the harmonics above the desired frequency range. A Chebyshev low pass filter is shown designed for a 500

ohm load. In Chapter 6 you were introduced to Chebyshev filters designed for 50 ohms. However, here we have no need for power, just voltage. Therefore, the filter is designed for 500 ohms, which is plenty of power for this application. Values are given for both a 80 meter VFO (3.5 to 4.0 MHz) or a 5 MHz VFO (5.0 to 5.5 MHz).

****

The 50 secrets of avoiding drift

Suppose you were to build the above VFO without reading the details in the following paragraphs: When you first turn it on, you will be disappointed to find that it drifts a hundred Hz per minute or more. ***The drift is caused by temperature change***. The components expand and contract with temperature change and this causes small changes in the capacitance and inductance of the components. Air wafting across the board doesn't allow the temperature to stabilize. ***Drift is prevented by preventing temperature change and by choosing components that change as little as possible with temperature.***

VFO building is an art form as arcane as Grandma's secret piecrust recipe or the fine points of building Cub Scout Pinewood Derby racers. As you'll see, there must be 50 ways to improve the drift problem. I have never built a VFO that was a completely "stable" and probably never will. But perhaps that's because I only know the 14 secrets listed below. If you apply as many of these as possible, you should get within the 20 Hz target - and maybe even under 5 Hz.

Secret # 1. Junction Field Effect Transistors (JFETs) The first secret of a stable VFO is using a JFET instead of a bipolar transistor. As described earlier, a field effect transistor is better because it is less sensitive to temperature. I have used 2N3823, 2N5484 and 2N4416 N-channel JFET's for VFO oscillators. My impression is that any small N-channel FET works well.

Secret # 2. Seal the VFO in a cast metal box. Simply protecting the VFO from air currents makes a huge improvement. Use a heavy, cast metal box so that the temperature will at least change slowly. In contrast, a flimsy, sheet-metal aluminum box will heat and cool relatively rapidly. On the other hand, ANY box is a huge improvement over not having the circuit sealed from air currents.

Secret # 3. Use single-sided PC board. A double-sided PC board is constructed like a capacitor. That is, thin metal sheets are bonded to a layer of insulator. Unfortunately, the resulting capacitor has a significant temperature coefficient. As temperature increases, the board material expands (thickens) and the capacitance across the board drops. If the VFO is built on traces and islands that have changing capacitance to ground, the frequency of the oscillator will drift slightly.

Secret #4. Mount the oscillator PC board away from the metal case on standoffs. Using the same principle as above, do not mount the single-sided PC board flush against the metal case. By standing the board up and away from the case, the capacitance between the traces and the metal case can be minimized.

Secret #5. Choose and mount all components affecting the oscillator LC circuit carefully. All the L and C components in the oscillator should be designed for minimum temperature drift. Referring to the diagram, it is not just capacitors C1 and C2 that affect the frequency. Capacitors in series with the 220 pF capacitor, C3, C4 and even C5 affect the frequency. To at least a tiny

degree, ALL components in contact with these capacitances can affect frequency drift. These include the diode, the RF choke, the transistor and the 100 K resistor.

Secret # 6. Mechanical variable capacitors should be chosen carefully. Although good mechanical variable capacitors are hard to find, they may be the best solution for you. Pick a capacitor of about 30 to 60 PF, not larger. High capacitance variable capacitors are too sensitive to temperature change. Smaller ones don't tune far enough. ***Don't use a capacitor with aluminum plates*** – they warp too much with temperature. ***Brass is the best metal. Try to find a capacitor with thick, widely spaced plates.*** Paper-thin plates are compact, but warp readily with temperature change.

If the capacitor tuning is linear with degrees of rotation, the frequency it produces will be somewhat <u>non-linear</u>. Ideally, the capacitor plates should have a non-linear shape that allows it to tune an LC resonant circuit so that the frequency will be linear. Rotate the capacitor through its range and you'll see that a compensated capacitor has rotor plates that are not simple half circles. As they rotate, they do not mesh with the stator plates at the same point. The non-linear correction isn't a big deal, but it is something to be aware of.

Secret # 7. Varactors are the most stable tuning element. It's hard to buy mechanical variable capacitors that are mechanically and thermally stable. Collins Radio formerly tuned their VFOs with special powdered iron slug tuned coils, but I've never seen any for sale. A varactor capacitor controlled by a quality pot is a good solution to these problems. Varactors are a kind of silicon diode biased with DC voltage. In my experience varactors are an order of magnitude more thermally stable than mechanical capacitors. They are at least two orders of magnitude more mechanically stable. You can slap the VFO with your hand and, although other components may vibrate, the varactor doesn't change its capacitance.

Unfortunately, varactors produce a non-linear scale on the frequency tuning knob. This means that the high frequency end of the VFO range will be extremely detailed while the low end may be compressed into a few degrees of rotation. For this to be usable, the potentiometer should be non-linear to compensate. Varactors are discussed in detail below.

Secret # 8. Use NPO fixed capacitors. When selecting capacitors, look for type NPO. These are supposed to have minimum temperature change. Use these for ALL fixed capacitors affecting the LC circuit.

Secret # 9. Use multiple NPO capacitors in parallel to achieve a given value. If you must use fixed capacitors in parallel with C1 or C2, it is better to use several small ones in parallel than one large capacitor. The temperature of a small capacitor stabilizes quickly, whereas heat builds up more slowly in a larger capacitor.

Secret # 10. Temperature compensation for the LC circuit is essential. It took me four prototypes to accept this, but temperature compensation is as important as putting the VFO in a box. Lots of guys claim to have succeeded without it, but I never have. Not using temperature compensation implies that every capacitor and inductance in the VFO must have a zero temperature coefficient. Alternatively, all negative coefficients must be balanced precisely with components that have positive temperature coefficients. Good luck doing that! Compensation circuits are described below.

Secret # 11. Use an air core inductor. As usual, it is most convenient to use a powdered iron

toroid core. Unfortunately, powdered iron changes its permeability (magnetism factor) with temperature. Therefore, by not using iron, another variable is eliminated. I have successfully used old plastic pen caps as little coil forms for air-core inductors. I bore little holes in the plastic to accept tiny pieces of stiff copper wires to serve as wiring terminals.

If you do use powdered iron, among the CWS (Amidon) cores, type 7 is supposed to have the best thermal stability. CWS Bytemark (Amidon) #6 cores have worked reasonably well for me but maybe #7 would be a few percent better. If you make a coil out of turns of copper wire on a plastic form, the copper will change its dimensions slightly with temperature too. And because an air core inductor requires more turns of wire, there is more opportunity for the copper to change its dimensions, its interwinding capacitance and also its resistance. Finally, an air-core coil will couple like a transformer to nearby parts whereas a powdered iron toroid couples far less. Sigh. Nothing is perfect.

After you have your coil wound and working over the right frequency range, epoxy or clamp it to the board. Without the epoxy, the frequency will warble with the slightest vibration. I once tried to use slug-tuned coils. They were convenient to adjust, but were mechanically and thermally unstable.

Secret # 12. Precision voltage regulation for the VFO supply is vital for precision frequency stability. The 12 volt supply for the VFO as whole must be regulated. Ordinary voltage regulators like the LM317 or LM7812 gave me regulation within 0.1 volt. This was OK for frequency stability down to about 20 Hz drift. But to get down to less than 5 Hz, I needed to regulate my VFO power supply to a few millivolts. To achieve this, I built a precision supply that just powers the VFO. The less current the supply has to deliver, the more constant its output voltage will be. The supply is discussed in detail below.

Secret # 13. The VFO should draw as little power as possible. The less power drawn, the less heating that occurs inside the VFO box. Also, the less power drawn, the easier it is to build a precision voltage supply to drive the VFO. That is why the VFO was designed for a 500 load rather than 50 ohms like most ham RF circuits. The VFO as a whole should draw less 20 mA DC. 10 mA would be even better.

Secret # 14. Forget tube oscillators. You old timers may be tempted to use a tube oscillator. I first tried to update an old tube VFO, but tubes get hot and make temperature compensation too difficult. You'll have plenty of trouble without this extra burden. You may use bipolar transistors for the final amplifier in your VFO, but not for the oscillator. For good measure you may as well use a JFET for the buffer as well.

Vernier mechanical tuning and frequency indicator

Because a VFO must be tuned precisely to the other fellow's frequency, it is vital to use a vernier tuning gear between the tuning knob and the variable capacitor. In my opinion, the tuning knob should rotate at least three times around for each revolution of the capacitor. Without vernier tuning, it will be exceedingly difficult to tune your receiver or transmitter accurately to the other fellow's frequency. A planetary reduction gear is generally mounted on the front panel. Machine screws clamp it to the ¼ inch capacitor tuning shaft that protrudes from

the VFO box. Tuning gear systems are usually combined with a dial and pointer that you can calibrate. A paper dial can be marked with ink for the calibrations. A plastic cover protects the paper from moisture.

On one VFO shown above I used a National Company brand vernier dial. Recent interest in QRPs has made these available again after being absent for some years. Look for the ads in ham magazines. Unfortunately, these dials are pretty pricey. For some of my VFOs I used a military surplus reduction gear that had no pointer and dial. I made the pointer out of super-thin PC board painted black. The dial calibrations were on thin white cardboard covered with 1/8 inch Lucite plastic and screwed onto the front panel.

If you use a varactor variable capacitor as described below, you may be able to find a multi-turn potentiometer for your tuning vernier. This solves the vernier problem, but doesn't offer a way to calibrate the dial. Some hams have built elaborate frequency counters or digital voltmeters as solutions for VFO calibration. All I can say is beware of digital circuitry in your ham equipment. Homebuilt digital circuits nearly always generate radio noise that will interfere with hearing weak signals. Commercial manufacturers make digital technology look easy. But so far, all my digital toys have generated a static "hiss" that I have regretted.

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Varactor Tuning

Varactor Tuned VFO

A VFO tuned by varactor. The round potentiometer adjusts the voltage on the varactor.
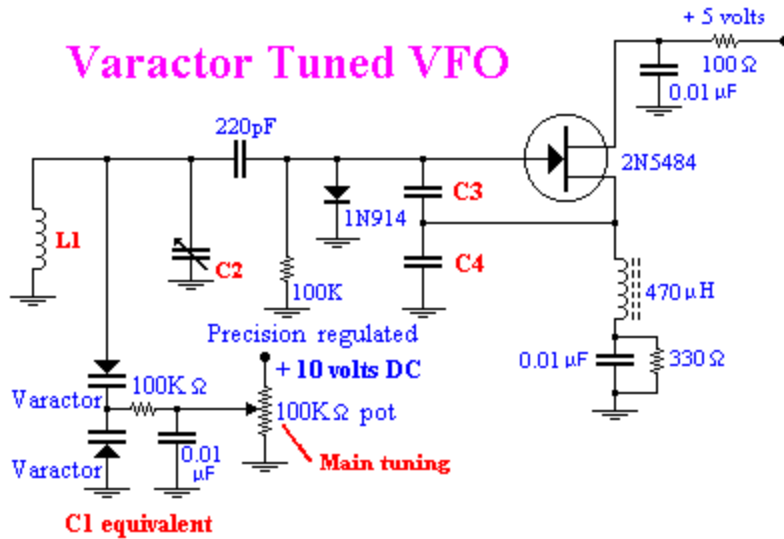
      While building a new receiver, I had to construct another VFO. In this prototype I explored replacing the mechanical tuning capacitor with varactors. Back-biased P-N junctions block the flow of charge as if they were capacitors. They not only act like capacitors, when back-biased, *they are capacitors*. The interesting aspect of this behavior is that, by biasing them with a DC voltage, say 0 to 10 volts, the capacitance can be tuned like a variable capacitor. As more and more voltage is placed across the diode, the ions in the semiconductor are used up and the charge it can store is diminished. In other words, PN junction diodes change their capacitance inversely proportional to the voltage on them. ***Varactors are voltage-variable capacitors.***

      Varactors are specialized P-N junction silicon diodes that were designed just for this purpose. However, I have seen VFO circuits that use ordinary silicon diodes like the 1N914 or 1N4148 for this purpose. One of the disadvantages of varactors is that they often don't have much capacitance. 5 to 20 pF is typical. Because of this, I didn't believe I could get enough tuning range from a varactor. It turned out that I could compensate by using two or more

varactors in parallel and by decreasing the size of the feedback capacitors C3 and C4. Tuning range wasn't a problem.

Since then I bought a varactor, Motorola type MV104, that has a capacitance of 110 pF. (!!!) This device has the potential to provide the large tuning range needed for covering the 10 meter band. Alternatively, it can be operated over a narrow range of bias voltage and thereby largely solve the non-linearity problem.

The advantages of varactor tuning are:

1. Varactors are mechanically stable. Assuming the potentiometer driving your varactor is mechanically stable, then the resulting VFO will be mechanically stable. You can bang the table with your fist and the frequency will barely warble in the receiver. With my mechanical variable capacitor VFOs, banging the table is almost a practical way to change frequency.

2. Varactors are more thermally stable than mechanical capacitors. When testing a mechanical capacitor VFO circuit with a hair dryer, I found that the blast of hot air on the circuit board caused the frequency to soar or plunge hundreds of Hz, sometimes even KHz. When my varactor VFO is given the same treatment, the frequency change is an order of magnitude less.

3. Varactors are available. Good mechanical tuning capacitors are hard to find, although sometimes RF Parts Co. has usable capacitors in stock. In contrast, varactors can always be purchased from Digi-Key, Mouser and other companies.

4. Varactors are tiny. Some of the ones I used are the size of a grain of sand. Soldering them on my circuit board required patience, sharp tweezers and a jeweler's loop. A VFO module made with a varactor can be much smaller than a VFO made with a mechanical variable capacitor.

5. Varactor VFO's may be tuned by phase-lock loops. Since the varactor VFO is tuned by a variable DC voltage, it can be part of a modern phase-lock loop design. A homebrew VFO doesn't have to be confined to old technology.

The problem with varactors

Alas, varactor-tuned VFOs are non-linear. However, you can turn this to your advantage. As the DC voltage is changed across the varactor, the frequency change it produces is not linear. When the voltage is first applied, the holes and electrons in the PN junction are filled in readily and decrease the capacitance rapidly. After the first big change, more and more voltage must be applied to fill in more holes and deplete the electrons in the N type semiconductor. In other words, the wider the tuning range, the more non-linear the relationship between applied voltage and frequency. This exaggerates the tuning of the high-end frequency end of the band. For example, if the varactor is pushed to its maximum capacitance range, then 75% of the voltage tuning range might be needed to cover the upper 25% of your total frequency range.

Suppose you are primarily interested in CW operation. The CW portion of the band is always at the bottom of the ham band with phone at the high frequency end. The linearity problem can become an advantage by designing the VFO frequency converter in your transmitter or receiver so that, for each band, the high frequency end of the VFO range covers the low CW end of the ham band. CW signals have little bandwidth, a few Hz, and the CW bands are often crowded. In contrast, although phone bands are sometimes crowded, the phone bands are several

times wider and the phone signals themselves each cover 3 KHz. In other words, good bandspread, (small frequency change for big knob rotation), is important for the CW band and not so important for the phone band. Yes, tuning in SSB phone requires fine-tuning. But you will find that tweaking the speech quality is more easily done with the BFO knob than with the VFO tuning.

For example, in a transmitter, the VFO might range from 5.0 to 5.5 MHz. To transmit on 40 meters (7.00 to 7.30 MHz), the transmitter could use a 12.5 MHz crystal controlled local oscillator to cover from 7.0 to 7.5 MHz. That is, 12.5 MHz minus 5.5 MHz = 7.0 MHz. In this way, the high end of the VFO tuning covers the *LOW* end of the ham band. In contrast, if you use a low frequency crystal, 2.0 MHz, the high frequency end of the VFO will cover the upper end of the band where bandspread isn't very important. That is, 5.00 MHz plus 2.00 MHz = 7.00 MHz. If you're confused, frequency converters are explained in detail in chapter 11.

Frequency offset on transmit

A transmitter VFO has a problem you may not have thought about. With an old-fashioned, wideband CW receiver, when you tune past a CW signal, you'll hear a whistle that changes from a high pitch to a low pitch or "zero beat," then rises back up to a high pitch as you tune past the signal. If your receiver were tuned precisely to the other guy's frequency, he would be at the "zero beat." His CW signal would have such a low pitch you wouldn't be able to copy it.

To fix this, modern transceivers automatically add a frequency offset between receive and transmit, usually 700 or 800 Hz. Also, fancy transceivers don't receive the lower half of the signal unless the operator selects LSB on the front panel. In general, the lower sideband (LSB) is used on 160, 80 and 40 meters while the upper sideband, (USB) is used on 60 meters, 30 meters and above. With a modern, narrow bandwidth receiver, modern hams may not even be aware that there are two sidebands. The upshot is that, when you answer a CQ with your homebrew VFO, you must tune in the correct direction about 700 Hz above or below his zero beat point. Otherwise he won't even hear you. Old timers used to tune around, but modern guys don't. I believe I had this problem when I first got on the air with my homebrew rig. Few stations seemed to be able to hear me. Yet, when I did talk to someone, I got good signal reports.

The simplest solution is to use the narrow bandwidth filters on your receiver so that you can only hear the upper or lower sideband at one time. Then when you zero beat your signal on top of the fellow calling CQ, you only hear your VFO when you are on the correct sideband. Narrow passband filters for a homebrew receiver are discussed in chapter 13.

VFOs for transceivers

If you build a VFO for a transceiver, the VFO will be used during both receive and transmit. As explained above, it may be useful to add a varactor tuned offset adjustment to the VFO so that you can send and receive on slightly different frequencies. To do this, add an auxiliary low capacitance varactor adjustor in parallel with the main tuning. The technology is the same as was just described for varactor tuning, but the tuning range will be one KHz or less.

****

A precision power supply for the VFO

One of my VFOs had a relentless upward drift of 200 Hz per hour. I was puzzled until I noticed that my 12 volt VFO power supply had a subtle downward drift. Ordinary voltage regulators are crude compared to temperature compensated regulator ICs. Regulators like the LM317 or LM7812 drift hundredths of a volt per minute, especially if the load is more than 100 milliamperes. A simple Zener diode regulator can easily allow one or two tenths of a volt change on the oscillator. The solution is to build a precision voltage regulator. This 12 volt regulator should be located <u>outside</u> the VFO box. So far as possible, anything that generates heat should be kept outside the VFO box.

Precision Zener diodes

The trick to building a precision, temperature-compensated power supply is a precision Zener diode reference. Ordinary Zeners vary their regulation voltage with temperature. Precision Zeners are integrated circuits that behave like precision Zener diodes, but have temperature compensation circuitry and can be adjusted to exactly the rated voltage. The LM336–5.0 Zener diode can be adjusted with a trim pot to precisely 5.000 volts DC. It is designed to have the best temperature compensation at that exact voltage. Other than the pot and the diodes, this part is used like an ordinary Zener.
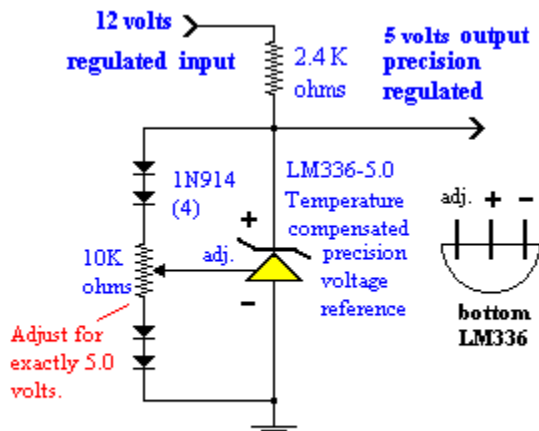
Precision 5 volt Zener

A precision 12 volt power supply

The precision voltage regulator shown below comes from the National Semiconductor Data Book for linear integrated circuits. This regulator will hold the VFO voltage constant to within about 2 millivolts. It uses a programmable LM317T regulator. The output of the big regulator is "modified" with a precision Zener reference regulator to hold the output voltage constant. The LM317 regulates the voltage across the 1.2 K ohm resistor to about 1.2 volts. The precision reference then regulates the voltage across the 620 ohm resistor to exactly 6.2 volts - that is, 1.2 volts plus 5.000 volts. Since the voltage across the 620 ohm resistor is held constant, the current passing through the 1K potentiometer is also held constant. Therefore, adjusting the 1K pot can adjust the total voltage

Precision Supply for the VFO
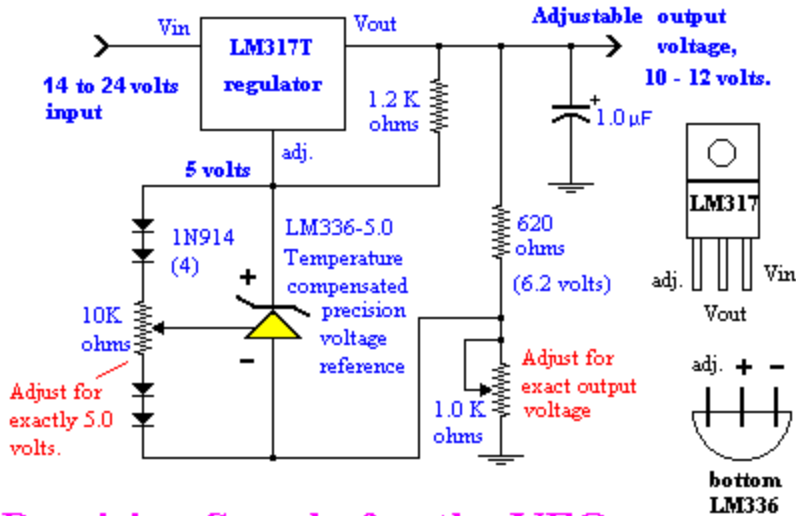
In order to maintain this high degree of precision, the above regulator just powers the VFO. When I tried to run other transmitter stages with the precision power supply, the load rose to several hundred milliamperes. Although the regulator chips were operating within specifications, the extra load ruined the millivolt precision regulation. I retrofitted my old capacitor-tuned VFO with the same precision regulator and found the frequency stability became as good as my newer varactor VFO.

I try to keep my VFO supply current down to less than 10 milliamperes. If you need more than a 3 volts peak output voltage, you'll probably find this difficult. In the full circuit shown above, by the time you get a 5 volts peak, pure sinewave, the current drawn from the supply is likely to approach 20 milliamperes. One way to compensate is to adjust the voltage from the precision supply to the bare minimum needed to provide the output waveform you need. That is, instead of using regulated 12 volts, use regulated 8 or 10 volts.

Separate regulation for the VFO oscillator

If your VFO is consuming more than about 10 mA, you may want to compensate for the temperature change inside the box by powering the oscillator inside the VFO box with 5 volts from a separate precision 5 volt Zener instead of using an ordinary 5 volt Zener.

A voltage doubler for battery use

If you're line powered, the regulator described above will probably work just fine, unless there is a brown out. On the other hand, if your transmitter is battery powered, its output voltage will fall well below 12 volts as the battery discharges. One solution is to run the VFO on regulated 9 volts. That way, even with 10 volts left on the battery, the regulator will still be providing 9.000 volts. However, if your VFO uses a varactor as the tuning element, you may need at least 10 volts to get the maximum tuning range from the varactor. My solution to this frustration was to first double the unregulated battery voltage. By starting with nominally two times the battery voltage, my VFO will always have at least 12 volts. Because the VFO only draws 10 to 20 mA DC, this DC voltage doubler does not have to be powerful.

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A DC voltage doubler

Square wave generation

Any time you wish to raise a DC voltage, it is necessary to use the existing DC supply to generate a source of AC voltage. For example, the AC voltage could be applied to a transformer to produce as high an AC voltage as you need. The high AC voltage would then be rectified back into DC at the required high voltage. Instead of using a transformer, the voltage doubler described below uses a ***charge pump*** to raise the voltage. As you'll see, this technique is a specialized kind of rectification.

The first task is to convert the DC supply to square wave pulses. It turns out there are many ways to generate square waves using integrated circuits. For example, I used an operational amplifier IC to generate the dots in the electronic bug in chapter 9. You may use an IC if you like, but you might enjoy doing it the hard way. As usual, if you're new to electronics, you'll learn some interesting stuff.
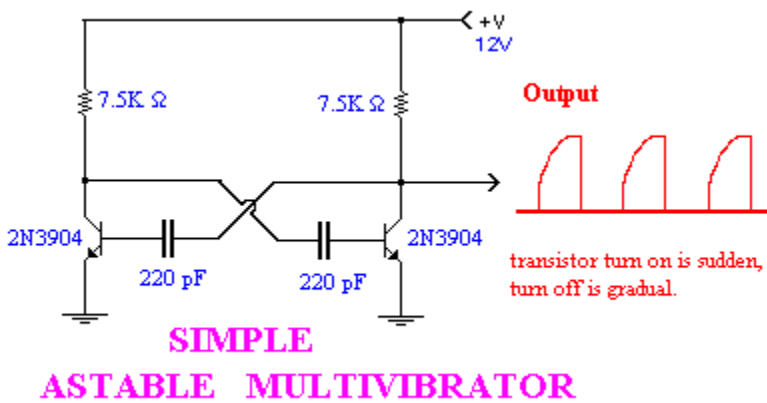
A <u>simplified</u> ***astable multivibrator*** oscillator is shown above. As you can see, this circuit consists of two grounded emitter amplifiers wired so that any change on the collector of one transistor is immediately coupled to the base of the other. Let's assume that the capacitor on the left is charged to a low voltage, say 1 volt. The capacitor on the right is charged to nearly 12 volts. The capacitor on the left is charging toward 12 volts through the 7.5 K resistor on the right. As the positive charge flows out of the capacitor and into the base, the left transistor turns on. This pulls its collector and its respective capacitor toward ground.

Since the voltage across the capacitor on the right can't change instantly, the voltage on the right base is pushed downward to roughly –12 volts. This extreme negative voltage turns off the right hand transistor. The right hand capacitor with its –12 volts will discharge toward zero volts since there is now no source of voltage to maintain negative 12 volts. This discharge takes a significant length of time because the current must bleed into it through the 7.5 K ohm resistor.

Eventually, the voltage on the right transistor's base rises above +0.6 volts which will turn the transistor back on. When the right transistor turns on, it pushes the left hand capacitor back down to –12 volts turning off the left transistor.

A practical multivibrator

The simplified multivibrator described above oscillates OK, but it doesn't always start spontaneously. In fact, you will find that it only runs at a specific range of supply voltage and must be turned on abruptly. If you turn up the supply voltage gradually, the multivibrator remains stable with one or both sides turned off and the oscillation never begins.
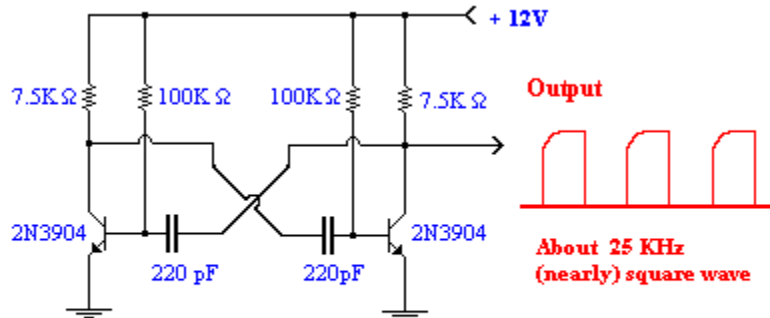
ASTABLE MULTIVIBRATOR

The unreliability of the simple multivibrator can be fixed by biasing the transistors partly *ON* with the 100K ohm resistors. These resistors insure that the capacitors will always be charging or discharging. Now the circuit will generate square waves even with very low voltages. When the power supply voltage is turned up slowly, the oscillation will always start. Also, the *ON* state of each transistor is maintained longer and a better square wave results.

Bistable multivibrators are RAM flip-flops

This is off the subject, but suppose that the two capacitors in the above circuit were replaced with high resistance resistors. Since there would be no reactance to charge or discharge, the circuit would "lock up" with one transistor *ON* and the other *OFF*. This is called a ***stable-*** or ***bistable-multivibrator.*** If a pulse is introduced to one transistor or the other, the circuit can be made to "flip-flop" to the opposite stable state in which the *OFF* transistor turns *ON* and the *ON* transistor turns *OFF*. This ***flip-flop*** circuit is the basis of static RAM memory (SRAM). One flip-flop can store one bit of information. So long as the supply voltage is applied, the circuit will "remember" one bit of information indefinitely. Or, it will remember it until another pulse comes along and resets it to the opposite state. In an integrated circuit SRAM literally millions of flip-flops are printed on a chip storing megabits of information.

Squaring up the low power square wave to drive a doubler charge pump

Now that we have a low-power, square-wave voltage, we need to clean up the waveform and amplify it so that we can produce about 30 mA squarewave AC for our VFO power supply. This is done with a simple buffer amplifier to make it square. A square waveform is important because the less time that the circuit spends "half turned on," the more efficient the power supply will be.

Buffer squares pulses

Input

Output

7.5K Ω

+ 12V

82K Ω

25 KHz
(nearly) square wave

100K Ω

2N3904

25 KHz square wave
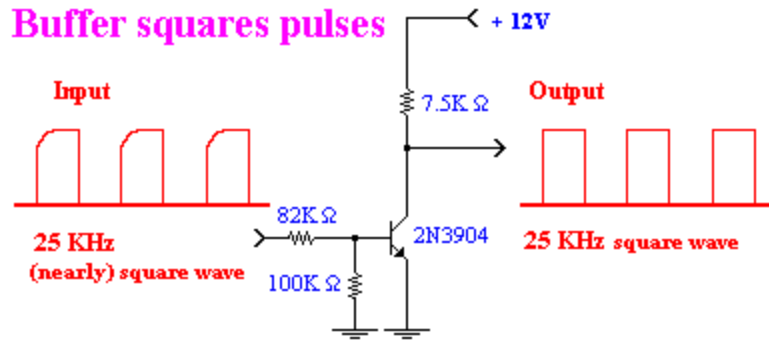
This square wave buffer is just a high gain voltage amplifier. During the sloping, rising input voltage, the upward slope of this voltage is exaggerated by 10 or 20 times. This diminishes the rise time until the rise time becomes negligible.

Diode voltage doubler

Charge pump voltage doubler

Schottky diode rectifiers

Output

+ 12V

Input

2N3053
NPN transistor

33 uF
15 WV

100 uF
35 WV

24 Volt DC

25 KHz square wave

2N2907
PNP transistor
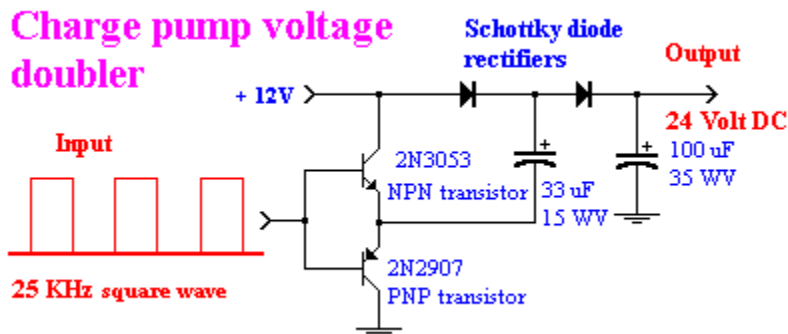
How can we "double" DC voltage using diodes? The idea is to repeatedly charge the 33 µF capacitor to +12 volts as though that capacitor were a rechargeable battery. Then the capacitor is switched out of its "charging mode" and added like a battery on top of the existing 12 volt supply. In other words, 12 volts plus 12 more volts equals 24 volts. This pulsing, 24 volt signal then charges up the large 100 µF storage capacitor on the right to 24 volts. Provided the current drawn from the 24 volts supply is small, the capacitor on the right can maintain a relatively constant voltage approaching 24 volts.

Complementary transistors in action

The switching tasks in the doubler are accomplished with transistors and diodes. The square wave buffer drives a complementary voltage follower power driver for the diode voltage doubler. In this circuit we use complementary NPN and PNP transistors. In chapter 4 I mentioned that it was often convenient to have transistors that work with opposite polarities. As the drive to one transistor turns it on, the same polarity turns its complement transistor off. The output is taken off the emitters. In effect, the complementary transistors connect the output back and forth between ground and the 12 volt supply. These transistors alternately make a solid connection to ground and the 12 volt supply line without any resistors becoming hot and wasting energy.

By the way, the logic circuits in your personal computer are almost entirely implemented

with integrated circuits made from complementary N-channel and P-channel MOSFET transistors. These ICs are called "CMOS." By avoiding resistor loads on the FET drains, heating is minimized and switching speed is maximized.

As shown above, the PNP and NPN transistors work together to pull the left hand capacitor up and push it down. When the PNP transistor is turned on, the bottom end of the capacitor is connected to ground. In this condition the diode on the left charges up the capacitor to 12 volts. When PNP turns off and the NPN turns on, the bottom end of the capacitor is suddenly shoved "up" and tied to the 12 volt supply line. Since the top of the capacitor is suddenly 12 volts higher than the supply line, the diode on the left is back-biased and can no longer charge it. Instead, the diode on the right is now forward biased and will discharge the 12 volts into the storage capacitor on the right. The capacitor on the right charges toward 24 volts, thereby creating twice the original voltage.

Use Schottky rectifiers for best efficiency

Now we have loads of extra voltage, even when the battery supplying the transmitter is nearly exhausted, so there is still be plenty of voltage for the precision regulator to generate 12.000 volts. The supply works best if the two diodes in the voltage doubler are power Schottky diodes. These rectifier diodes only waste about 0.2 volts per diode when conducting current. The down side of Schottky rectifiers is that they can usually only tolerate about 30 volts maximum, but that's plenty for this application. In the circuit below I used ordinary 1N4001 silicon rectifier diodes. Each of these wastes about 0.7 volts when turned on. Consequently, my 24 volt supply only delivers about 22 volts when the input is 12 volts.
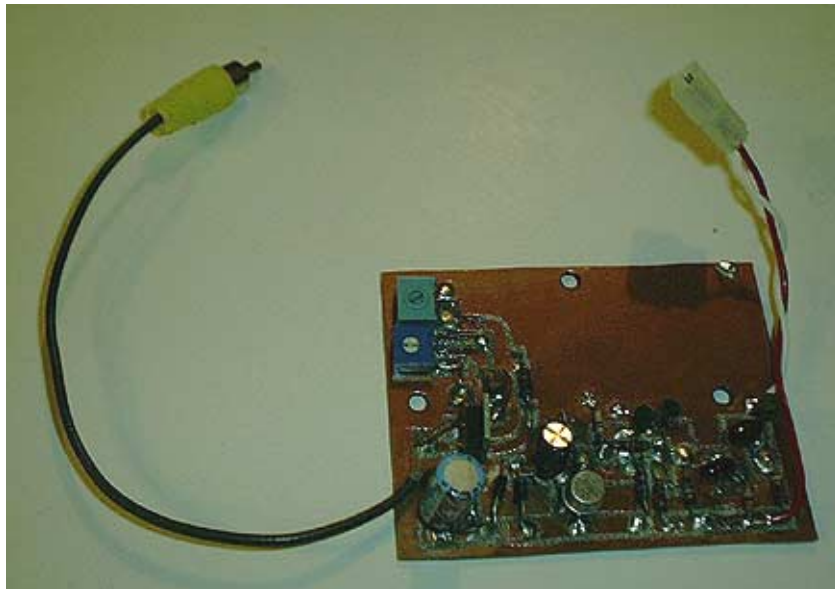
VFO power supply board. Variable battery voltage input, precision regulated 12 volts output.

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TEMPERATURE COMPENSATON

Supposedly, good VFOs can be built without temperature compensation. Personally, I've

never succeeded, but don't let me be a wet blanket! Go ahead and try. Just leave room on the PC board to add compensation later.

The strategy of compensation is to substitute C2 or C4 with a capacitor that has an adjustable *positive temperature coefficient*. ***Nearly all the parts in an LC circuit typically have a negative temperature coefficient***. That is, when the temperature rises, the capacitance drops and the frequency rises. Therefore by paralleling the capacitance with a capacitor that has an equal but opposite <u>positive</u> temperature coefficient, the capacitance change will be cancelled. I suggest you start with this method of temperature compensation since it is the easiest.

Positive coefficient trimmer capacitive compensation

If you look in Digi-Key, Mouser or other parts catalogs you'll find occasional trimmer capacitors with positive temperature coefficients. That is, capacitors that increase their capacitance with temperature. I used 20 to 40 pF variable trimmer capacitors made by Sprague-Goodman, type GCL. I replaced some of the fixed capacitance in the capacitive divider, C2 and C4, with two positive coefficient trimmers in parallel*. **The clever part is obtaining both the correct positive coefficient and the correct amount of positively changing capacitance. This is done by using a similar negative coefficient trimmer in parallel with the positive trimmer.*** By balancing the positive coefficient trimmer directly against the negative coefficient trimmer, you can produce a total positive coefficient value that compensates for the actual negative coefficient of the rest of your LC circuit.
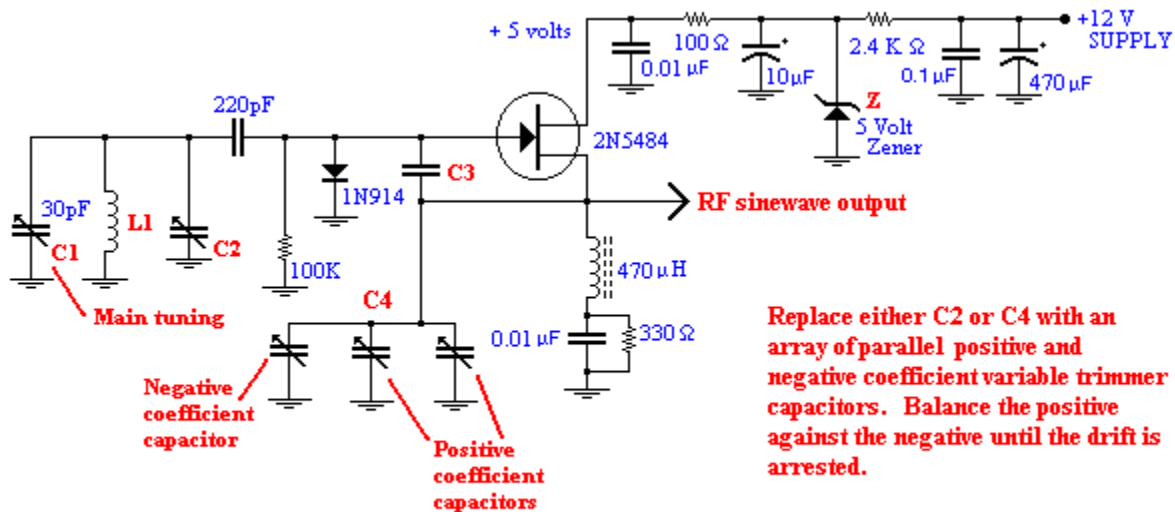
POSITIVE TEMPERATURE COEFFICIENT COMPENSATION

Adjusting VFO temperature compensation

Put a 500 ohm load on the VFO output and put probes across the load for your scope and frequency counter. Check that your voltage supply is set where you want it, say 12.000 volts. It should rock stable within a millivolt or two. If you're using a mechanical variable capacitor, set the capacitor to maximum capacitance. Now adjust the positive and negative coefficient trimmers to midscale at the desired low-end frequency of the VFO. For example, with a 5 to 5.5 MHz VFO, you would set it to 5.000 MHz (or just below). Check that you can still tune up to 5.5 MHz using the main tuning capacitance. If you can't, you may have to change C3, or fiddle

with C4 or C2. Remember that C2 can also be a positive or negative coefficient trimmer, depending on what you need.

Now put the lid on the box but don't screw it down. Watch the frequency drift on your frequency counter. You will almost certainly see it ***drift relentlessly up or down.*** If it is going down, assume this is caused by increasing temperature in the box. Turn a positive trimmer to *LESS* capacitance, then adjust a negative trimmer to restore the frequency back to where you started. Repeat this again and again until the drift direction reverses. Now it should be going relentlessly *UP*. Now take off just a bit of the negative trimmer until the drift comes to a halt. When you get them balanced well, the frequency will still change, but now it will ***wander up and down but soon return to the same frequency***. That is, the frequency will no longer march continuously in the same direction. When you get to this point, you have done as well as you can with your present set of components. With luck, during any given minute it won't wander up or down more than 5 Hz.

****

Thermistor temperature compensation

You may find that your positive trimmer capacitance compensator just doesn't give you enough positive compensation to do a good job. A ***thermistor*** compensation circuit may be just what you need. I had good results with the ARRL handbook circuit below.
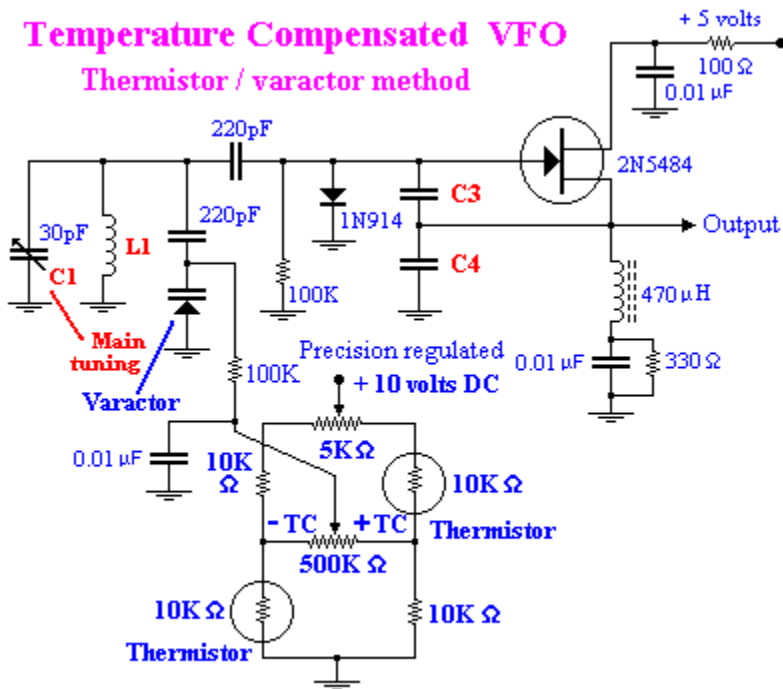
Resistors are usually designed to change as little as possible with temperature. However thermistors are resistors made from semiconductor that has a large temperature coefficient. The coefficient can either be positive or negative, and both kinds can be used in the above circuit. The

thermistors are placed in a bridge circuit with a thermistor on each side of the bridge. The entire circuit is powered by a precision regulated supply, 5 to 10 volts. By adjusting the 5K and 500K trimmer pots at the top and middle, the degree and direction of compensation can be selected. Tuning the 500K pot to the right selects more positive compensation. Tuning to the left selects less positive compensation or even negative compensation. If you need more capacitance, you can always parallel two (or more) varactors.

Temperature regulation

Another approach to temperature compensation is to hold the temperature constant by heating the VFO and regulating the temperature with a thermostat. I built such a device inside the lid of my cast metal box. The heater had a resistive heater element and a thermistor-controlled temperature regulation feedback system. The good news was that it regulated the box temperature to within 0.1 degree Fahrenheit. The bad news was that it took the temperature at least 30 minutes to stabilize and, when installed in the transmitter, the regulator was trying to heat the entire transmitter and perhaps the whole room. In other words, a heated VFO box will need extensive thermal insulation in order to be practical. I gave up on this idea.

In conclusion, precision voltage regulation, temperature compensation and careful adjustment can produce a homebuilt VFO that doesn't drift like a homebuilt. When you get on the air and describe your rig as "all homebrew," the stations you work will often shower you with praise. Enjoy every compliment. If you needed as many prototypes as I did to develop a reasonably good VFO, you deserve every compliment. Actually, the best complements I've had were when I yacked with guys for an hour without any complaints about my drift. Especially if I was able to avoid discussing my funny homebrew transmitter. For all they knew, I was using a high quality modern transceiver.

CRYSTAL SETS TO SIDEBAND
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Chapter 11

Building a VFO and QRP for the higher bands
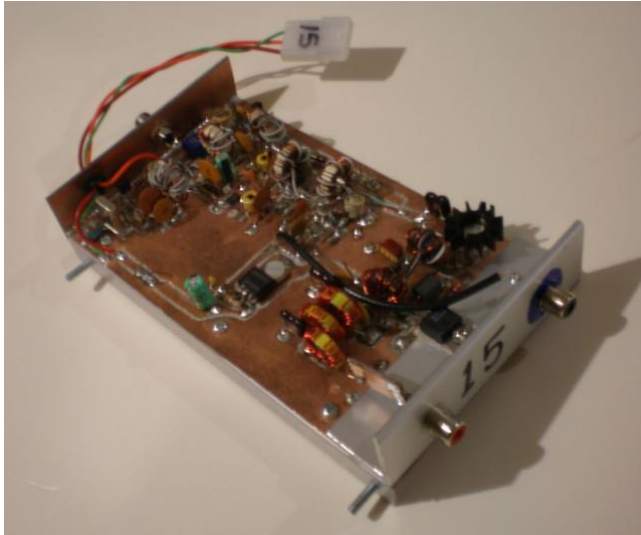
A QRP CW module for 15 meters is shown above. In some ways this module resembles the crystal controlled QRP module described in Chapter 6A. Instead of a crystal, it uses the low frequency VFO described in Chapter 10. A crystal-controlled premix oscillator (PMO) converts the low frequency VFO sinewave up to the desired ham band. This may seem overly complicated, but it's the best way to transport the stability of a low frequency VFO up to higher bands. The high frequency crystal oscillator drift is usually no more than 2 Hz per minute. This drift is added (or subtracted) from the low frequency drift and results in drift that is acceptable to modern hams receiving on their store-bought digital masterpieces.

If we had built a VFO for 21 MHz and we used all the tricks described in Chapter 10, the VFO drift would be at least 5 times worse. You may remember that the receiver described in Chapter 7C has a high frequency analog VFO. Unfortunately, if I used it to control a transmitter on 15 meters, I would receive howls of complaints. Other stations won't complain if your receiver drifts, but the Chapter 7C receiver drifts so much that I was not able to add multiple crystal filters or even sharp CW audio filters.

The 15 meter module receives an 80 meter VFO signal and converts it to cover the 21.000 to 21.450 MHz hamband. The VFO signal and DC power come in at the back. The 5 watts of RF output exits from the red phono jack at the left front on the heat sink. The telegraph key port on the right is marked with blue. The Chebyshev output filters are visible in the foreground. The PMO filter amplifiers are at the rear. It would be more professional if it were enclosed in a metal shield, but I like to see all the components.

You can't multiply frequency anymore

In the old days, it was customary to build a VFO for 1.8 to 2.0 MHz or 3.5 to 4.0 MHz.

Then for higher frequencies, we ran the signal through successive frequency multiplier amplifiers to get 7, 14, 21 and 28 MHz. A frequency multiplier was simply an amplifier tuned to the second or third harmonic of the input frequency. By using an amplifier tuned to multiples of the base frequency, the desired harmonic can be selected. For example, the tapped-coil tuned amplifiers described in Chapter 6A work well for this purpose.

If your driving oscillator is crystal controlled, then frequency multiplication is still practical. However, if your VFO drifts more than about 2 Hz /minute, you may get complaints on the upper bands. For example, if you have an 80 meter VFO you will have to multiply the frequency eight times to raise the frequency up to 28 MHz giving a drift of 16 Hz. But, if your VFO drifts 5 Hz, then the multiplied signal will drift 40 Hz at 28 MHz.

Fortunately, carefully built high frequency crystal oscillators can be quite stable even up to 30 MHz. The solution to the drift problem is to "add" a low frequency, wide band VFO to a stable high frequency crystal oscillator. These crystal oscillators are called *Pre-Mix Oscillators* or *PMOs*. A *mixer* performs the frequency addition by literally combining two sinewave signals. The composite signal contains, not only the original signals, but also signals with frequencies that are the sum and difference of the original frequencies. Filters follow the mixer to extract and amplify the desired frequency component. The process is illustrated by the block diagram of a 20 meter QRP transmitter shown below:
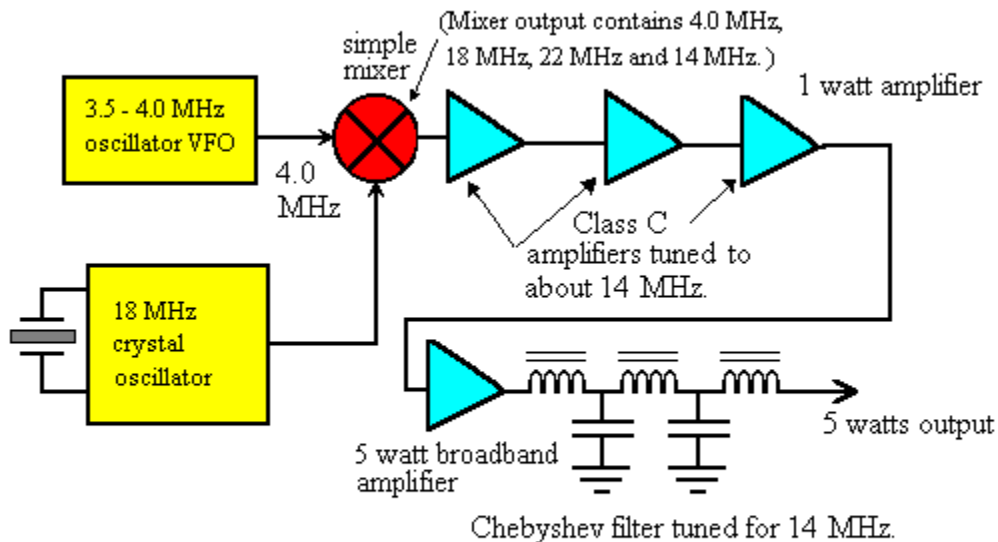
20 Meter 5 Watt QRP Transmitter Block Diagram

PreMix Oscillator method of frequency translation

In the diagram above, an 80 meter VFO is "converted" to 20 meters. The 80 meter sinewave is mixed with the output from an 18.000 MHz crystal oscillator. When the VFO is set to 4.0 MHz, the output from the mixer is a messy looking waveform that contains four frequencies, namely - 4.0 MHz, 18 MHz, 22 MHz and 14 MHz. By tuning the next three

amplifier stages to 14 MHz, the "contamination" goes away and we get a pure 14.0 MHz sinewave tunable up to 14.5 MHz. The Chebyshev filter attenuates frequencies above 15 MHz. Without it, there might be a significant signal broadcast on the second harmonic, 28 MHz. The crystal oscillator may contribute a Hz or two of drift, but basically, the drift on 20 Meters is the same as it was on 80 Meters. The mixer is comparable in function to those used in superheterodyne receivers, but PMO mixers are much easier to build. Low noise and extreme image canceling aren't necessary because both input signals can be as large as you like.

****

CRYSTAL OSCILLATORS ARE STABLE, AREN'T THEY?

Several years ago I thought I had the VFO problem conquered. I had just enjoyed a nine-month "VFO vacation." During this time my signal was so stable that no one ever commented on it. I was quite proud of myself. Then I built QRP modules to get on 17 and 30 meters. Suddenly the complaints started up again and I was mystified. After all, I was using the same VFO. What had changed?

I checked out my VFO. I discovered that, when it was cold, it drifted downward 20 Hz the first minute. Then, after a few more minutes, it stabilized and the drift was plus or minus a 2 or 3 Hertz /minute. Of course, by definition, whenever I start sending, the VFO is cold. Therefore, unless I send for minutes on end, it will always be drifting. But even so, that didn't explain the 100 Hertz complaints.

Surely, it couldn't be the frequency converter crystal oscillators, could it? Crystals drifting!!?? Blasphemy! I checked out my 17 and 30 meter crystal oscillators. The 30 meter crystal oscillator drifted downward 50 Hz the first minute, 25 Hz the 2nd minute and eventually stabilized 150 Hz below the starting frequency.

Use HC-49 or larger crystals

The drifting of my 30 meter converter was caused by the crystal. The crystal was a teeny-weeny flat metal can, about 1/4" square and a 1/32" thick. It had come from my junk collection and I don't know what size number it was. However, I've since concluded that all the tiny ones in my collection aren't as stable as the HC-49 or larger crystals. Little bitty overtone crystals are particularly bad. Yes, eventually they settle down and become reasonably stable. But by then you have switched the QSO (conversation) over to the other guy. Now your oscillator is cooling off again so it will be ready to drift during your next transmission.

Not all tiny crystals are bad. I have some little half-size 9.00 MHz HC-49 crystals that work quite well in my receiver BFO and IF filters. The lesson I learned was that I need to check my oscillator stability during that first critical minute. The drift after 5 minutes is interesting, but not important for a ham transmitter.

TTL oscillator blocks

The 17 meter board had one of those sealed-in-a-can, TTL oscillator blocks. They're like an integrated circuit with the crystal and oscillator sealed in the same package. I used one because it was the right frequency and I happened to have it in my junk collection. Yes, I remembered to run it at the correct 4.5 volts TTL voltage, not 12 volts. My oscillator started out at the right frequency, but it ran surprisingly hot. Then it dropped at 25 Hz per minute. Although

the drift slowed, the frequency never stopped sinking. I had a big bag of various frequency oscillator blocks and they all did that. Every one I tried was terrible! All except the really high frequency ones - like 50 or 100 MHz. ... Those were <u>really</u> terrible. Some moved as much as 500 Hertz a minute. The only good news is that they're consistent - they all drift downward. It did not occur to me to try running the oscillator blocks at lower voltage, say 3 volts or lower.

Solutions to crystal drift

I could leave the crystal oscillators running continually. That could work with the ones that stabilize. There is no reason why crystal oscillators in a receiver can't be left running. The transmitter doesn't have to listen to receiver oscillators. However, I would probably be able to hear harmonics of a transmitter oscillator signal in the receiver. No, thanks. I already have some whistling artifacts in my receiver. Also, transmitter stability is more critical than receiver stability. If your receiver drifts a little, you're the only one who will notice. You could blame the drift on the fellow you're talking to. On the other hand, we homebrew guys shouldn't be quick to criticize others. The problem is probably ours, not theirs.

All oscillator circuits are not equal
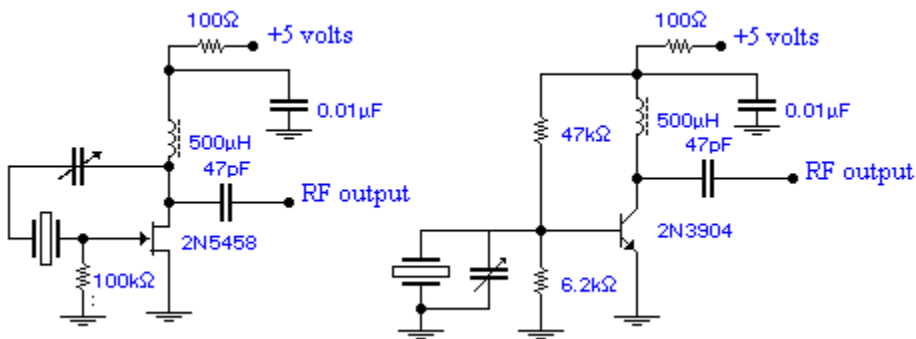
Two common crystal oscillator circuits

The drawing above shows two common crystal oscillator circuits that I used in some of my early QRP PMO converters. The variable capacitors are used to trim the frequencies to the exact Hertz. Both oscillators have the crystal connected to the base or gate. Remember that feature and you'll know which oscillators to be wary of. In my experience, *these gate or base-connected crystal oscillator circuits drift downward when first turned on.* Finally, after a minute or two, they stabilize.

Plan your frequency converters so the drifts cancel

Suddenly I understood why I received no complaints while using my 40-, 20- and 15-meter crystal-controlled frequency converters. They used oscillators with the crystals connected to the bases like those above, but the crystal frequencies were 4 MHz above the target band. As the oscillators drifted downward for the first minute, typically at 20 Hertz per minute, my 4 MHz VFO was also drifting downward at the same rate. For example, (25 MHz - 20 Hz crystal drift) minus (4 MHz - 20 Hz VFO drift) = 21.000,000 MHz. The result was a relatively constant frequency and no complaints. After a couple minutes the drifting stopped and the crystal oscillators were slightly more stable than the VFO.

Notice that if these converter crystal oscillators had been below the target hamband, then the drifts would have been added instead of subtracted. It turned out that my receiver was designed this way. Oops! Oh well, no ham has ever complained about my receiver during a QSO. Because I run my receiver oscillators non-stop, initial drift isn't important.

Butler is better
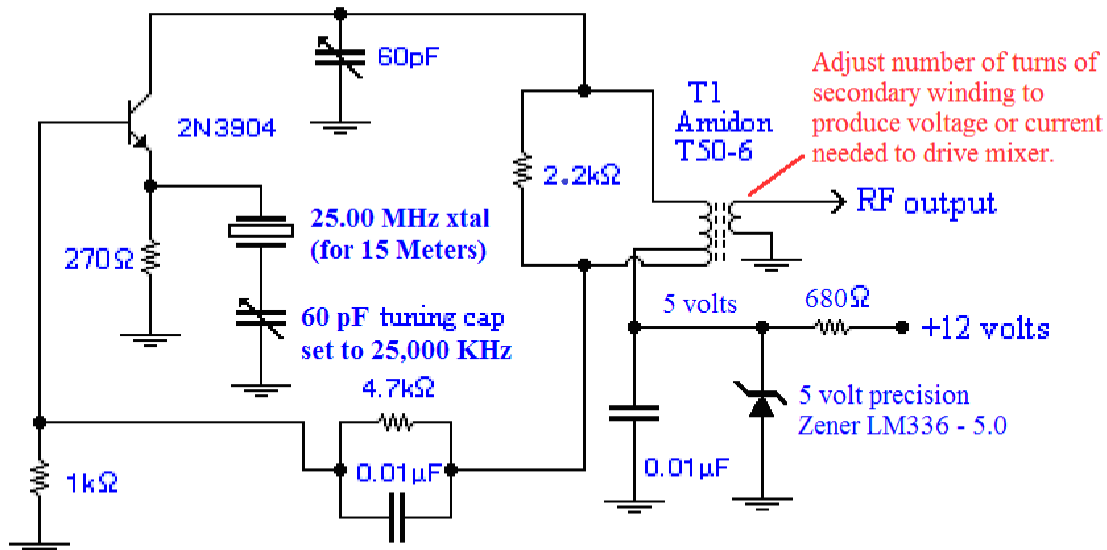
BUTLER OSCILLATOR WITH 5 VOLT PRECISION SUPPLY

A Butler crystal oscillator

I checked out every oscillator in my rig and discovered that some of them didn't drift when turned on. The stable ones used the Butler crystal oscillator above. Notice that the crystal and its capacitor are in parallel with the emitter resistor. This circuit is stable the moment you turn it on. Perhaps it's because the crystal has little voltage across it and receives little power to heat it. Anyway, Butlers typically drift no more than a hertz or two per minute. Two of my oscillators showed zero Hertz drift during the first minute. This is the same oscillator I recommended in Chapter 6. Depending on your application, Butler also has the advantage that the series capacitor can pull the frequency lower than the base-connected oscillators above.

You may be wondering about the purpose of the 2.2K ohm resistor across the primary winding: Without this resistor the oscillator will have maximum output. However, it will lock onto the crystal poorly and the frequency will be primarily controlled by the LC tank circuit. Also, the frequency will drift noticeably with changes in voltage or temperature. When the resistance is low, such as 2.2K, the frequency will always be controlled by the crystal. Unfortunately, the output amplitude may not be adequate. If your crystal isn't very active, you may have to increase the resistance to say, 10K ohms. Or you could try another crystal. As you can see, the resistor value is a tradeoff between stability and amplitude.

Drastic solutions to crystal drift

Suppose that you have done all of the above and your oscillator still drifts significantly. This is likely to happen with the higher frequencies, such as 25 MHz or 32 MHz. If necessary, the techniques in Chapter 10 for making a stable VFO can be applied to crystal oscillators. The simplest alteration is to run the oscillator on regulated 5 volts instead of 12 volts. This is illustrated above. This requires little board space and can be done without starting over with a new circuit board. Yes, I know. I've gone bonkers with the LM336 - 5.0 precision regulators. I started out just using them in VFOs and power supplies, but now I'm using them with crystal oscillators as well. Drifting is a huge problem and I've found that this is one of the few simple improvements that always makes an obvious difference.

The decoupling and voltage dropping resistor to the 12 volt supply is a 680 ohm resistor. A Zener diode is wired across the 0.01 µF "voltage reservoir" capacitor. The LM336 - 5.0 volt regulator can be used without the four diodes and trim pot. Without this fine adjustment it will still provide the stability you need to get you through those first 2 minutes of transmitting. If you measure the 5 volt supply during use, it will stay within a millivolt of where it started. This eliminates a big variable. Ordinary 5 volt Zener diodes do not work nearly as well.

Of course, when you reduce the oscillator supply from 12 to 5 volts, the oscillator output voltage will drop to 41% of its former level. If the crystal oscillator is driving a dual-gate MOSFET mixer, the mixer input impedance is extremely high. MOSFETs require very little drive current at only 1 or 2 volts. The oscillator will still function if you wind 2 or 3 times more turns on the secondary winding of the oscillator transformer. This will restore the 1 or 2 volts drive to the mixer. You will have to retune the oscillator because of the extra accidental capacitance the windings have added. However, the mixer will function as before. If you are using another style of mixer, a large secondary winding may demand too much current from the oscillator and stall it. In this case you will need to add an amplifier after the crystal oscillator. There may not be room on your circuit board, so this might be awkward. In short, build your crystal oscillator first and be sure it has the stability and voltage drive you need before you proceed.

A VFO controlled QRP
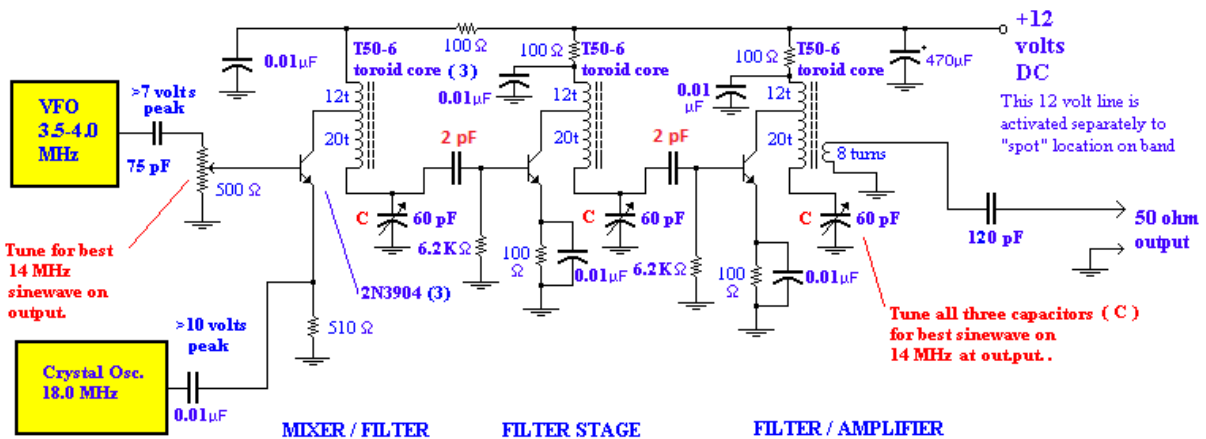
QRP DRIVER FOR 20 METER CW (14 MHz)

My first successful design for a CW QRP driver is shown above. Unfortunately each QRP driver covers just one band. However, once it's tuned and working, it covers the entire band without further tuning or fussing. Taken as a whole, the entire circuit shown above can be considered as "a 14 MHz VFO." It took me all those parts to generate a stable sinewave on 14 MHz! A simple crystal oscillator using 14 MHz crystals gives the same result, but of course it will only tune a few KHz at best. Life is hard for homebuilders in the 21st century.

I should mention that the same filter train can be designed so that it could be tuned up for several different bands, for example 20 meters through 10 meters. But of course, changing bands would mean changing the crystal oscillator and retuning the entire chain for the new band – not exactly convenient band switching.

Multi-band QRP modules

So far, I've built seven versions of this design covering 40 through 10 meters. My 80 meter QRP is just a simple amplifier that directly amplifies the VFO. Boy, was *that* easy! So why didn't I build one driver that works on every band? Each of the 7 difficult QRP modules are different and each one had to be tweaked and modified to get it working. By the time I had built the last QRP for 12 meters, my circuit was somewhat standardized. Unfortunately, I predict your versions will also need modifications in order to get 4 or 5 watts of clean sinewave out of each QRP module. I have only recently reached the confidence level where I might (again) consider attempting a multi-band transmitter. I did manage to build three different 2-band SSB QRP modules as described in Chapter 15. However, each 2-band module ended up unique and each needed many hours of troubleshooting and adjustment. Somehow, a circuit that worked on one band didn't work properly on another without changing the turns on a broadband secondary, changing transistor bias, different interstage coupling or using a transistor with lower or higher gain-bandwidth product (high frequency rating). A bandswitching CW transmitter that covers 160 through 10 meters is a formidable challenge for a homebuilder. A multi-band SSB transmitter is even harder.

Back in the vacuum tube days, multi-band transmitters were easy to build. That's because the spectral purity and stability of our signals back then was awful. Even the inexpensive commercial equipment was poor. I returned to ham radio after a 30 year absence. I brought my faithful old Heathkit DX-20 with the Heathkit VF-1 VFO down from the attic. The complaints about my signal quickly drove me off the air. I gave the these antiques to my local amateur radio club. The club sold them to raise money at a hamfest. Today I'll bet they slumber in someone else's attic. If you're a lightly-equipped tinkerer like me, you'll find that building even one band to work to modern standards is much harder than it looks. I suspect that's why hardly anyone does this kind of scratch-built homebrewing anymore. I strongly recommend that you start simple.

Changing the direction of tuning

In the 20 meter QRP driver above, the 80 meter VFO is mixed with an 18 MHz local oscillator. Note that the oscillator could also run at 10.5 MHz. As an experiment I ran my 20-meter QRP with both 18 MHz or 10.5 MHz crystals. All I had to do was change the crystal and it worked well. The 14 MHz filter remained properly tuned with no adjustment. The operational difference is that the direction of the VFO tuning reverses. As explained in the last chapter, this might be useful if you are using a varactor VFO and need to have the high frequency end of the VFO range tuning the lower end of a ham band.

The NPN transistor mixer needs a big local oscillator drive signal

The mixer stage in the 14 MHz converter shown earlier is just an RF amplifier made out of a bipolar 2N3904 transistor, much like the amplifiers in the filter train. This mixer is a class C amplifier stage with a 500 ohm emitter resistor. We can use class C because the input signals are much larger than 0.6 volts. One input, usually the VFO, feeds into the transistor base in the usual fashion. However, this drive level is adjustable with the input pot.

The local oscillator input is applied across the emitter resistor. I usually inject the higher frequency input across the resistor, but I've done it both ways. Unlike the input to the base, the input to the resistor has no amplification gain whatsoever. In order for the emitter signal to produce a big signal on the collector, all of the signal amplitude must be impressed onto the 500 ohm resistor.

A lesson I learned the hard way was: ***Both input drive signals must be strong enough to turn the mixer stage full on and off like a switch, cycle by cycle.*** In the bipolar transistor design I needed at least a 20 volts peak-to-peak sinewave on the emitter resistor. A wimpy little 2 volt crystal oscillator signal will produce little difference-frequency component in the output and it will take many stages of filtering to extract the desired frequency. To get 20 volts pk-to-pk signal drive, I had to amplify the output of the crystal oscillator through an additional amplifier stage before it went into the mixer. I threw out two boards before I figured this out. I'm a slow learner.

On the other hand, the second input signal from the VFO, can be small because it is amplified by the transistor. Later, when you're tuning up the whole filter/ amplifier string for best output, you'll find that the maximum output and purity occurs at a specific setting of the input pot. The optimum VFO input level is not simply the maximum available amplitude.

The LC filter/ tank circuit on the mixer collector is tuned to the desired sum or difference frequency.   Using the formulas in your CWS (Amidon) T50-6 core literature, calculate the inductance needed to go with your trimmer cap to resonate at the desired band, just the way we did in Chapter 6A. I found that T37 cores were too small and didn't produce the gain per stage that I got out of the T50s. In contrast, the T68 cores were unnecessarily large. Chapter 13B describes a superheterodyne receiver that uses band converters similar to these PMO QRPs. There is a table of coil specifications which can you guide you on the type of powdered iron core to use and the numbers of turns for the windings.

The simplest mixer of all

I can't believe I didn't try this sooner! Here is a single transistor class A amplifier just like my usual NPN hi-Q RF amplifier. Instead of the amplifier amplifying just one signal, it amplifies both the VFO and the high frequency crystal signal simultaneously. It is driven by two 220 pF capacitors connected to the base.

CAPACITIVELY ADDED TUNED MIXER
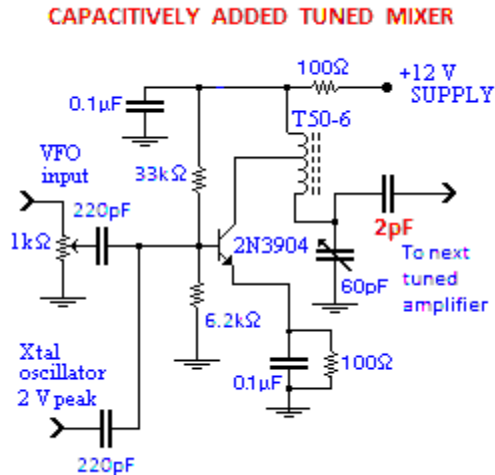
It worked perfectly in my rebuilt 40 meter QRP. One capacitor is driven by the VFO and the other is from the higher frequency crystal oscillator. The two signals are added across the one base-to-ground resistor. You need greater than 2 volts from both sources for this to work.

As you can see, mixers for this application can be quite simple. I have since learned that the following mixer designs are more complex than needed. The dual gate MOSFET mixer is suitable for superheterodyne receivers and is an expensive extravagance for this application. On the other hand, it works well and, because I hadn't yet tried the dual capacitor input mixer, I used MOSFET mixers for most of my QRP drivers.

Dual gate MOSFET mixers
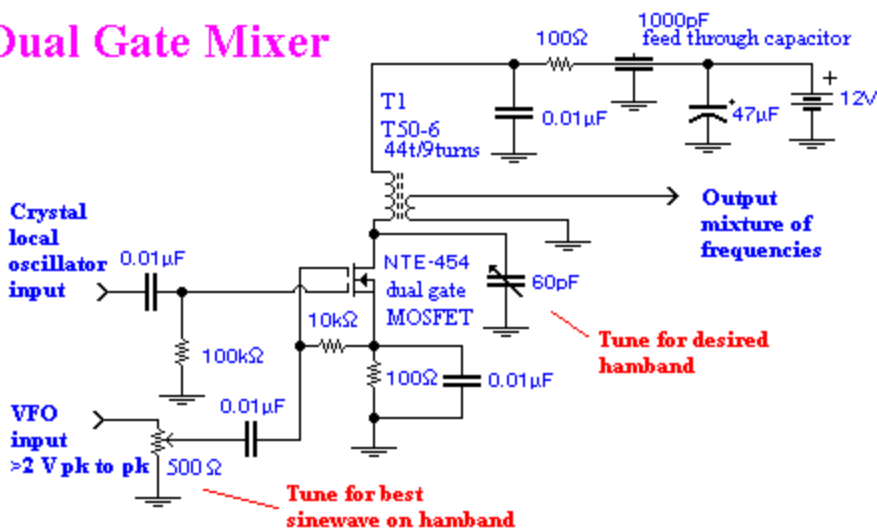
I began using dual-gate MOSFET transistor mixer stages in a receiver project and found them superior in several ways. A dual gate MOSFET is a small RF transistor with *TWO* input gates. Otherwise, in principle a dual gate works just like the power MOSFETs described in Chapter 6. Since both gates have lots of voltage gain, small signals may be used on both inputs. I found that each gate only needs 2 volts peak-to-peak and the output is much easier to tune and

filter. Dual-gate MOSFETs formerly cost $7 to $10 each. Consequently, I didn't use them everywhere I would have liked. However, in 2012 dual gates such as the 3N140 became more widely available again and cost $3 or $4.

Even better, the surface mount versions such as the BF994S or BF996S cost about 70 cents each. The bad news about surface mounted dual-gates is that they are the size of a grain of sand with 4 tiny pins projecting from the corners. Using a knife, I cut an "X" in the PC board making 4 electrically isolated quadrants. The transistors are so tiny that the cuts to form the center of the "X" must be very fine, no more than about 0.5 mm wide. Solder a tiny drop of solder to one quadrant. Under a jeweler's loupe and holding the transistor steady with a pencil point, place the transistor in the center of the "X" and press the point of your sharpest soldering iron onto the pin over the solder droplet. After it sticks in place, you may solder the 3 other tiny pins in the remaining quadrants. Finally, go back and properly solder the first pin.

Steel tweezers work poorly to hold surface mount transistors because the magnetism in the steel sticks to the nickel in the transistor leads. These miniatures work as well as the "gigantic" old style TO-72 transistor case versions and, needless to say, they take up far less room on the board. I believe any dual gate will work well in the VFO frequency converter application. Mixers in superheterodyne receivers are not so uncritical, and some types may work better than others in your circuit.
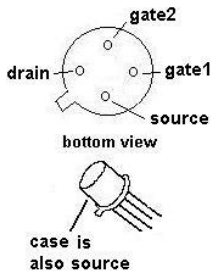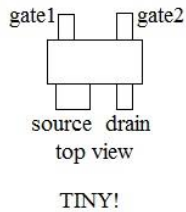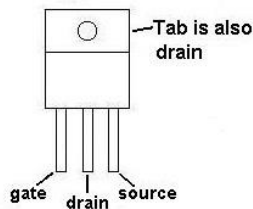
The economy dual gate mixer
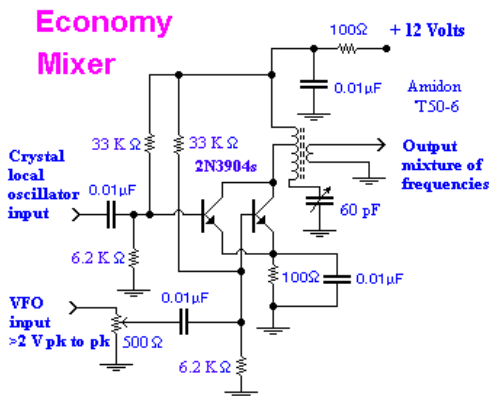
It turns out there are many ways to build QRP mixers. Two bipolar transistors in parallel can produce gain like the dual-gate MOSFET. If both input signals are small, both transistors will need forward bias, the 33K resistors. If one of the inputs is large enough, say 5 volts peak or larger, you won't need the forward bias for that input. This circuit would be plenty sensitive for a receiver mixer. However, because it has PN junctions, it will be noisier than the dual-gate MOSFET mixer and not recommended for receivers.

Tuning the mixer

When you first apply the two input frequencies to the mixer stage, the scope will show a messy, complicated waveform on the collector (or drain). It will be impossible see what setting of the trimmer capacitor on the drain is best. The first step is to disconnect the input frequency that is farthest from the desired output frequency. Now it will be easy to tune the trimmer for maximum gain. For example, in the 20 meter filter train shown earlier, tune the first mixer/ amplifier to the crystal frequency of 18 MHz. When it's peaked at 18 MHz, look to see if the trimmer is at or near maximum or minimum capacitance. If it is near minimum capacitance, but not quite there, the mixer stage should tune up well at the lower frequency, 14 MHz. If the gain at 18 MHz is maximum while the capacitance is tuned to either minimum or maximum, then you know that your toroid coil has too many or too few turns. Trimmer capacitors usually rotate freely around and around, so minimum and maximum are not obvious. *When your mixer coil and capacitor are correctly matched to your desired frequency, there will be two optimum settings in each 360 degree rotation of the adjustment screw*. If there is only one best setting, it means that your coil has too much or too little inductance and the mixer is not working as well as it could.

Later in the receiver Chapters 13A and 13B and the sideband Chapter 15 there are examples of un-tuned, broadband mixers that could also be used. Broadband mixers don't need tuning and they are less likely to self-oscillate. However, they have less gain and for PMOs you will need more stages to reach the same degree of frequency purity.

Filtering the desired frequency from the mixture

At the mixer drain (or collector) there are four frequency components and you must filter the one you want into a pure sinewave. I first considered using complex Chebyshev filters as described in the ARRL Handbook. I was discouraged by the many inductors and capacitors needed to achieve the desired "pure" output. Besides, my first attempt worked poorly. Eventually I realized that Chebyshev filters have the advantage that they can be designed for arbitrarily low impedances - in other words, high power signals. In the PMO application here the signal is extremely high impedance (low power) and relatively simple parallel LC filters are adequate. Chebyshevs are not needed. Using LC filters between broadband RF amplifiers for frequency conversion is illustrated in the SSB transmitter in Chapter 15.

My CW transmitter uses two sharply tuned amplifiers as filters, just like an IF amplifier in a receiver. The ease of filtering depends on how far the desired frequency is from the local oscillator and other mixer products. For example, on 14 MHz, the 4.0 MHz VFO is 28% of the desired frequency. 14 MHz compared with the 18 MHz crystal oscillator is 77% of the desired frequency. 18 MHz is pretty close but isn't a problem. Now suppose we use a 32 MHz crystal on 10 meters (that is, 28 MHz). With a 4.0 MHz VFO, the desired frequency is 88% of the crystal frequency. You will find that tuning this is much more "tweaky," difficult, but still practical. In general, having the crystal oscillator *BELOW* the desired frequency makes tuning the filters easier.

In summary, the tuned amplifier approach is reliable for CW and is extremely hi-Q. It can separate frequencies that are quite close. However, it is not suitable for use in an SSB transmitter because the hi-Q amplifiers tend to self-oscillate during pauses in the speech signal.

Bandpass "filter amplifiers" - they just filter and don't amplify

Each filter/amplifier stage is essentially like the bipolar transistor mixer shown earlier. However, the emitter resistor is bypassed with a capacitor so that, from the point of view of the RF, the emitter is connected to ground. The purpose of the parallel RC connected to the emitter is to stabilize the gain and reduce the DC current drawn by the stage. You may use either class A or class C amplifiers. I often use class A amplifiers, meaning the stage is biased "ON" at all times with a 33K resistor, just as we did back in Chapter 6A. Class A amps draw more current than class C amplifiers that are basically the same circuit. However, they handle wave components of any amplitude. To say it another way, class As work over a wider range of input amplitudes and don't introduce harmonics that must be filtered out.
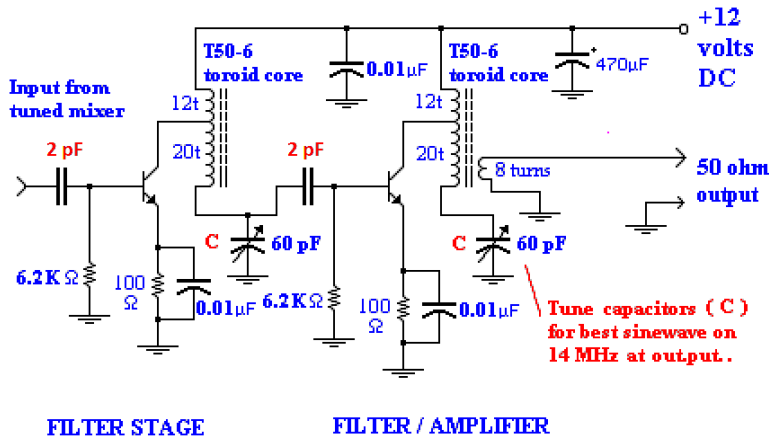
FILTER FOR 20 METER CW (14 MHz)

An RF filter/ amplifier stage

Two stages of filter/ amplifiers are shown above. Including a tuned mixer stage, three stages of tuned amplifier were enough for any HF band using an 80 meter VFO. However, as explained earlier, when you are trying to separate two frequencies that are only 10% different, having only 3 filter stages is just barely practical. If you are having trouble getting a pure sinewave, just add another tuned stage. As shown above, the above stages are class C. If desired, you could forward bias these amplifiers on with 33K ohm resistors and convert them to class A amplifiers. In this way, they could handle smaller signal levels.

Use tiny interstage coupling capacitors

The *BIG SECRET* to making "filter amplifiers" work is to use tiny coupling capacitors between amplifier stages. Notice the **2 PF** capacitors between stages in the diagram above. The purpose of these amplifier stages is filtering, not power gain. The LC circuit "rings like a bell" when the input contains a frequency that resonates with the LC. This ringing exaggerates the desired frequency component. If you load the LC circuit by trying to couple significant power to the next stage, it's like putting your hand on a ringing bell. The ringing will be damped and the filter effect dies. To avoid damping the ringing, use tiny 2 pF capacitors. OK, on 80 Meters maybe 5 pF is acceptable. And on 10 meters 1 pF works well. However, 2 pF works over the entire HF spectrum. If you use large coupling capacitors, say 50 pF, that 50 pF becomes part of the LC resonance and will dominate the tuning and lower the Q. Also remember that your scope or counter probe contributes another 15 pF or more. *To make a final adjustment of a filter*

stage, you must put the oscilloscope or counter probe on the output of the stage FOLLOWING the one you are adjusting.

With one stage of filtering after the mixer, the waveform will still look "messy" on the scope.   But after two stages of filtering it should be possible for your frequency counter to lock onto the correct frequency. As you tune the VFO, the reading on the counter should track solidly with no drifting and dancing digits. When properly tuned, the sinewave will look nearly perfect on the oscilloscope after two stages of filtering. When you first try to tune up all three stages at once, you may be frustrated, but keep trying. When your counter "locks" onto the desired band, look at the ringing on the trimmer of the last stage with the scope while tweaking all the previous stages for the best sinewave. Notice that perfection occurs when you trim the input level of the VFO on R1. Now you understand why the input is applied through a trim pot.

If you own an RF signal generator, you have a simple way to tune up filter/ amplifiers. Unplug the VFO and replace that signal with a test signal from the generator set to the desired ham band frequency, i.e., 30, 20, 15 meters, etc.. If your L-C tuned circuits are designed correctly, they will peak up in the right ham band immediately. Your circuit will appear to ignore the signal from the crystal oscillator. Then, when you plug the VFO back in, the L-C circuits will be tuned correctly with little or no adjustment.

In general, QRPs for 40 meters are easy. But if you use an 80 meter VFO, your filters will easily tune up on twice the VFO frequency. That means the tuned amplifiers could ignore the 11 MHz input and tune up on double the VFO frequency. For instance, if you want 7.040 MHz and you use an 11 MHz crystal, the VFO must be set to 3.960 MHz. I found it easy to tune the filters out of the band to 7.920 MHz.

An advantage of the filter-amplifier design is that the 2 pF interstage coupling capacitors are extreme high pass filters. This means that the filter produces a clean sinewave with few or no low frequency artifacts. In other words, when you look at the waveform on the oscilloscope, there will be no tall waveform cycles and no short ones that occur periodically. A messy waveform makes it difficult for your frequency counter to lock and produce a stable, reliable frequency reading. If you use the filter method described in Chapter 15, it will produce more low frequency artifacts and the final amplifier stages may have to be modified with low pass filters to get rid of these impurities.

Running low on 2 pF capacitors?

Tiny 1 pF or 2 pF fixed capacitors are rare. If you don't have any, simply solder a couple inches of insulated wire to the base of the transistor of the following stage. Then pass the free end of the wire through the transformer core of the preceding stage and wind one to 3 turns. Do *NOT* solder the free end to anything. (If you ground one end, it will short out the DC bias resistors.) The wire is merely "a conductive object" that makes a small capacitance with respect to the primary winding. For instance, I measured 2.5 pF of capacitance with two turns on a T50-2 core.

The capacitance between the center conductor of coax to the outer coaxial shield can also be used to make small *homebrew capacitors*. Here is a terrific example: I used to work with an electronics engineer, Bob Anderson. Before I knew him he had worked on the Apollo command module spacecraft, the moon ship. Bob's job was to design and build the manual joystick control

system used by the pilot. The only time the manual system was ever used while re-entering the atmosphere was during the Apollo 13 mission. The crew capsule was crippled and frozen, the batteries were nearly dead and the crew was exhausted. As you can imagine, the joystick servos had to be fast and tight with a precise response. A slow or sloppy response might have allowed the crew module to tumble during re-entry causing them to burn up in the atmosphere.

At that time NASA insisted that analog parts in electronic designs could not be adjustable. Trimmer pots and trimmer caps were specifically forbidden. NASA didn't want technicians to diddle with trimmers after the electronics left the factory. Unfortunately a servo system with this speed and precision required little trimmer caps, exactly the kind we use in our QRPs. Bob managed to make his servos meet specifications easily enough, but he was stumped by how to tune the damping and overshoot without variable capacitors.

It was a Friday and he was supposed to demonstrate his finished servos to NASA engineers Monday morning. He struggled all weekend, living rough in the lab. Late Sunday night he had the brainstorm. He soldered one end of short lengths of thin coax, (such as RG-174), across the points where trimmers were needed. He used his diagonal cutters to clip the loose ends of the coax shorter and shorter until the servo stabilized. If he cut off too much, he soldered on a new, slightly longer piece of coax and then carefully pruned it to the ideal length. Monday morning arrived and NASA was satisfied. The servos never failed on a flight.

Where to get crystals for your local oscillators

Yes, you need a separate crystal for each band. Fortunately, when using an 80 meter (4 MHz) VFO, standard microprocessor frequencies can cover the major ham bands. The 40, 20, 15 and 10 meter bands can be covered by standard crystals for 11 MHz, 18 MHz, 25 MHz and 32 MHz respectively. Mouser Electronics and Digi-Key sell these for less than $1 each. For WARC bands and 160 Meters you may have to spend some money or be creative. As explained earlier, don't use those TTL oscillator blocks. Cheap ceramic resonator "crystals" are also a poor idea. Significant drift is not worth saving a few dollars. I simply surrendered and ordered custom crystals for 30 and 17 meters, 13.7 MHz and 21.9 MHz, respectively. For 12 meters I used an 86.15 MHz VHF overtone crystal (case size H-49) I happened to have. I tuned the oscillator to the crystal primary frequency, 28.72 MHz, and it worked well. $86.15 \div 3 = 28.72$ MHz. I haven't built a QRP for 160 meters because my largest antenna is inadequate for that band.

The QRP power amplifier stages

Your VFO now tunes the HF band of your choice. To increase this signal up to 3 to 5 watts, you will need two or three stages of power gain as described earlier in Chapter 6A. My QRP boards use two power amplifier stages. The first is a tuned stage. The second is a broadband amplifier followed by a Chebyshev lowpass (or high pass) filter designed for 50 ohms. This scheme seems to combine the advantages of both systems. For example, suppose I connect the QRP output to a non-inductive 50 ohm dummy load. All the CW QRP boards I have built have no trouble delivering a clean sinewave into a dummy load. Tuning is easy, *until* you have to connect it to a real antenna or to a final amplifier. A tuned stage gives you a way to adapt to loads which have some reactance.

QRP 5 watt amplifier
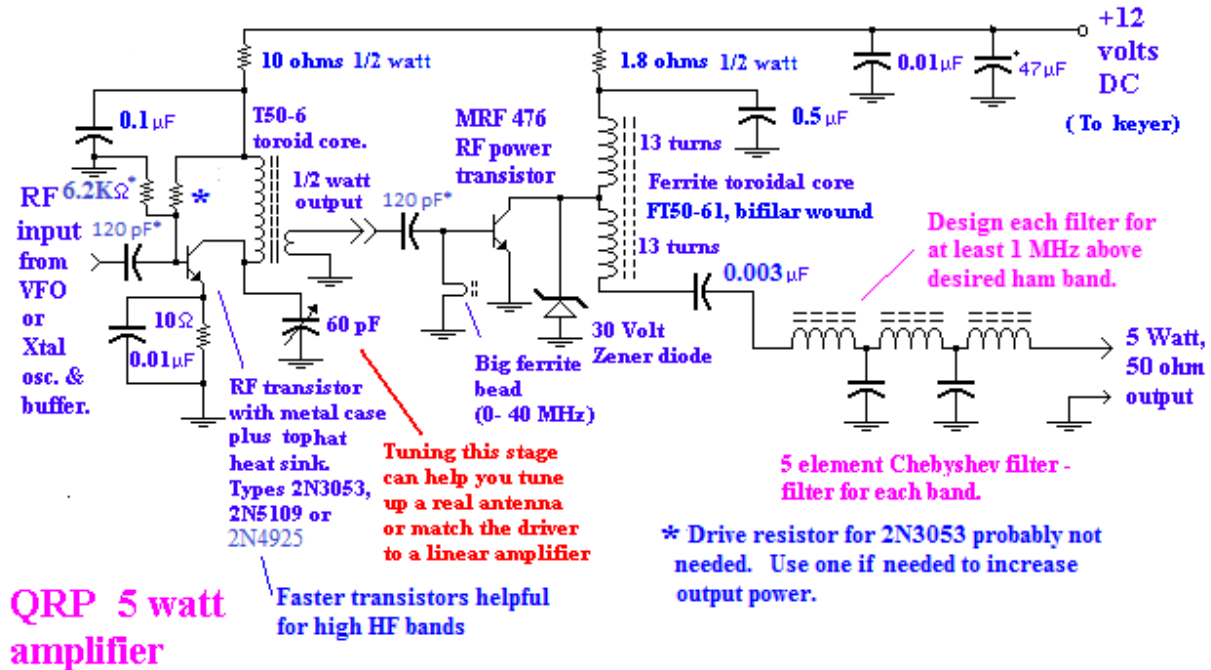
I recently built a prototype 10 meter AM modulated walkie-talkie that used this circuit for the second amplifier following the crystal oscillator. I began by using a tapped inductor tank circuit like the inductors in the oscillator and buffer. However, I got better performance and more power output by using a simple L-C parallel tank as shown above. The L-C circuit simply becomes an inductor essentially in parallel with the tuning capacitor. For 10 meters the walkie-talkie used 15 turns primary and 4 turns output secondary on a T50-6 toroid.
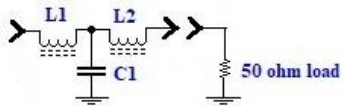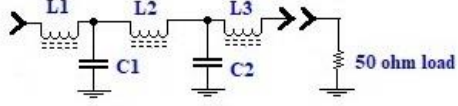
The driver stage above is tuned and resembles the buffer stage following the crystal oscillator stage. Depending on the number of turns on the coils in the tuned amplifier stages, these stages can tune two or more bands. For example, with 27 turns on the primary using a T-50-6 toroid, you can (barely) cover 20 to 10 meters assuming your capacitor tunes widely enough. The secondary would be about 4 to 6 turns. The input of a grounded emitter transistor amplifier is a low impedance. Therefore the transformer lowers the voltage and raises the current to "match" the impedance.

The driver transistor 2N3053 or other type may need a metal heat sink "hat" clamped on top to help keep it cool. The smaller 2N2222 transistor will also work, but will be damaged easily because it lacks the mass and surface area to dissipate the heat. I worked a fellow with a homebrew QRP who was using three 2N2222s in parallel to achieve sufficient cooling for his two watt output stage. Be sure to design the printed circuit traces to be as short as possible on all power stages. Notice the big ferrite bead with a loop of wire through it that connects the base of the MRF476 transistor to ground. This is an example of a low pass filter needed to shunt low frequency artifacts to ground. The MRF476 transistor is hard to find these days. Fortunately the 2SC2166C is a direct (and inexpensive) replacement. I tried some and confirmed that they work OK. Because they are relatively cheap, you might also use a 2SC2166C in place of the 2N3053. It can share the heat sink used for the MRF476. Unlike small, free-standing transistors, heating won't be a problem.

Chebyshev output filters

Some readers complained about the design method for designing Chebyshev 5 component Low Pass filters that was described in Chapter 6A. That method looks confusing and requires *MATH!* I sympathize. I also find math annoying because, as soon as it gets complicated, the equations usually don't simulate the real circuit and *DON'T WORK*. However, **simple equations**, like the ones used in this book for inductors and filters, are often a Godsend. If an equation accurately predicts circuit values, it can save you a day of trial and error. Have faith and try it!

Here is an easy method for designing 50 ohm output filters. The data is from page 15.11 in the 1986 ARRL handbook. The downside of the formulas shown below is that the tables only cover 50 ohm loads and a certain level of ripple - noise. If you want a higher impedance load, like 500 ohms, you'll need the other method.

3 Component Low Pass Filter

L1, L2	C1
5.007 µH	3088.5 pF

Inductors in µH, Capacitors in pF, (Ripple in dB = .01)

Components "normalized" to 1 MHz, 50 ohms.

Example: For 10 meters, pick a frequency well above 29.7 MHz to minimize interference. 34 MHz will work. Divide the 1 MHz values by 34.

$L1, L2 = 5.007 \, \mu H / 34 = 0.147 \, \mu H$

$C1 = 3088.5 \, pF / 34 = 90.8 \, pF$

5 Component Low Pass Filter

L1, L3	C1, C2	L2
6.019 µH	4157.3 pF	12.55 µH

Inductors in µH, Capacitors in pF, (Ripple in dB = .01)

Components "normalized" to 1 MHz, 50 ohms.

Example: For 10 meters, pick a frequency well above 29.7 MHz to minimize interference. 34 MHz will work. Divide the 1 MHz values by 34.

$L1, L3 = 6.019 \, \mu H / 34 = 0.177 \, \mu H$

$L2 = 12.55 \, \mu H / 34 = 0.369 \, \mu H$

$C1, C2 = 4157.3 \, pF / 34 = 122.3 \, pF$

High pass output filters

Higher frequencies like 15 meters and above are often plagued by low frequency components. If the output capacitor from a stage is a tiny capacitor, it can often reduce low frequency noise. Naturally there is a trade off between low frequency noise and attenuation of the output from the stage. The QRPs described here tend to produce low frequency noise that makes the output appear in bursts or even chaos. Low capacitances such as 120 pF can serve as high pass frequency filters which can remove low frequency distortion from the output sinewave. The capacitance value is a compromise between distortion and loss of power. 0.01 µF may work in the final stage instead of the 0.003 µF "high pass" coupling capacitor shown above. The values shown above settled my 40 meter QRP into a stable sinewave with just a tiny trace of low frequency, AM-like, modulation. A T-type antenna coupler removed the last of it.

High Pass 50 ohm output filters

For upper HF bands and VHF bands, like 10 meters and above, a simple small output capacitor and the ferrite bead on the MRF476 base may not be enough. The 50 ohm output filters shown below will help get rid of the low frequency contamination and improve the quality of your CW tone. In Chapter 15 they were necessary to the remove the audible rough noises and produce clear SSB speech. Yes, there will probably also be higher frequency components that might

interfere with TV or UHF frequencies. A TVI preventing filter like the one in Chapter 9 may solve your harmonic problem. Alternatively ... MORE FILTERS!   You're the engineer - fix the problems one by one as they attack you.

Here are the equations for calculating high pass output filters:

3 Component High Pass Filter

C1	C2	L1
5059.1 pF	5059.1 pF	8.201 µH

Components "normalized" to 1 MHz, 50 ohms.

Inductors in uH, Capacitors in pF, (Ripple in dB = .01) Example, for 10 meters: Pick a frequency well below 28 MHz to minimize interference. 24 MHz will work. Divide each 1 MHz value by 24.

$C1, C2 = 5059.1\,pF\,/24 = 211\,pF$

$L1 = 8.201\,µH\,/24 = 0.341\,µH$

5 Component High Pass Filter

C1	C2	C3	L1	L2
4208.6 pF	2018.1 pF	4208.6 pF	6.098 µH	6.098 µH

Components "normalized" to 1 MHz, 50 ohms.
Inductors in uH, Capacitors in pF, (Ripple in dB = .01)
Example: For 10 meters, pick a frequency well below 28 MHz to minimize interference. 24 MHz will work. Divide the 1 MHz values by 24:

$C1, C3 = 4208.6\,pF\,/24 = 175\,pF$, $C2 = 2018.1\,pF/24 = 84\,pF$

$L1, L2 = 6.098\,µH/24 = 0.254\,µH$

Noise mode

A common problem when checking out the completed QRP is that it may work properly at low supply voltages, like 6 or 8 volts, but when you raise it to 12 volts, the output turns into a roar of random noise and overlapping blurs on your oscilloscope. You may even hear the static in your FM radio. This is usually caused by feedback through the power supply between the output stage and previous stages. This is why you need the RC decoupling circuits on the +12 V DC supply line which go to each transistor stage. Increasing the resistor values, starting close to the final and working back toward the mixer, may fix the problem. Another cause can be the coupling capacitance between stages discussed earlier.

The last tuned stage in the amplifier/ filter chain

Notice that the capacitors and resistors surrounding the last tuned stage have asterisks next to the component values. When I examined each of the high band modules to re-write this section, I realized that *no two of my modules were alike!* I apologize, but this circuit is finicky. The best operation is achieved when you experiment with the bias and coupling to the tuned stage. Forward bias, the 33K resistor, may not be needed.

I recently built a 10 meter AM modulated walkie-talkie prototype. I discovered that I got more power out of the tuned stage by not using the tapped output coil. Consequently in this stage of amplification the L-C circuit is simply an inductor in parallel with the tuning capacitor. Because the power supply has big capacitors and little ceramic capacitors across it, the RF passes through it as though it was simply a wire - an impedance of zero ohms. That means that soldering the tuning capacitor to ground is equivalent to connecting it to the supply voltage. The advantage of connecting it to ground is that the adjustment screw on the trimmer is now at ground voltage and it may be touched with a metal screw driver without effecting the tuning.

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A related problem with this QRP design is that it's sometimes difficult to get the full 5 watts, even at relatively low frequencies like 20 meters. Also, when you do get your 4 or 5 watts, the output may not be stable and will tend to go into noise mode. A sign of the cause can be that, when you adjust the last tuning capacitor, it only has one optimum point. This optimum point is usually at **minimum** capacitance and doesn't tune sharply. The can happen when the secondary of the transformer is coupled to the final stage with a large capacitor, like 0.01 µF. (0.01 µF = 10,000 pF.) This capacitance may be coupled back to the primary and swamp the little 60 pF trimmer. That is why the output of the QRP driver circuit shown above has a 120 pF capacitor at the output, not a 10,000 pF capacitor. When the minimum coupling capacitor is used, you can tune the last stage and get optimum power output. On the other hand, 0.01 µF may work well for you. I was just examining my 3 highest frequency QRP modules. Two of them have the 0.01 µF cap. If it works well, it's good enough!
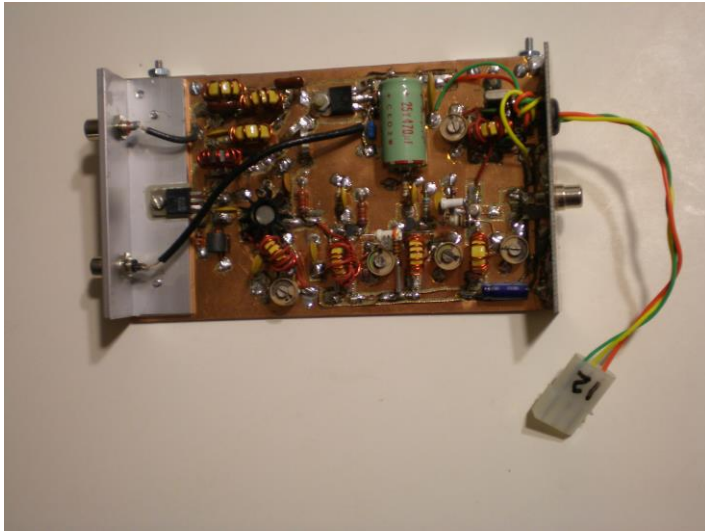
The 12 meter PMO QRP module. The last tuned stage is on the lower left.

12 Meters and higher frequencies need compact circuitry

At 10 and 12 meters it was impossible to get 5 watts out of my QRP drivers. At first, 2 watts output was the best I could do at 10 meters with the design described above. Moreover, the linear amplifier described in Chapter 12 could only increase this power level 4 or 5 times. So, although my linear delivers 100 watts at 80 meters, I could only get 10 watts on 10 meters. I tried adding a broadband "booster amplifier stage" between the QRP output and the linear amplifier input to increase the power. The booster made absolutely no difference in the power delivered to the antenna.

The light dawned when I discovered that I could mistune the tuned filter/ amplifier stages

in the QRP so that they resonated at 14 MHz instead of 28 MHz. The slope of the rising portion of the sinewave on the oscilloscope screen was the same as it had been before, but now the voltage had time to rise twice as high before it had to turn around and descend to the bottom of the 14 MHz sinewave. That is, the same rate of change on the voltage sinewave produced twice the voltage and 4 times the power. Suddenly my 2 watts QRP output on 28 MHz became 8 watts on 14 MHz. Wow!

This experience teaches us that, the higher the frequency, the better the craftsmanship must be. All component leads and printed circuit traces must be as short as possible to avoid stray inductance and capacitance. Every bit of extra wire is an inductor that must be magnetized before a surge of sinewave current can flow through it. Every component or wire that is close to its neighbor is a tiny capacitor that must be charged before the voltage on that component can rise or fall. It's like a mechanical clock filled with viscous molasses. The higher the frequency, the thicker the molasses. Needless to say, I am in awe of guys who homebrew UHF rigs.

I eventually improved the 10 meter QRP to 4 watts by rebuilding the output stage so that the printed circuit trace between the emitter and the previous stage and the trace between the collector and the output filter were as short as possible. That is, I redesigned it until there was hardly any exposed trace distance at all. Whenever a trace must carry high current at a high frequency, the trace becomes a significant inductor and reduces the potential power it will deliver.

VHF transmitters mean careful planning and construction

The 1986 ARRL handbook has a design for a 3 watt 6 meter (50 MHz) transmitter that uses the same MRF476 and 2N5109 transistors that I used in my higher band QRPs. The final and its driver are stuffed into a tiny module in which every part is strategically positioned like a jigsaw puzzle. There are only a couple inches total of circuit board traces. They are entirely covered by circuit components soldered to the traces at right angles. There is ZERO extra trace distance. Obviously this design had to be exactly right the first time. Modifications are nearly impossible. In spite of this perfection, they only get 3 watts at 50 MHz.

For the high HF bands it helps to use transistors rated with a ***gain bandwidth product*** much higher than the frequency you're building for. As examples, the 2N4925 is rated at 500 MHz bandwidth product. The 2N5109 is rated up to 1200 MHz. In contrast, the otherwise similar 2N3053 can work at 28 MHz, but it is only rated at 100 MHz bandwidth product. A circuit board design using a 2N3053 must be superior to get the same power at 28 MHz that the 2N5109 will deliver. On the other hand, the 2N5109 is more likely to go into noise mode on lower bands.

Tuning the QRP output to an antenna or amplifier

Suppose after tuning it up with a dummy load, I connect the QRP to a high power final amplifier or to an antenna tuner. Suddenly I discover that the QRP output is badly distorted. The output stage broadband amplifier may even go into "noise mode." If I had designed both QRP power amplifier stages as broadband, I wouldn't have anything to adjust. Strange as it seems, tweaking a tuned stage will usually match up the broadband output stage to my final amplifier. The most extreme example of this I have observed was on 10 meters. I loaded my antenna with the 10 meter QRP driving a 40 watt linear amplifier (power gain of ten) in series with the TVI low pass, the antenna tuner and the antenna. The "T-type" antenna tuner (Chapter 9) was not able to

produce a clean sinewave output. I had to re-tune the last tunable stage of the QRP in order to match the antenna! In contrast, the lower ham bands like 40 and 80 are extremely easy to match to the linear and the antenna.

I assume that the ability of early stages to effect the tuning of an antenna has to do with "*phase shift*." The phase of a sinewave is the instantaneous relationship of the voltage sinewave to the current sinewave passing through the circuit. Because of the way capacitance slows the rate of change of a voltage waveform and inductance slows the rate of change of a current waveform, the current and voltage sinewaves in the output of a transmitter are rarely perfectly synchronized. Or to say it another way, a real antenna rarely looks like a perfect resistance without any capacitive or inductive component. Think of water sloshing back and forth in a cattle watering trough. The length of the trough and the frequency of the waves must be aligned perfectly or the waves quickly become chaotic. In other words, they go into noise mode!

In summary, when you build an amplifier input that is nominally designed for "50 ohms resistive load," you may find that it has lots of reactance (accidental capacitance and/ or inductance) and is quite different than planned. Notice that Chebyshev filters are designed for specific input and output impedances. To say it simply, filters don't filter when they are mismatched.

"Spotting" with a VFO

Now suppose you are on an upper band using your new VFO driven QRP. You hear a station calling CQ. But if you key your transmitter and adjust the VFO to the same frequency as the station, you will be sweeping the band with your transmitter and making yourself unpopular. Besides, you have probably wired the antenna and power supplies so that the receiver shuts off while transmitting. In order to hear your own QRP in the receiver you need to turn on those parts of the QRP that generate the desired frequency, but not the power amplifiers. You also want the antenna to remain connected to the receiver and you don't want the receiver to shut off. To hear the VFO we need to direct power from a "Spot" switch to the VFO power supply. But we also need to turn on the QRP PMO sections that generate the desired frequency.
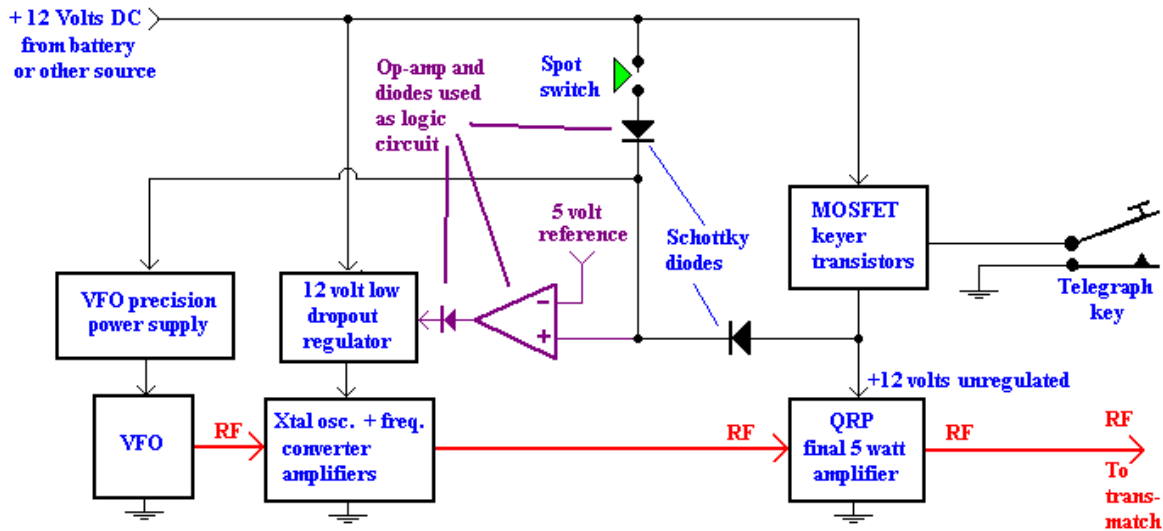
QRP KEYER WITH "SPOT" BUTTON

If you are running your transmitter on battery power as I usually do, then the low dropout supply only has to run the crystal oscillator and the filter/amplifiers. The power amplifier (or amplifiers) can run directly off the battery and that unregulated 12 volt line can be activated by the MOSFET keyer circuit. Now when you push the spot switch, the VFO and the low power sections of QRP will turn on without shutting down the receiver. Below is the low dropout regulator with the turn-ON control line from the Spot diodes.
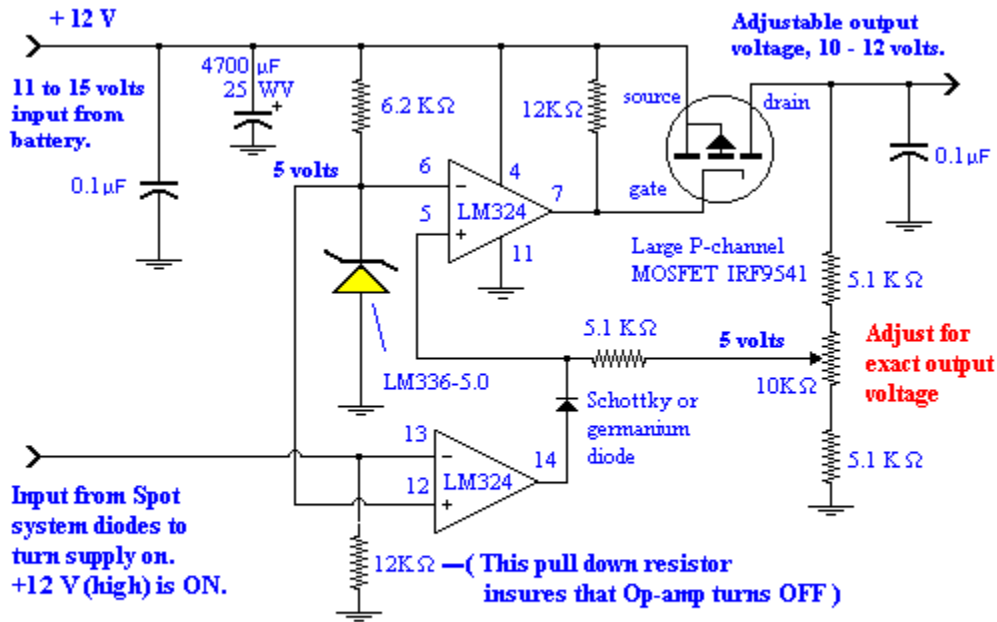
Low Dropout 12 Volt Power Supply with Remote

Multi-band QRPs

When I began trying to get on the air with my first CW QRP, my goal was simply to reach 15 meters. This chapter summarizes what I learned on that journey. Since one band was plenty of challenge, I didn't worry about expanding the QRP to cover multiple bands. After a while I began to wish I could operate on 40 meters, so I just built another version of the same QRP design. Because soldering is such fun, I eventually cloned the unit for every HF CW band. This was grossly inefficient. In retrospect, it's a bit embarrassing, especially since I included a separate keyer MOSFET on every band module. Surely you can improve on that!

If you are an experienced builder and want to make a multi-band QRP, then check out the Single Side Band (SSB) QRP modules in Chapter 15. In that system the amplifiers are wide-band/linear and are separate from the passive band filters. If everything works as planned, arrays of oscillators and filters for each band can be switched in with only one set of linear amplifiers. The CW PMOs described above use filters that are tuned amplifiers that are easier to make work, but confined to just one band. One limitation of the broadband/separate-filter approach is that there are no tuned amplifiers to adjust to help you match the QRP to an antenna or to a linear amplifier. Beginners beware. Multi-band units are comparable to flying submarines. Flying submarines will almost certainly be poor airplanes and lousy submarines. It is difficult to build one machine that performs multiple functions well.

Don't scrap a prototype that works - until you have one that works better!

The first QRPs for 15 and 20 meters I built used the original filter-amplifier design. They were extremely ugly with lots of patches and crude soldering, but they worked well. *My big mistake was scraping the old QRPs* and using the parts to build the inferior 2-band version shown below.
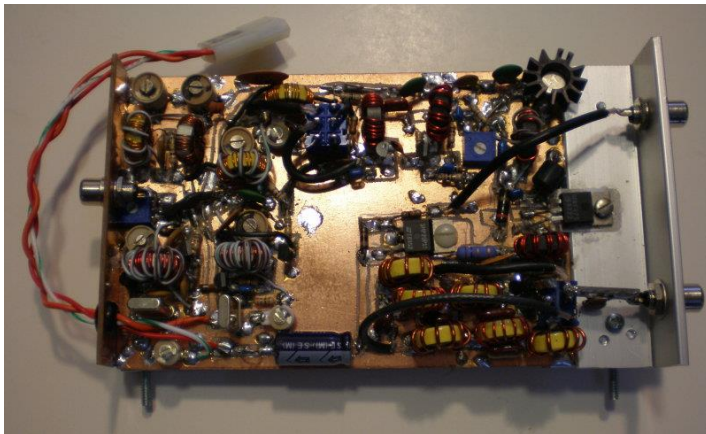
This QRP covers both 20 and 15 meters using passive tuning networks and broadband amplifiers. Two DPDT switches swap the filters and crystal oscillators for the two bands. It works, but it was difficult get 4 or 5 watts. Also the waveforms had low frequency artifacts, so the frequency counter didn't always lock. A crude solution to this was to place a 120 pF capacitor in series with the output. In other words, I added a simple high pass filter. When I still had loading difficulties, there was no tuned amplifier stage in front of the final to tweak. So in desperation I tuned the "broadband" amplifier just following the passive filters. I hoped I could at least get it to work well on one band. Strangely enough, a single tuned setting worked adequately

for both bands. The final 2-band QRP was much more likely to go into noise mode than the original separate units, but with vigilance I managed to make it work.

Eventually I tired of struggling to make the 2-band unit work reliably and exiled it to the junk pile. I replaced it with brand new, separate 20 and 15 meter QRP modules. The single band QRPs work well, of course.   So much for progress!

Now the big mystery is why my single sideband (SSB) 2-band modules work so well. 2-band CW modules should have been easier than the SSB modules. The SSB modules produce the final frequency with two frequency conversions, not just one. (See Chapter 15)

Watch out for frequency drift

After you have used these VFO driven QRP boards for a few years, you may suddenly hear complaints about frequency drift. The cause is almost certainly in the VFO (Chapter 10). Before you attack your VFO, it is worth checking your crystal oscillator to confirm that it is stable. Also, after some years the little trim capacitors become "set" where you left them. This is seen as an initial stiffness, almost like a detent, when you first re-tune them. Because of this subtle mechanical alteration, the tuning of your tuned stages may no longer be optimum.

Another kind of frequency drift is "chirp," a change in the musical tone of CW while you are sending a dot or a dash. I have almost never had a chirp problem when using a QRP module barefoot without an amplifier. The exception occurred when I ran my QRP on weak flashlight batteries. In general, the more power you draw from your power supply or batteries, the more likely you will have chirp. As explained in Chapter 12, a poorly tuned antenna can also produce a subtle chirp at the end of a long dash, presumably because the amplifier is drawing higher current surges. Unlike vacuum tube transmitters (Chapter 14), the transistorized transmitters described here are unlikely to chirp.

The next Chapter discusses building an amplifier to increase the QRP output to 40 to 100 watts, depending on the band and the power output of your PMO QRP.

CRYSTAL SETS TO SIDEBAND
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Chapter 12

SIMPLIFIED AMPLIFIER DESIGNS

When I first got back on the air as a retiree, I built a QRP that put out 4 watts on 15 meters. I spent two days answering CQ's and calling CQ. Unfortunately no one heard me. I gradually came to the conclusion that QRP is a hobby for guys with expensive, huge beam antennas, not guys with verticals and dipoles. Without that extra 10 dB of gain, I figured my QRP signal must be down in the noise. The other way to get 10 dB of gain is an amplifier. In this chapter I shall describe my efforts to build a good linear amplifier. Now that I have "QRO" power when I need it, my transmitter has become a reliable communications system. If having a strong signal is important to you, you'll find that 50 watts or more watts are a big improvement over QRP.

Actually, now that I'm older and wiser, I now realize that low power and simple antennas weren't my problem. In the old days our receivers had passbands several KHz wide, while modern receivers are usually just listening to a few hundred Hz. When I put my 4 watts on 15 meters, I didn't realize that using the upper sideband is the standard convention for 20 meters and higher. On 15 meters the other stations were tuned to the upper sideband while I was often zeroed in on the lower sideband. My receiver was so wideband, it wasn't obvious to me which sideband I was on. When I answered those CQs, I was usually off their frequencies by about 1.5 KHz.

In this chapter I describe three different final designs that I used successfully on the air. I don't recommend building the first one. I describe it here because it was educational. It was a ***tuned class B amplifier***. It worked, I learned from it and it covers 20 through 10 meters. Unfortunately, it was too hard to tune. Moreover, you would probably have a hard time finding the dual-section, butterfly variable capacitor I used to tune the output to resonance.

The second amplifier is an ***untuned class B*** design. It works on all bands and is suitable for CW only. Someday when you graduate to single sideband phone you can upgrade this amplifier to the third design, which is an all band ***Class AB linear amplifier***. Rather than just read the descriptions of the finished products, you may get some insights by reading my odyssey of how I worked my way up to a real linear amplifier.

The quest to build a 50 watt amplifier

I began my QRO project by searching my 1998 ARRL handbook for linear amplifier construction projects. I found three examples of linear amplifiers. One of them, "An HF 50 Watt Linear Amplifier," was a complex schematic that covered two pages. The other two examples were buried in diagrams of elaborate transceivers that seemed to be "illustrative" rather than something I was encouraged to build. I could almost hear a big, baritone voice saying, "For your own safety, do not build this at home."

I studied the HF 50 watt linear amplifier project closely. It used a pair of MRF-477

transistors. I looked them up in my RF Parts Company catalog. It said, "call for pricing." That was ominous. It turned out that a pair of them was $45. I also worried about all those feedback loops that protected the transistors from **overdrive**, from **excess SWR**, from **excess collector voltage** and from **thermal runaway**. In addition, there were at least three kinds of frequency compensation feedback. In short, the schematic seemed to be telling me that *high power RF transistors are extremely fragile.*

The article gave me the impression that, if all those protection circuits didn't work perfectly the first time I turned it on, my pricey transistors would turn into toast before I could say, "expletive deleted." I had never built a high power transistorized RF power amplifier before. My only comparable previous projects had been 100 and 300 watt switching power supplies. Until I got those projects working, they had devoured numerous $20 transistors like popcorn. I was extremely wary of this project.

I retreated to my 1979 handbook and found a more primitive linear transistor amplifier project. This one also had thermal protection, but at least it didn't look like it had to work perfectly in concert with a flawlessly adjusted bi-directional power meter. The most reassuring feature was that MRF-454 transistors seemed to be the cheapest power transistors available, about $13 each. These transistors are big, rugged and able to dissipate a great deal of heat. Just in case, I bought two extra sets of transistors.

At this point you may be thinking, "Even at $13, those are expensive transistors! Why doesn't he use a cheaper power transistor that has adequate power and frequency ratings?" The answer is that the MRF-454 will produce high power with a 12 volt power supply. Sure, if you're willing to build a 48 volt, 200 watt DC power supply, you can find dozens of cheap transistors that will work.

Basic features of a modern linear amplifier

A typical modern amateur radio "linear" final amplifier has six basic features:

First, *Two separate power transistors are driven with a center-tapped transformer.* The transformer is wired so that it turns on one transistor for half of the sine wave while the other transistor is turned off. During the next half cycle, the first transistor turns off while the second transistor turns on.

Second, *it is a class B design operating in "push pull."* An advantage of class B is that, when there is no RF on the input, both transistors are nearly completely turned off. This means that that they don't get hot and don't waste energy. Even when running with forward bias to make the amplifier linear, very little forward bias is needed and the efficiency approaches 50%. Also, class B tends to cancel out even harmonics.

Third, *the transistors must be cooled with a large heat sink.* Large power transistors are designed to be bolted onto a heat sink. They have metal flanges with mounting holes for this purpose. For a 100 watt amplifier, the heat sink is typically a large, aluminum casting perhaps five or six inches on a side. Heat sinks usually have multiple cooling fins ¾ of an inch high.

Fourth, *the output from the two transistors drives a second center-tapped, untuned high inductance transformer.* Since this output transformer is untuned, it can amplify nearly *ANY* RF signal over a wide range of frequency. So long as its circuit board is properly designed

and the input signal is pure, then only a pure sinewave comes out. The tricky part of this design is that, if any noise or "complex waveform" is introduced into the circuit, the amplifier may run away and produce wideband noise. More about this problem later.

       Fifth, *a linear amplifier is not running "Class B" but rather it runs "Class AB."* This means that a small amount of forward DC bias is injected into the bases of both transistors to turn them slightly on at all times. By having the transistors already turned on, they respond instantly when a tiny input signal appears on the bases. Without the bias, an input signal would have to exceed some threshold limit before the transistors could turn on.

       Sixth, *a low pass output filter limits the frequency components in the output waveform.* In other words, the filter suppresses harmonics so that, if you're transmitting on 40 meters, nobody will be able to hear you on 20 meters or 10 meters. Each band you operate on needs a separate filter that clips off harmonics that would radiate at higher frequencies. You can get by with using the same filters for 12 and 10 meters and for 15 and 17 meters. I built my filters on little circuit boards that I plug into a card edge connector on the main board. I use several connector pins in parallel to keep the inductance of the connection as low as possible.

****

It looked easier in the handbook

       When I began my work, I built the linear as close as I could to the drawings in the 1979 handbook, although as usual I had to substitute some parts. After I had carefully tested the forward base bias regulator circuit, I gingerly put 12 volts on the output transistors. Without any RF input drive, the transistors immediately ran away and drew huge currents. Gee, something must be wrong with the bias circuit! I soon discovered that *ANY* forward bias caused the transistors to run away. Obviously, the guy who designed this amplifier used MRF-454's that behaved differently than mine.

       Next I disconnected the bias circuit and powered it up again. In other words, I was hoping it would run as an untuned Class B "sort-of-linear" amplifier. This time at least the transistors didn't run away. I put an RF signal on the input and found that the amplifier was operating in what I call "noise mode." As you know, linears are supposed to act like hi-fi amplifiers. They uncritically amplify whatever frequency signals you put in. If you put 80 meters or 10 meters in, you are supposed to get amplified 80 meters or 10 meters out.

Noise mode

       An unfortunate mode of operation for a linear is "HF broadband noise generator." I put in a clean, filtered 5 watt sinewave and I got a blast of wideband noise from the output that made my FM radio roar like a waterfall. Using an oscilloscope, the waveform across the dummy load looked like dancing grass in a tornado. My new amplifier had terrific power output into a dummy load. Unfortunately, little if any power was at the desired frequency.

Class B's are easier

       I concluded that my linear had at least two fundamental problems. I had already encountered "noise mode" while I was building my first 15 meter QRP. At that time I hadn't found many cures for that disease, even at the milliwatt level. So I wasn't optimistic about fixing it at the 50 watt level. I was tired of not having a working transmitter, so I decided to start over

and build a simple class B *TUNED* amplifier. I was almost certain I could get that to work. Of course a tuned class B would only work on two or three bands without changing the output transformer and tuning capacitor. However, that was better than being off the air, possibly for months.
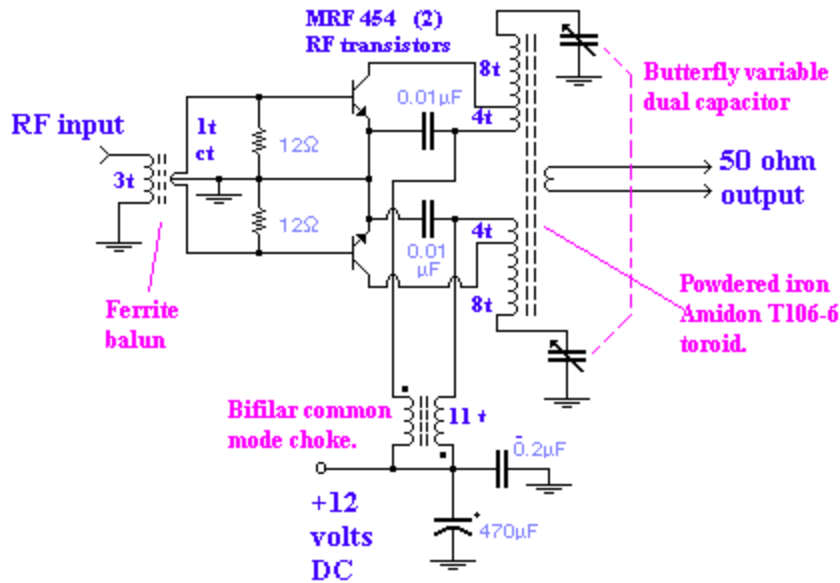
Amplifier # 1. A simple class B tuned amplifier. This works, but I don't recommend it.

The tuned class B worked great. The only trouble I encountered was getting the input transformer to match properly and deliver the required big drive currents. After two unsuccessful attempts at winding powdered iron toroid input transformers, I tried the ferrite balun transformer from the linear amplifier. Success! Ferrite balun transformers really are different from powdered iron toroids. They match those low impedance power transistors when nothing else will. At least *SOMETHING* from the linear design worked.
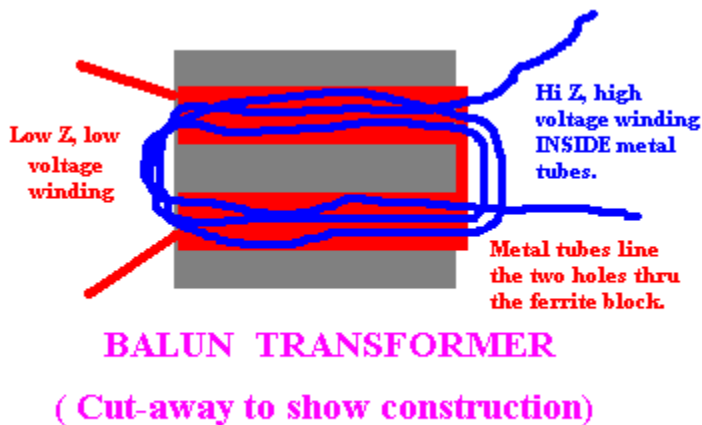
Ferrite balun transformers

Think of the ferrite balun transformer as two large ferrite beads placed side by side. The beads are simply hollow cylinders made from high A_L ferrite, so when a coil is wound around them, the ferrite produces a large inductance with very few turns. Sometimes the two beads are cast as a single block of ferrite with two cylindrical holes side by side through the block. In principle, the transformer is just like the transformers you have met before. That is, it consists of two coils wound on the same iron core. The high impedance, higher voltage winding has the most turns and is just 3 or 4 turns of wire wound through the hollow centers of both beads. So far, this is pretty ordinary.

The tricky, unobvious part is the low voltage, low impedance winding.   What I haven't mentioned yet is that the hollow centers of the two beads are lined with non-ferrous metal tubes. The high impedance, high voltage winding is passed <u>through</u> these tubes. At one end of the assembly, the two tubes are connected together electrically so that they form a "U" passing through the two beads. This "U" is the entire low impedance winding. Like any transformer winding, it has two output leads and these are the two legs of the "U." The center tap of the low impedance winding is the connection between the two tubes, on the right in the above drawing. That is, the bottom of the "U" is soldered to the PC board ground. The ungrounded ends of the tubes go to the balanced, low impedance transistor inputs.

For the input balun transformer, I made my "U" out of tubular mesh tubing from the outer conductor from a length of RG-174 coax. I forced holes in the sides of the outer braid mesh to bring the insulated secondary winding wire in and out of the braided tubing. This is tricky to make and you may have to try a couple times. I used Teflon insulated mulistrand wire for my secondary windings to be sure there would be no short circuits between primary and secondary. I bought the small input balun ferrites from CWS Bytemark. These small ferrites consist of a single, flat block of ferrite with two parallel holes molded through the longest dimension.

The tuned class B worked, but I don't recommend it

The diagram of the tuned class B was shown earlier. Depending on the range of the ganged, dual tuning capacitor, it can tune between 10 and 20 meters. I got on the air and talked to lots of people with my 50 watt Class B. I was pleased, but whenever I changed frequency more than about 50 KHz, I had to retune the amplifier. Using a scope, my procedure was to tune the amplifier and a "T" type transmatch for maximum amplitude with minimal low frequency artifacts. When tuned, it produced a clean sinewave output and I could see no evidence that the lack of forward bias was distorting the output. Just to be on the safe side, I ran the output through the multistage, TVI low pass filter described in chapter 9. This TVI filter is designed to work with any HF band since it cuts off above 10 meters. The transmitter ran quite cool and I didn't burn up any transistors, even though I had omitted all those exotic feedback safety circuits.

The disadvantage of my tuned class B was that it was a bit tweaky and tended to go out of tune whenever the battery voltage declined. The best reason for not building one is that the class B <u>untuned</u> amplifier described below works better and doesn't use any hard-to-find parts.

A CLASS B, UNTUNED, SORT-OF-LINEAR AMPLIFIER

Episode two of the power amplifier saga

15 meters was dead in the evenings so I wanted to get on 40 meters. Rather than build a new tuned Class B amplifier just for 40, I went back to work on the linear. First I ordered a data

manual for Motorola RF transistors. When I got my manual, I discovered that the MRF-454 was the only transistor in its class that *WASN'T* recommended for linear operation. The manual didn't say why it wasn't, but I thought to myself, "No wonder MRF-454s are so cheap and no wonder they run away with forward bias!" I got out my RF Parts Company catalog and priced all the similar RF transistors that were recommended for linear operation. They were all much more expensive than the MRF-454, but I picked out the cheapest and ordered a matched pair of MRF-422s. The output from the transistors goes to a large balun ferrite transformer. Large balun transformer assemblies are also available from RF Parts Company. I have used the 1 inch and 1.5 inch versions (PN # T1 & T1.5). Both seemed to work fine with no signs of saturation.

When my new transistors arrived, I put them in the linear and... they ran away, just like the MRF454s. I added lower and lower resistance swamping resistors to the bases until the transistors stopped running away. Of course, by that time, I had zero RF output. Apparently forward bias works for everyone else, but the laws of physics are different at my house. However, unless you are planning to go on SSB (voice), you don't really need a linear amplifier. Old fashioned class B or class C amplifiers work fine for CW.

Trouble with Chebyshev output filters

I tried again to run my "linear" amplifier as an untuned class B. As before, it just produced high power noise. I looked more closely at my Chebyshev output filters. Were they defective in some way? I had built them from the 1979 handbook linear amplifier plans. I had followed the winding instructions exactly using identical CWS (Amidon) 106-6 toroid cores. To test the 15 meter Chebyshev filter, I substituted it for the TVI low pass output filter on my working tuned Class B amplifier. It should have worked fine, but instead, the old tuned Class B amplifier went into noise mode, just like the new amplifier. Very little power arrived at the dummy load and the filter cores got quite hot. Something was wrong with the filter.

Apparently the parts list or coil turns listed in the table were just plain wrong. I used the Chebyshev design tables from the 1998 ARRL handbook and redesigned my plug-in filters. I used the procedure described for making 5 element low pass Chebyshev filters that I previously explained in chapter 6. The main difference between the QRP filter and the big amplifier filter is that for 100 watts you need large powdered iron cores. Instead of T50-6, I used T106-6. For 40 meters and below you might want to use T106-2 cores.

It turned out that the instructions in the 1979 manual described filters that were more appropriate for several bands below each band listed. For example, the 15 meter filter was designed about right for 160 meters, and so on. The filter for 160 meters would have been correct for low frequency transmissions from submerged nuclear submarines.

I checked out the redesigned 15 meter filter on my old amplifier and … it worked perfectly! Progress! Next I put the new filter on my new linear amplifier and held my breath. Behold ... it was still operating in noise mode. Now I was mad. I got out my wood-carving gouge and cut the PC board traces to the transistor bases. Now they were free from all that R-C-L frequency compensation network gobble-de-gook. I wired the bases up just like the tuned Class B linear input above. As far as I can tell, it works perfectly. It puts out 100 watts of lovely sinewave on 40 meters and doesn't blow transistors. I only get 50 watts on 15 meters because my driver isn't as powerful. I soon worked dozens of stations on 15 and 40 and I got excellent signal reports.
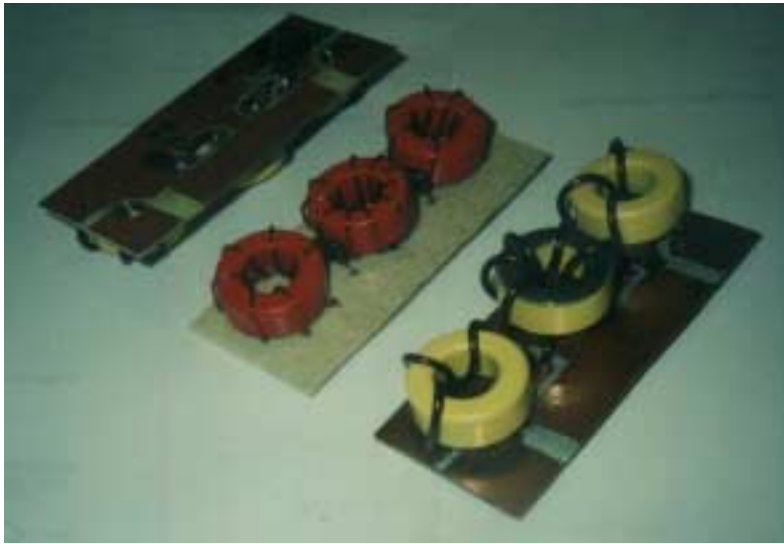
Chebyshev output low pass filters for an untuned class B. They plug into a card edge connector.
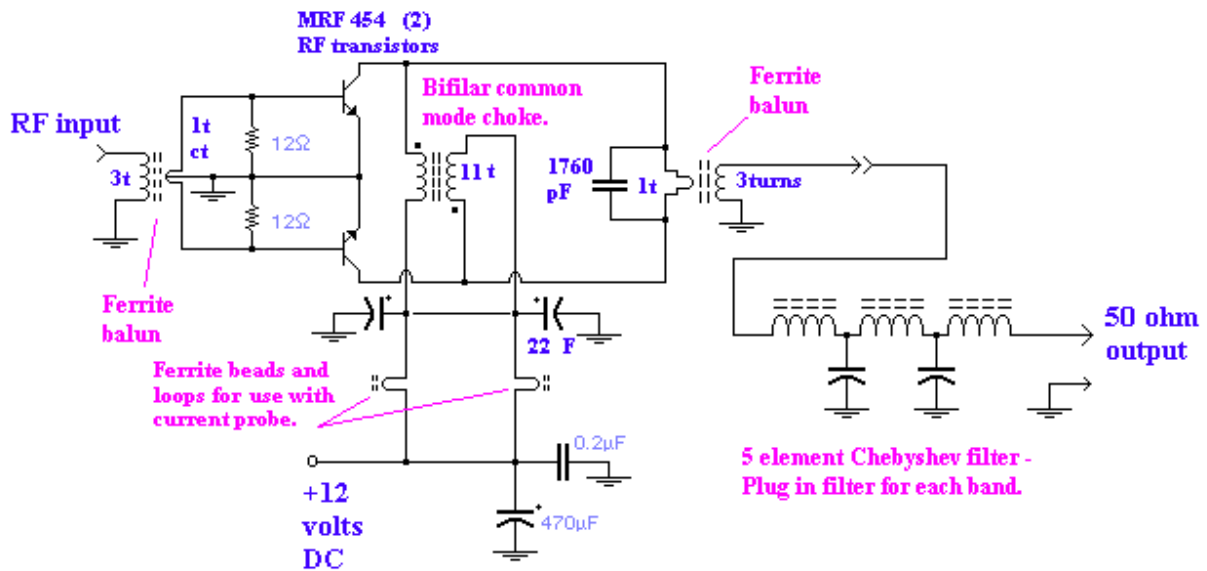
Amplifier # 2. A simplified class B untuned amplifier

    Why didn't I need fancy frequency compensation feedback loops? The answer may be that I am driving the linear with complete QRP transmitter drivers that have their own Chebyshev output filters. In other words, the input signals are quite pure. I have observed that any defect in the input sinewave is faithfully reproduced in the output. Even without forward bias to make it class AB, it is "hi-fi" to a large degree.

    After all my worry, I never did ruin any transistors. Once I was testing the linear at 80 watts output. I was happily looking at the scope when I smelled something burning. Oops! I

had forgotten to screw the big heat sink back on. I shut off the linear and no harm was done. RF power transistors aren't so fragile after all.

The completed linear amplifier. A 15 meter low pass filter is plugged into the output.

You may already be using an adequate low pass filter

I have occasionally had trouble loading antennas on 17 meters and above. Even with the T-match coupler described in chapter 9, sometimes I couldn't get a good sinewave signal on the antenna lead wire. The waveform was contaminated with low frequency modulation(s) and the frequency counter was usually reading low and wouldn't lock. Sometimes I have been able to correct the problem by using an output filter for the next band higher than the one I was on. For example, if it wouldn't load on the correct 15 meter filter, it would sometimes load well using the 10 meter filter.

Finally it occurred to me that I was already using the multistage 30 MHz cut off low pass TVI filter described in chapter 9. Therefore, for those high bands my 10 meter output filter on the final was redundant. I built a "blank" filter that was just a piece of RG-58 coax that shunts from one end to the other of the PC board connector. In summary, using the TVI filter on its own is another alternative for your bag of tricks.

Keying the 50 watt linear amplifier
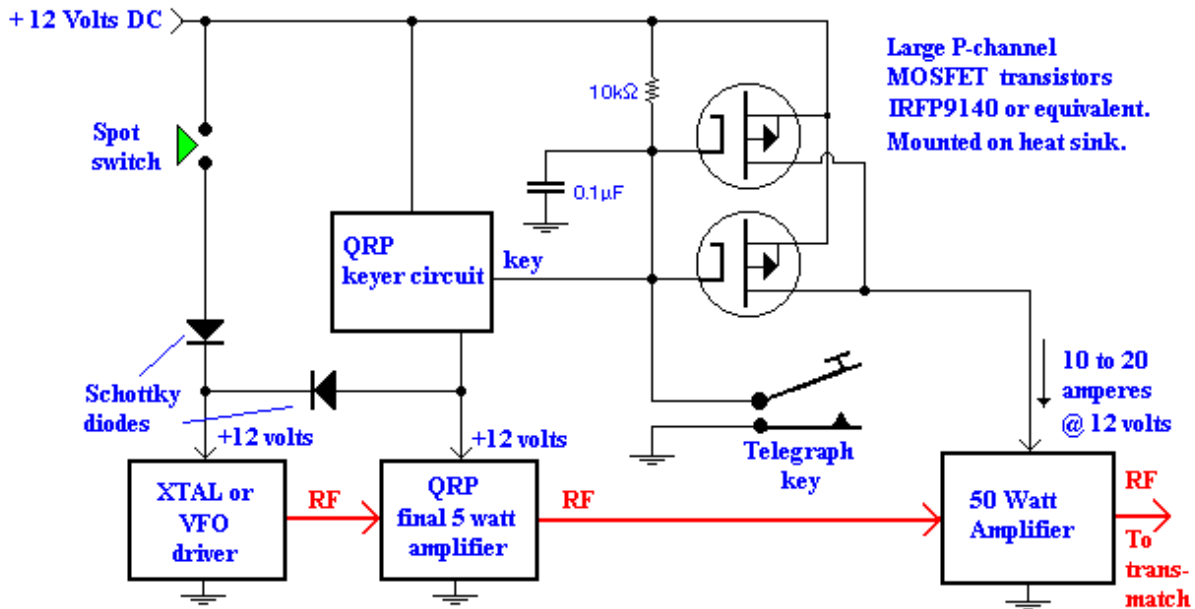
50 WATT TRANSMITTER KEYER

50 watt CW transmitter keyer and spot switch

When I first began using my finals, I kept them turned on all the time. That is, whenever a signal appeared at the input, the final was supposed to amplify it. When there was no input to the amplifier, there should have been no output. This way, I could leave the 12 volt power supply connected all the time. Unfortunately, every so often the final would begin oscillating all by itself at some random frequency outside the ham bands. I often had two or three successful QSOs without trouble. Then suddenly, for no reason that I could determine, the oscillations began.

I have been told that professionals solve this problem by loading down the input of the final amplifier with a resistor, perhaps as low as 100 or even 50 ohms. I haven't experimented much with this approach, but I'm certain that it cuts drive to the final and lowers my output power. If I were you, I'd experiment some more with this cheap approach. However, if you don't like your results, you can always fall back on my keyer circuit shown above.

My solution was to build a giant version of the same MOSFET power switch I used to key my QRP modules. Naturally I had to use humongous P-channel MOSFETs with low on-resistance. Referring to the figure above, the telegraph key pulls the MOSFET gates down turning on the MOSFETs and bringing power "down" to the amplifier. The MOSFETs are mounted on a small sheet of 1/8 inch thick aluminum plate which in turn is bolted to the thin aluminum chassis. This is enough heat sinking. Even at heavy current loads I haven't noticing the MOSFET transistors becoming warm to the touch.

What had I Learned so far?

1. The ARRL Handbooks are excellent but occasionally they print errors. Don't believe everything you read in a parts list.

2. I understand the need for class A forward bias. In practice, for CW use there is no need for it. However, I was mystified how the experts do it without a runaway. In my experience, the transistors ran away instantly with the first milliamp of forward bias. This happened even when the transistors were stone cold. It couldn't have anything to do with temperature feedback being defective, because there wasn't time for heating to occur. Moreover, runaway wasn't related to the RF drive, because it happened with or without RF input.

3. Ferrite balun transformers are neat. They produce tight coupling at really low impedances and they don't need tuning.

4. If your Chebyshev output filter doesn't work the first time, check it out carefully for solder splash shorts on the PC board. If you're sure it should work, but it doesn't, go to the design table in a recent ARRL handbook and redesign the filter yourself starting from scratch. If it still doesn't work, try a different core size.

5. A Chebyshev filter in a QRP driver worked poorly when I designed it with T68-6 cores. But the same filter worked great when I rebuilt it using smaller T50-6 cores. Sorry, but I have no idea why. Sometimes it helps to be open-minded and try things that may seem silly. Persistence is your ultimate weapon!

6. Finally, it seems to me that much of the complexity in recent designs in QST and QEX is great in theory, but sometimes unnecessary in practice. The guys who wrote those articles are over-educated. Their sophistication often discourages us. Don't let them rain on your parade! Build it simple and work up from there.

****

A LINEAR AMPLIFIER, THIS TIME FOR SURE
Adding linear bias to the Class B amplifier

As explained above I was able to run my final amplifier as an untuned Class B, but when I applied DC bias to make it "linear," the amplifier "ran away." That is, it drew huge currents and blew fuses. In the end, I left it as a class B broadband amplifier. Class B amplifies both halves of the driving sinewave, so there's only a small cross-over non-linearity. So who cares if it isn't class AB? At the end of my project I was happily working guys on CW and I always used a lowpass filter to suppress harmonics. So what's the fuss over "linear" amplifiers? *I* certainly didn't need one!

Sideband needs a linear

Eventually I got bored with HF CW and built an SSB exciter. I fed SSB English speech into my class B "nearly-linear." All that came through were the voice peaks. It sounded like African click language. I couldn't understand the speech, but I finally got the message: ***The key virtue of linears for sideband is that they amplify all AMPLITUDES equally.*** Yes, linears also amplify all *frequencies* equally. They are a sort of "RF Hi-fi," but the broadband part isn't so important. A sideband amplifier only has to amplify a signal 3 KHz wide. In theory at least, a tuned class A amplifier would work fine on sideband, even if you have to retune it every time you QSY a hundred kilohertz.

When class C or class B amplifiers are operated CW, a big drive signal comes in on the base(s) of the final amplifier and you get a big, constant output signal with about 10 dB gain over

the input. The big drive signal exceeds the base forward voltage drop of the output transistors by a wide margin. ***The amplifier only operates at one amplitude***, so the base voltage threshold problem never arises.

Why does sideband need a linear when AM modulation was so easy?

Sideband is different. The drive from an SSB exciter has a range of amplitudes and all must be amplified equally. At first glance SSB doesn't seem so different from AM. So why was AM phone so easy back in the old days? Amplitude modulators usually modulated the final, not the driver. For AM we tuned up the tube final on CW, then *we modulated the power supply or the screen grid, or the cathode of the final tube amplifier with audio frequency*. The final acted like a mixer that produced sum and difference frequencies. With no conscious engineering effort we produced two audio frequency sidebands in addition to the original RF carrier.

Guys who could afford big AM modulation transformers modulated the power supply for the final. We cheapskates modulated the screen grid or cathode of our final amplifier tube. Either way, we were modulating the gain of the final amplifier, not the drive signal. Now that I think about it, I guess I knew that some guys used *LINEAR AMPLIFIERS* to boost the power of their low power AM exciters. The fog clears. Yes, you can broadcast AM with class B or even Class C, but you can't amplify a low level AM or SSB drive signal without a linear.

Biasing a linear amplifier without thermal runaway
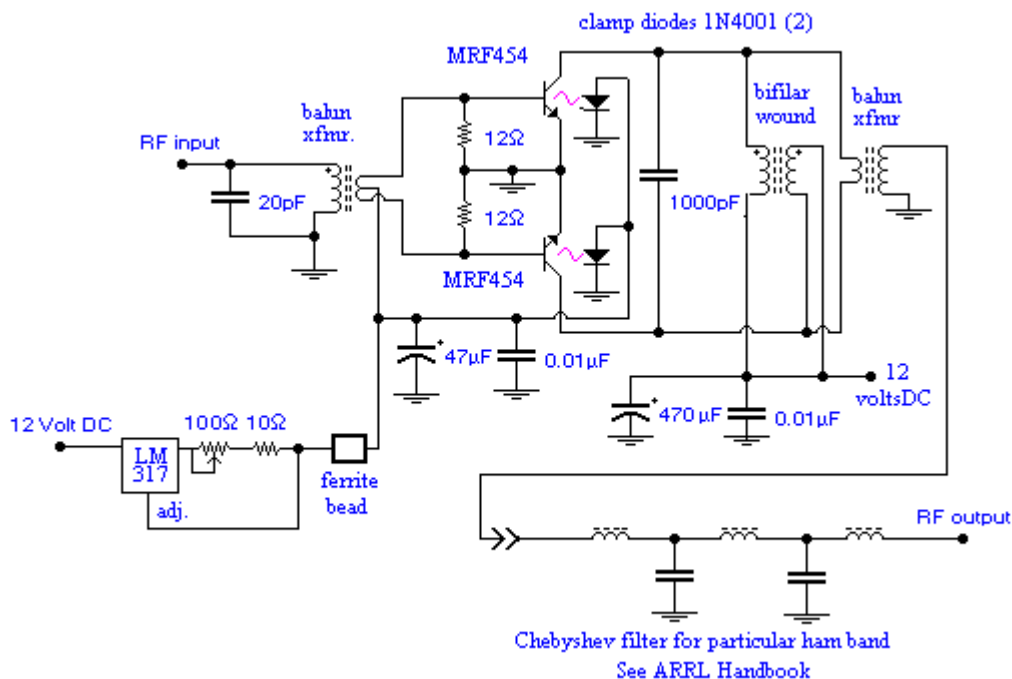
Amplifier # 3.   A push-pull linear amplifier

The entire linear final is shown above. The bias circuit at the lower left solved my run-away problem and gave me the linear amplification I needed. I found the bias circuit lurking in a big schematic describing a commercial transceiver in the 1998 ARRL handbook. This deceptively simple circuit performs three functions:

* It provides an adjustable, constant DC bias current into the transistor bases.

* Diodes (1N4002) shunt the bases to ground, limiting how high the base voltages can rise.

* The diodes heat up with the transistors and provide temperature compensation.

An LM317 voltage regulator is used as an adjustable current source to feed roughly 100 milliamperes of DC into the bases of the high power output transistors. The LM317 is a three-terminal, 1.2 volt voltage regulator. The regulator output passes through a variable current-set resistor. The voltage drop across the resistor is monitored by the "adjustment" lead of the regulator so that the voltage across the resistor is held constant at 1.2 volts. The regulator is RF-isolated from the amplifier by a big ferrite bead on a short chunk of wire. The rest of the circuit is almost identical to the final in an SSB transceiver in the ARRL 1986 handbook. The 1000 pF capacitor across the collectors is found in all these push-pull circuits. I took mine off and I got a few percent more gain. I don't know what it's supposed to do.

Clamp diodes prevent run-away

The critical parts of the bias circuit are the two rectifier diodes which clamp the base voltage (V_{be}) to ground. Their most important function is that they instantaneously clamp the base voltage to less than roughly 0.8 volts, like a Zener diode. They limit how high the drive voltage to the transistors rises when the whole assembly gets hot. As the input drive to the transistors increases, the DC base-to-emitter voltage of the output transistors rises which causes the collector to draw bigger and bigger currents. For example, while operating sideband, the DC base voltage rises to well over 0.8 volts on voice peaks. If it were allowed to rise to 0.9 or 1.0 volts, runaway might result.

The second function of the diodes is that they also change with temperature and automatically compensate for temperature rise. They are strapped across their respective transistors so they are in thermal contact with the transistor cases. As the transistors and piggyback diodes heat up, the forward voltage drop of the diodes ***decreases*** with increasing temperature. When cold, the V_{be} peaks might start at 0.8 volts, but as the transistors heat up, the V_{be} voice peaks will try to rise higher still. So, under the same bias current level, but at a higher temperature, the diode clamp voltage might typically drop from 0.8 to 0.7 volts or even lower. The decreasing voltage drags the base voltages down, preventing runaway. While holding the transmitter key down, I can watch the DC base voltage slowly sink, while the total DC current drawn by the entire amplifier remains constant.

The difference between this bias circuit and the ones I tried earlier is that there were no clamp diodes. Yes, there was a reference diode mounted on the heat sink for temperature compensation, but my output transistors ran away immediately before the temperature had a chance to rise. A current source with just a temperature compensation circuit has no instantaneous clamping function.

Mechanical construction

The linear 50 watt amplifier. Notice the large ferrite balun output transformer in the center of the assembly. The bias circuit is at the right rear. Also notice how the base clamping diodes are strapped across the output transistors so that the any transistor heating will immediately be passed onto the diodes.

The completed amplifier module is made from a two-sided circuit board screwed down into holes tapped in a large, finned heat sink. The major RF traces are wide, about 3/8 inch or more, to keep the inductance down. This is a simple circuit and all the traces were cut into the board with a small wood-carving gouge. ***It is vital to arrange the collector and emitter traces so that they are symmetrical and equal in every way.*** Otherwise, one transistor will have more trace capacitance and inductance than the other. The input and output transformers are the balun type which were described earlier.

The input comes in through a mini-UHF connector. Mini-UHF connectors are the only affordable, small RF connectors I have found. At $5 a mated pair they are expensive compared to phono plugs. But if you pay $12 a pair for SMA, SMB or SMC connectors, $5 looks cheap. The output connector is a big UHF SO-239 that, strangely enough, has always been affordable. For high power, >5 watts, I suggest avoiding connectors like phono plugs which weren't designed for RF power. You can get away with phono plugs on 20 meters and below, but the standing waves make it difficult or impossible to tune the amplifier on 10 meters. Also, if you plan to amplify sideband with this, it's a good idea to build a shield cover to fit over the top of the board.

I built my Chebyshev lowpass filters for the linear on separate PC boards that plug into the linear board using a card edge connector. To keep the inductance low, I soldered eight connector pins in parallel at each end of the card connector and the rest of the pins were used for ground. To change bands, I plug in another lowpass filter. If you like, you can use little RF reed relays to switch in different filters. Personally, I like the old-time flavor of plug-in coils.

In conclusion,

I talk to guys on sideband and they seem to understand what I'm saying. If my final

weren't close to "linear," they wouldn't have understood a word. In the end I was able to build a linear using the cheap MRF-454 transistors, just like the handbook said - even if their darn bias circuit didn't work.

How much power the linear amplifier delivers depends on how much power I put in and what band I'm on. Not all my QRP drivers are equal. On 10 meters I only get 20 watts, while on 40 or 80 meters I get as much as 120 watts. As usual, lower frequencies are easier. The efficiency is about 50 percent. For example, to get 120 watts output I need 18 amperes input from the battery.

Hmmmm... Now that it works, I wonder what would happen if I unsoldered the base clamping diodes? It should run away, of course. After all, these are the same individual transistors I used before. It better run away! So I unsoldered the diodes. It didn't run away. The temperature compensation no longer worked, but it didn't run away. I have no idea why it didn't. Sometimes electronics drives you crazy! Persistence is your only weapon against the innate perversity of inanimate objects. A good engineer is a persistent engineer.

33CRYSTAL SETS TO SIDEBAND
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Chapter 13

BUILDING A HOMEBREW HF RECEIVER

The Vanishing Art

The 1986 ARRL Amateur Radio Handbook reported that hardly anyone was building homebrew ham receivers. Since then, handbooks have had fewer and fewer practical details on building radios. Out of hundreds of contacts, so far I've only worked three guys, George, K7DU, Mike, NØMF, and Biz, WDØHCO, who were using homebrew receivers for the QSO. Two of these receivers were made from vacuum tubes. The third was an old-fashioned, super-regenerative design. However, the super-regenerative was implemented with modern FET transistors and integrated circuits. All three of these receivers must have worked well because they were pulling in my modest signal on 40 meter CW. I talked to one other fellow, Gil, N1FED who told me he had just finished a vacuum tube receiver. Unfortunately, it was performing so poorly he was still using his modern transceiver on the air. Gil told me he didn't like transistors. I guess he found printed circuit boards and those pesky oscillations too much trouble.

In spite of this pessimism, *you CAN build transistorized receivers that work reasonably well.* I built mine because I was intrigued by mysterious circuits like "balanced mixers," "product detectors," "cascode amplifiers" and "crystal ladder filters." Before this project, I could recite the purposes of these circuits, but I had no "feel" for how they worked and why receivers are designed the way they are. What better way to learn than to build one?

What's a reasonable goal?
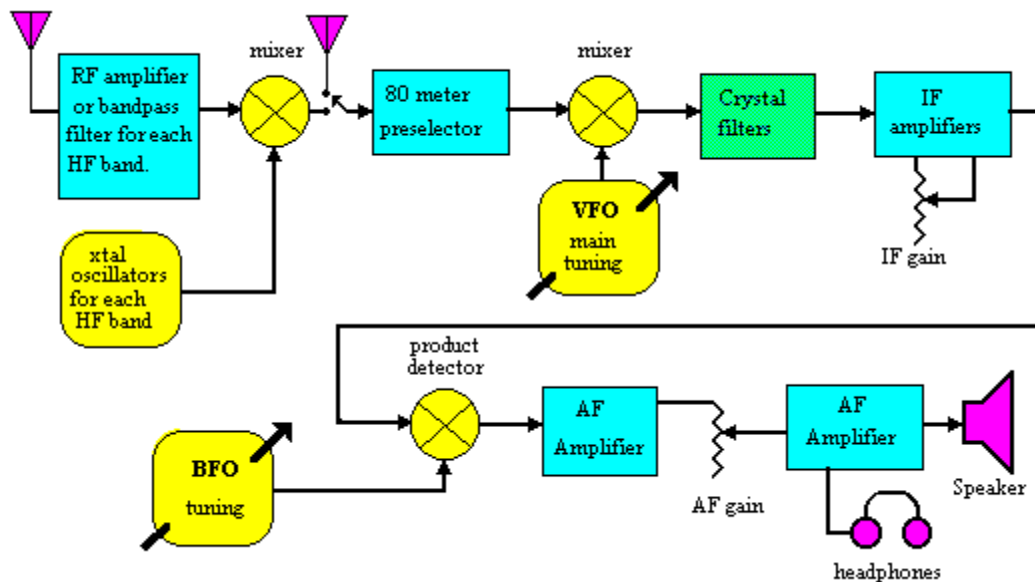
An "adequate performance" communications receiver

My receiver is based on the "High Performance Communications Receiver" designed by W7ZOI and K5IRK described in most of the annual ARRL Handbooks in the 1980s. In my opinion "High Performance" is optimistic, but certainly "adequate performance" is realistic. I define *adequate sensitivity and noise figure* to mean that I can hear the DX and QRPs that other stations are working. Before I built the receiver described here, I often had the impression I was hearing only the loudest signals. For me, *adequate selectivity* means that it's good enough for CW QSOs in the evening on 20 and 40 Meters. On these bands there are often dozens of narrow CW signals operating within a few hundred Hertz of each other. With a 10 KHz bandpass, you may hear many stations simultaneously and not be able to copy any of them.

Adequate sensitivity will allow you to hear most QRP signals. I believe that 45 years ago hardly anyone had receivers that were "adequate" for QRP contacts. When I was a novice, my first transmitter was a 7-watt homebrew for 40 and 80 meters. I know it worked OK, because I talked to my novice buddies around town. Unfortunately I hardly worked anyone outside of town. It wasn't until I bought a 50-watt commercial kit, just like all the other novices, that I was able to talk to all the same stations my buddies were working. I was still using the same dipole antenna, so I can only assume the improvement was the extra power.

The sensitivity of the receiver described in this chapter is well under 0.5 microvolt on 80 meters and lower bands that have no RF preamplifiers. On the upper bands where the receiver has preamplifiers I could l hear a calibrated signal source at 0.02 microvolts. Wow! No wonder I can hear those QRPs! In the old days sensitivity less than 1 microvolt was considered hot stuff.

Another issue is *adequate stability.* When your receiver is equipped with sharp crystal filters, it is vital that the VFO and crystal oscillators are stable enough that the signals you're listening to do not drift in and out of your passband. If you have built a VFO like the one described in chapter 10, you will have no drift troubles.

Does it have to be so complicated?

Looking at the block diagram above, each one of those blocks represents one to three transistor stages. The front-end converter has three transistor stages for each separate HF band. That means you need to build about 20 transistor amplifier or oscillator stages for the converters to cover all the bands. You're probably wondering if there isn't some simple receiver you can build that will get you on the air rapidly. The best news is that you can build the above receiver in stages. The core of the all-band HF receiver is a quality 80 meter receiver. You can build that first, then at least you'll be in business on 80 meters. In the beginning you can also do without the loudspeaker and multiple crystal filters. After you have a functioning receiver, you can add features and the converters to hear the other hambands.

Yes, you can build a less complicated receiver, but I doubt it will "adequate." My direct conversion receiver in chapter 7 worked well, but was not selective enough. There are modern super-regenerative receiver designs with two or three integrated circuits that *MAY* be pretty good, but I haven't built one, so I'm not convinced. Chapter 14 describes a vacuum tube regenerative receiver that was great fun to build and quite good for listening to foreign short wave broadcast stations. Unfortunately, it was *NOT* selective and sensitive enough for ham communications. In summary, *YES, a decent ham receiver does have to be complicated.*

A homemade ham receiver built in 1967

      A homebuilt ham receiver from 35 years ago is shown above. It has 11 tubes, a simple crystal filter and covers 80 through 10 meters. It doesn't cover the WARC bands. Yes, it works OK. But compared to the all-transistor receiver described in this chapter, it is insensitive, noisy and has poor selectivity.

      Being realistic, any receiver you build probably won't match the performance of high-end, commercial rigs. But every time your receiver brings in DX on a new band or whenever you conquer one of the dozens of glitches you will encounter, you'll have a thrill and pride you'll never get from a commercial rig. If you decide to build your own version of the W7ZOI / K5IRK receiver, I recommend you find a copy of an old ARRL Handbook from the 1980's and Xerox their original descriptions. You'll find they built most circuit blocks differently than I did. Going back to the original description may give you some useful ideas. Perhaps their version will work out better for you.

PLANNING YOUR RECEIVER

Superhetrodynes offer crystal filters for CW

      A superhetrodyne uses a mixer to produce a constant intermediate radio frequency (IF). This intermediate frequency signal is always the same so it can be filtered with fixed crystals or mechanical filters to establish bandpass widths for CW and upper and lower SSB. Before you commit to any design, make sure you can buy the critical parts you need, especially the crystal or mechanical filters for your IF. For example, many receiver designs use a 455 KHz IF. Unfortunately, I have yet to find an easy source for 455 KHz crystals for building filters and

BFOs. Consequently, I have avoided this frequency. Among homebuilt ham receivers the most common IF frequency seems to be 9 MHz.

Why not single conversion?

I had always wondered, "Why are homebuilt all-band HF receivers almost always dual conversion?" It turns out that the fundamental challenge of homebuilt receivers and transmitters is building a stable VFO. Yes, you can build a reasonably stable VFO, but homebrew VFOs usually don't have much tuning range. 0.5 MHz is typical. And, in order to drift as few Hertz as possible, the VFO needs to be relatively low frequency. Homebrew VFOs are usually in the range of 2 to 7 MHz. The disadvantage of a low frequency VFO is that its harmonics will appear as one or two loud whistles on some upper HF ham bands.

Compared to the practical VFO range of 2 to 7 MHz, the HF spectrum is huge, 1.8 to 30 MHz. Right away one can see that a homebrew direct conversion 10-meter receiver is difficult because it needs a stable VFO that will tune 28 to 29.7 MHz. This problem can be solved by "converting" the VFO oscillator up to 28 MHz using a crystal controlled oscillator and a mixer plus 28 MHz filter/amplifiers. This complexity ruins the simplicity of direct conversion. If you're going to operate above 40 meters, you may as well build dual conversion like the rest of us.

How do modern receivers do it?

Modern receivers use integrated circuit frequency synthesizers to generate VFO signals anywhere they like. Sometimes modern HF receivers escape from artifact images and harmonics by using an IF frequency way up in the VHF range. In addition, after the initial mixer stage, some commercial receivers use multiple conversions to get the signal back down to an audio output. At each conversion stage, different kinds of filtering are applied. For example, the Yaesu FT1000MP has four down-conversions from an 89 MHz IF. (!) This includes the digital signal processor with its 32 KHz input.

In a superhetrodyne the VFO interacts with the incoming RF signals to produce an intermediate (IF) frequency. A 5 MHz VFO implies that the IF is going to be within 5 MHz of the band or bands it covers. Such a receiver might cover 28 MHz, but that would imply an IF of 23 MHz or possibly 33 MHz. The lower bands would be out of range unless the VFO could be tuned many MHz. Consequently, a single conversion homebrew superhetrodyne can only cover one band well, and can't possibly cover the whole spectrum.

In some old ham designs the VFO tuned 5.2 to 5.7 MHz. They used a 1.7 MHz IF and either subtracted or added the IF to the VFO frequency to cover either 80 or 40 Meters. Specifically, 5.7 MHz *minus* 1.7 MHz = 4.0 MHz and 5.3 MHz *plus* 1.7 MHz = 7.00 MHz.)

Homebuilt all-band dual conversion HF ham receiver

Start with a single band, single conversion superhetrodyne

Begin by building the best single-band receiver you can. The core of my receiver tunes 80 Meters. To cover the other eight HF bands, separate crystal controlled converters convert the signals down (or up) to 80 meters. This makes the receiver "dual conversion" on every band except 80 Meters. In the old vacuum tube days each homebuilt amplifier stage was designed to work on several bands. This meant that the front panel of a 1970 homebrew receiver usually had a bunch of tuning knobs to tweak each stage. Today, a transistor amplifier or mixer stage is physically tiny, so it's practical to build a separate converter and amplifier pre-tuned for each band. My experience was that building the converters to translate the bands to 80 meters was relatively easy. Unfortunately, building a decent 80 meter core receiver was much harder. Maybe with the help of this chapter, you'll find the core receiver easier to build than I did.

My 80-meter receiver has a 9 MHz IF. 9.00 MHz crystals are available for less than $1 from Digi-Key and Mouser. The low price is important because, depending on your filter plans, you may need as many as 11 or more 9 MHz crystals. The downside of 9.00 MHz was that I had to wait months for the crystals to arrive.

An 8 MHz IF wasn't such a good idea

At first I used the more common 8.0 MHz crystals. Unfortunately, to receive 4.0 MHz, the VFO had to tune 4.0 MHz. I expected the 4.0 MHz VFO signal would be "a little birdie" that would mark the high end of the band. I thought this "edge-of-band marker" would be kind of

convenient. Instead, the "birdie" was more like a screaming siren that overwhelmed the IF and made the upper end of the 80 meter ham band unusable. So when the 9.0 MHz crystals eventually arrived, I rebuilt everything for 9 MHz. Now the VFO (the big tuning knob on the above receiver) tunes 5.0 to 5.5 MHz to cover 4.0 to 3.5 MHz. That is, 5.0 MHz + 4.0 MHz = 9.0 MHz. Of course the BFO frequency also had to change from 8 MHz to 9 MHz.

An unusual adventure

Once your receiver begins to work, you'll have interesting glitches. Until I got my 80 meter preselector filter working, I usually heard rap music from my local 1190 AM radio. Also, the 31 meter shortwave band is just above the 9 MHz IF. Before it was aligned, I was hearing sermons from HCJB in Quito, Ecuador. Later, my 20 meter converter was overwhelmed by Dr. Scott, a Los Angeles evangelical minister, who preaches on 13.8 MHz. Once I had my modules tuned and sealed, Dr. Scott and his friends were silenced. Actually, I got a kick out of these problems.

Building a receiver revived my interest in shortwave listening. I've had shortwave radios since I was a kid. Some of them, like my Army surplus Collins R-388, were excellent. In spite of this, I rarely listened when I wasn't actively hamming. But once my homebrew receiver(s) began to work, I found myself exploring the bands as never before. For instance, on 80 meters I was amazed to hear hams from all over the continent. I had heard about guys who work DX and earn WAS certificates (Worked All States) on 80 meters, but I never really believed it. I have even worked QRP stations on 80 meters. 80 meters is usually so noisy, I didn't know that was possible. Until this year, I had never heard "spy code stations" before. Some of them have an announcer reading apparently random letter groups, but most of them are CW "spy stations" sending Morse code 5 letter groups, just like the WWII Enigma signals. As I built converters for each of the HF bands, it was like hearing them for the first time. The "WARC bands" were interesting because they were near to shortwave broadcast bands I hadn't listened to in years.

Building with modules

Aside from the need to shield circuit blocks from one another, a homebrew receiver with a single big board full of discrete components has another problem. If you build the whole thing at once without buying a kit and pre-cut board, I guarantee it won't work. ***To make homebrew stuff that works, you have to develop your own technology based on parts can get and circuits you understand.*** This was a different mind set for me. Rather than "building a receiver," I had to lower my sights and build one circuit at a time, e.g., "an oscillator," "a mixer," "an audio amplifier," etc. Then I put the blocks together to complete my project. Some of these circuit blocks didn't work the first time and I had to build a new block. There were various reasons they didn't work. Usually, I wasn't able to buy the exact parts used in the circuits I was copying. Or my craftsmanship or shielding wasn't adequate. Sometimes I never did figure out why one version of a circuit block was superior to another.

On rare occasions my circuits didn't work because there were errors in circuit diagrams in QST magazine or in the handbooks. I found some serious errors in my 1979 Handbook and a minor one in my 1998 edition. Perfect editing is not possible, so we shouldn't expect it.

By building my receiver on separate little shielded modules for each circuit block, I could replace a circuit block whenever I managed to build an improved version. Otherwise, I would

have ruined the whole big board. If painstaking R & D is new for you, prepare for a long battle. On the other hand, you'll learn a lot and victory will be especially sweet.

Mechanical construction

Homebrew receivers should be built in big cabinets. That way there's lots of room to add features and swap modules. The table in my shack is small, so I shoe-horned my receiver into a fairly compact package. In general, roomy boxes with lots of panel space are a better idea. My long-range dream is to recycle my receiver modules into a larger cabinet. Eventually I want to add DSP, frequency counters, phase lock loops and other goodies that intrigue me. With a big enough chassis, a receiver can grow and improve continually.

The receiver modules are interconnected with phono plugs and skinny coax.

Metal boxes shield each circuit block

A basic reason for building a receiver in metal-shielded modules is that capacitive coupling from one circuit block to the next can degrade performance. For example, my first 80 meter receiver module was built on one board. A crystal filter determined the selectivity. I made two "plug-in" crystal filters so I could use different filters for CW and for SSB. Using my 20 meter converter, I was tuning around 20 meters one day. I could hear lots of hams, but I was bothered by poor sensitivity and poor selectivity. I thought, "What's wrong with this receiver today?" I soon discovered there was no filter at all plugged into the 80 meter receiver board. What I was hearing was just stray coupling between the mixer and the IF amplifier. Amazing! So if you want band-pass filters with 50 dB skirt attenuation, you're going to need at least that much isolation between the stages. That means you need metal shields between all stages, coax interconnects and lots of bypass capacitors.

The metal-shielded modules can be small circuit boards mounted in commercial boxes.

What I usually do is make shallow rectangular boxes out of pieces of two-sided circuit board material soldered together. The circuit is then carved into the floor of the box using small wood-carving chisels. The press-fit lid of the box is made from thin sheet aluminum folded over the corners of the PC board box.

Egg carton construction of the "mother board" of an 80 meter receiver

The compartment on the left is the product detector and audio amplifier. The large area in the center is the IF amplifier and AGC. The two modules on the right are the mixer and an optional RF pre-amplifier for the crystals.

If you plan on having more than one circuit block on the same board, you can isolate circuit blocks from each other using circuit board barriers soldered in place. The result is "egg-carton construction." Power can be routed between compartments using feed-through capacitors. If you suspect that a circuit block might not work, then wire your circuit on a separate square of PC board, then mount it on the floor of the desired compartment. All of these techniques are illustrated above. The IF amplifier in the center compartment is on a separate PC board.

Shielded modules and shielded cable interconnects

For connections between stages I use thin **RG-174 coax and phono plugs**. Right angle phono plugs are not designed for RF and have too much capacitance. However, they're cheap, available, easy to wire, and don't take up too much room. I don't pretend that phono plugs are OK for 6 meters and VHF. I got some feel for their frequency limit when I discovered that switching from a phono plug to a UHF PL-259 on my 50 watt transmitter amplifier vastly improved performance on 10 meters. So far, I haven't seen any problems when working with lower frequencies and far lower power levels. Fortunately, receivers have tiny currents and low voltages. Most phono plugs have plastic bodies. That means that about 3/8 inch of the center conductor is not be shielded. For my crystal filters I used metal-bodied phono plugs that are at least a slight improvement.

TV cable connectors are electrically superior to phono plugs, but they are dreadfully intermittent. Personally, I've found them unusable and I wish the TV industry would junk them. Proper RF connectors like BNC, SMA or TMA cost $2 - $6 each. Some of them are hard to

assemble and your receiver could easily contain $300 worth of "proper" connectors. Also, most of these connectors are too long to fit gracefully in a small receiver. Right-angle phono plugs are quite short and quite cheap. Long live phono-plugs!

Use plastic knobs

One odd little problem I encountered was that touching the metal control knobs or the front panel caused scratchy noise in the headphones when I listened on the higher bands. Yes, the metal panel was grounded and the chassis was wired to the station ground. The station ground is a heavy 12 gauge wire that grounded all the chassis's to a copper metal pipe next to the station. I don't really have explanation for this, but I switched from metal to plastic knobs and the annoying scratchy noises improved.

Bottom view of the receiver

Band switching and power supplies

The precision power supply for the VFO is at the top right. The low drop-out regulated supply for the rest of the receiver is at the bottom right. These are the same circuits used earlier with the VFO & QRP transmitter modules. The band-switch is the multi-wafer ceramic switch on the left. The black wires on the left are skinny coax that interconnect the inputs and outputs of the converters for every ham band except 80 meters. It is desirable to cover the bottom with a metal plate to help keep stray signals out of the power leads.

80 Meter input preselector

The core of the receiver is an 80 meter single-conversion superhetrodyne. The "front end" of this receiver is a mixer. No RF pre-amplifier is needed on 80 meters because, if the receiver works well, then the atmospheric noise coming in from the antenna will be louder than the receiver internal noise. In this situation an RF amplifier won't help. However, the mixer does need a sharp bandpass "preselector" filter to keep out the low frequency AM radio and limit the input signals to 3.5 to 4.0 MHz. It's especially vital to filter out AM broadcast stations. These stations put big voltages on the antenna and tend to overwhelm the mixer unless they are well attenuated.

The mixer subtracts the VFO frequency, (5.0 to 5.5 MHz) from the IF frequency, (9 MHz), to tune 80 meters, (3.5 to 4.0 MHz). The two inputs to the mixer are the VFO signal and the antenna signal. When I first examined the 1986 ARRL design, I was disappointed to see that the pre-selector had a primitive variable capacitor that the operator was supposed to tune for maximum gain for a particular part of the band. After all, the bandpass filters for the other HF bands were fixed and not accessible from the front panel. I attempted to build my own fixed bandpass filter, but my filters had too much attenuation (poor sensitivity) and sometimes let in AM broadcast stations - it was like listening to a crystal set.
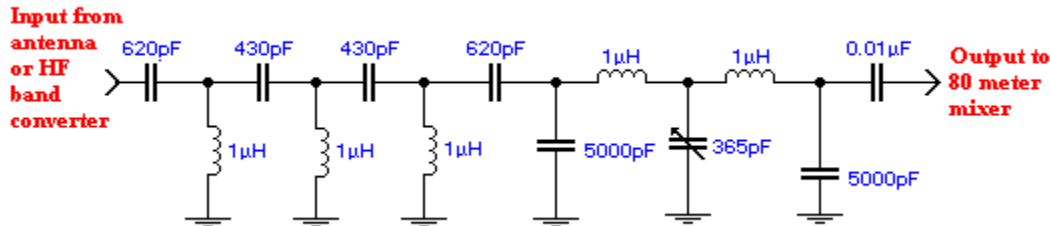
The recommended 80 Meter preselector filter for the core receiver mixer input.

So I returned to the ARRL design with the 365 pF variable capacitor.   It had so much attenuation on 80 meters, I couldn't hear a thing. I ran the ARRL circuit on a Spice program, and, according to Spice, it should have worked well. However, mine didn't. Using trial and error, I removed some parts and ended up with the circuit shown below. My filter works pretty well, although, according to my Spice program, it shouldn't have. Sigh.....
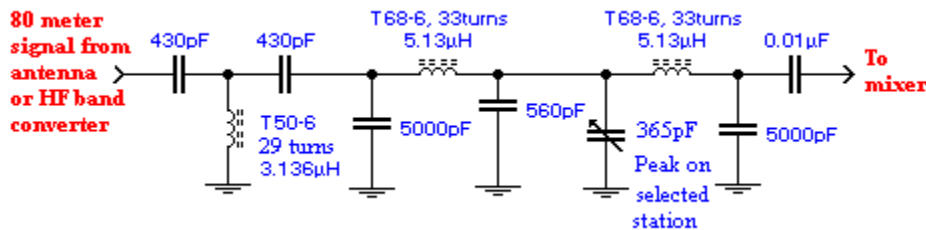
My version of the 80 Meter preselector filter for the mixer input

I mounted the preselector in a shielded box up on the front panel where the peaking capacitor was accessible. Someday, when I figure out how to build a better preselector, I shall replace the whole module. On the positive side I found that the variable peaking capacitor is quite useful as an attenuator for receiving strong single sideband signals. That is, strong SSB phone signals are often much more intelligible when the preselector is mistuned and signal strength is decreased.

The preselector is built in a little box up front behind the front panel.

The variable frequency oscillator (VFO)

The receiver VFO is the same as the 5 MHz transmitter VFO discussed in chapter 10. The big tuning knob controls the VFO. Actually, in superhetrodynes the VFO is usually called a *local oscillator*. The range and stability of the VFO determine what VFO and IF frequencies are practical. Like a transmitter VFO, a receiver VFO should be stable to less than 5 Hz/ minute drift, although less than 20 Hz will probably be OK.

Unfortunately, if the VFO frequency is too low, it probably won't span enough Hz to cover the bands you're interested in. Notice that 10 meters is so huge, 1.7 MHz wide, that you may have to cover it with multiple converters. So far, my receiver just tunes the first 500 KHz of 10 meters, which includes all the CW activity. I guess I'll worry about the rest when I get on 10 meter SSB. The VFO frequency and its harmonics should avoid the ham bands as much as possible. Frequencies with round numbers are best because they make calibration easy. Put all these factors together and you'll find your choices are actually fairly limited.

In fact, once you've built separate transmitters and receivers and used them on the air, the disadvantage of having to tune two VFOs makes it obvious why most modern rigs are transceivers. When planning a homebrew receiver and transmitter, you might consider using a common VFO modules. A common VFO would be a great help on the air. But, if you use just one VFO, you will have to master the 500 to 800 Hz send/ receive frequency-offset problem. Also, an isolation amplifier is needed to keep the cable connecting one to the other from loading down the receiver VFO. And finally, when used on the upper bands, each crystal oscillator in the converter and each transmitter PMO must be on the corresponding frequencies in order for the receiver to listen on exactly the same frequency used by the transmitter. This represents lots of work.

A varactor tuned 5 MHz VFO. Tuning is accomplished with the big round potentiometer.

Mixer magic

The purpose of a mixer is to translate the frequency of an incoming radio signal to a constant intermediate frequency (IF) that can be amplified and filtered more easily. Mixers combine a local oscillator sinewave with the incoming radio signal to make a composite signal. The new signal contains the original frequencies, plus the new sum and difference frequencies. Mixers intended for moving a VFO up to a high band were described in chapter 11. Mixers for this purpose can be quite crude and will work well. Unfortunately, receiver mixers are much more difficult because the signal input can be so tiny.

One way to look at mixers is that a big local oscillator sinewave keys the incoming RF signal on and off, cycle by cycle. The lesson is that the local oscillator (the VFO tuning knob) must be a big signal while the RF input signals may be arbitrarily small.

The ARRL Handbook presents six or eight different mixer designs made with discrete diodes, inductors and transistors. However, in most ARRL receiver designs since the 1980's, the mixer is an integrated circuit or little canned assembly labeled "mixer." I guess everyone else was having mixer trouble too, so they resorted to integrated circuits. Last year there was a simple receiver project in QST that used an IC that contained both the mixer and the VFO. I'll bet these marvels work fine, but the contents of these ICs are a mystery. Use one if you want.

Mixers will give you lots of static... and squeals, howls and squawks

So far I've built four different mixer designs from discrete parts. First I built a classic balanced mixer with ferrite cores and a hot carrier diode ring. When I turned it on, I heard loud, roaring static in the headphones. "Oh goodie!" I thought, "Listen to all that atmospheric static! It must be working!" I soon figured out that the static was coming from the mixer and the IF amplifiers and had nothing to do with the outside world. I had just learned a basic truth about mixers: Mixers aren't just prone to generate "a little background noise." They often produce gigantic Niagara Falls noise that obscures everything coming in the antenna. However, once I had the mixer input levels and resonant circuits tuned up as best I could, the noise disappeared and I began to hear stations. Unfortunately, as I tuned across the band, there were loud whistles like marker beacons every few KHz. In between the whistles, I could sometimes barely hear

strong stations. So much for diode ring mixers.

DUAL GATE MOSFET MIXER

T1
T50-6
44t / 9turns

9.00 MHz output to crystal filters and IF amplifiers

80 meter input from preselector

0.01µF

NTE-454   60pF

100kΩ

10kΩ

100Ω   0.01µF

VFO input >2V pk to pk.   0.01µF   500Ω

100Ω   1000pF feed through capacitor   12V   47µF   0.01µF
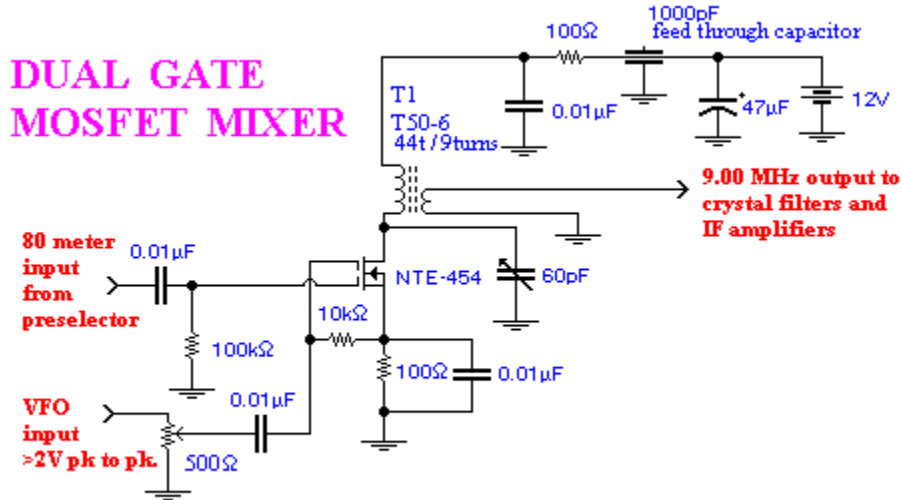
A practical mixer

The only mixer that has worked well for me is shown above. All the others suffered from noise, "birdies" and usually insensitivity as well. My successful mixer is made from a dual gate MOSFET. Unlike diode mixers, the operation of this mixer is obvious. The dual gate mixer is essentially an ordinary tuned transistor RF amplifier. The radio signals come in on one control gate. This modulates the large current passing from drain to source of the transistor. The small voltage on the control gate controls the large drain current thereby amplifying the original signal. A second input gate amplifies the local oscillator signal. The local oscillator signal is so strong it turns the drain to source current totally on and off, "chopping" the input RF signal into tiny segments. The big output current from the transistor becomes an amplified "mixture" of the two input signals. I originally used a tuned version of this mixer in which the transformer primary was tuned with a capacitor to resonate at 9 MHz as shown above. That works OK, but is rather tweaky and subject to noise and birdies. I now prefer an untuned version (not shown above) which has slightly less gain, but isn't so easily misaligned. Just use a CWS (Amidon) FT50-61 ferrite core with 20 turns primary and 4 turns secondary.

Because of the high gain of the MOSFET, the VFO sinewave signal can be low amplitude, 1 volt peak, and still fully chop the radio signals on and off. In contrast, a diode ring mixer needs a big local oscillator signal, 12 or more volts peak, to chop the signal. Other transistor mixer designs use junction FETs or bipolar transistors. These designs use the emitter resistor as the VFO input port. The emitter or source has no gain, so these designs also need big local oscillator signals.

A small local oscillator signal is especially helpful for building the converters you will need for each of the other nine HF bands. Each of these converters must work through its own mixer. If the dual gate mixer were not used in the converters as well, each of the eight local oscillators you will build would need separate amplifiers to get the local oscillator signal up to 12 volts peak. You could also put in a common, broadband pre-amplifier for the crystal oscillator inputs to a common untuned mixer.

All dual gate MOSFETs are not equal

Alas, a dual gate MOSFET mixer isn't a guaranteed success either. When I first built a MOSFET mixer, I couldn't buy any of the transistors recommended in the handbook. I first tried a generic part, the NTE221 transistor. This produced the usual oscillations and insensitivity. I was getting discouraged, but I tried the similar NTE454 and *IT WORKED!* The only obvious difference in the specifications was that the gate shut-off voltage was smaller. In other words, the NTE454 was more sensitive. Since then, I've discovered the NTE222 seems to work as well as the NTE454. The NTE455 seems too sensitive. In my circuit, at least, it produced whistles, birdies and noise. On the other hand, the NTE455 worked great as a product detector (Chapter 7).

I first tried to use two dual gate MOSFETs in a "semi-balanced" configuration. The handbook said this is superior to the simple mixer shown above. Balanced designs are supposed to help cancel images, that is, birdies. My semi-balanced mixer produced the usual oscillations, but at least the noise and sensitivity were adequate and I began to hear weak 80 meter stations with my receiver. I also tried an "economy mixer" made from two JFET transistors as was described in chapter 11. This worked in my receiver, but was too insensitive. The dual JFET trick seems to be limited to frequency converters in transmitters.

Reading up on mixers, I learned that mixers are only happy when they receive the exact input levels. That's why I put a pot on my VFO drive to inject the optimum level. As I turn up the VFO input to the mixer the signal strength rises abruptly then levels off. Higher levels of VFO contribute only slightly more gain, but much more noise. I adjust the VFO input to where the gain first begins to level off. (Note: My VFOs are designed to work into a 500 ohm load, hence the 500 ohm pot.)

The sensitivity of mixers to ideal levels explains why most modern transceivers have input attenuators so that they can be adjusted to tolerate strong signals. I got a QSL from a guy who wrote, "Sorry about the 529 signal report. After we signed off, I discovered I had the attenuator on." As mentioned earlier, the 80 meter preselector filter may be deliberately mistuned so that it acts as an attenuator to limit signal strength.

Note: Reception on 80 meters and 160 meters is best with a tuned transmatch

By accident I discovered that reception on the two lowest HF bands is much better when the receiver is sharing the antenna with the transmitter and the antenna is tuned with the "T" transmatch described in chapter 9. In my neighborhood, at least, the signals from the local AM radio stations are so high that they tend to overwhelm the 80 meter mixer. This results in a lack of audible signals on 80 and 160. When you tune up the transmatch, suddenly numerous ham signals appear. The obvious conclusion is that my receiver preselector filter is too non-selective. However even my old Collins receiver is greatly improved by a tuned transmatch.

Crystal filters and BFOs

Crystal IF filters give you the selectivity you will need for working CW. They eliminate interference from nearby stations and also eliminate a great deal of the atmospheric noise. The output from the superhetrodyne mixer is a weak, broadband, IF frequency signal that needs amplification and filtering before it is ready to be detected. The bandpass filtering is usually done right after the mixer.
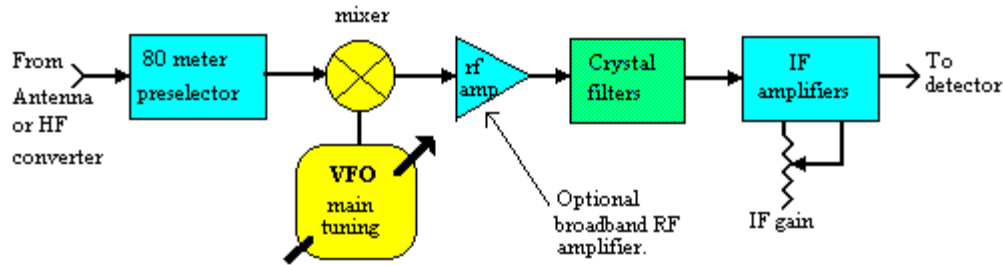
Location of crystal filters in a superhetrodyne

The filter could be mechanical if you are using a low frequency IF, but if your IF is 9.0 MHz, like mine, you'll need one or more crystal filters. Before I describe building filters, I'll discuss the Beat Frequency Oscillator (BFO). You will probably need the BFO as a tool to select the crystals for your filters.

The Beat Frequency Oscillator (BFO)

A beat frequency oscillator is an RF oscillator that operates on the intermediate frequency of a superhetrodyne. The BFO mixes with the IF signal to make CW and single sideband transmissions audible and/ or understandable. Without the BFO, CW signals would be inaudible or a thumping sounds at best. Single sideband phone would be just unintelligible "Donald Duck" noises. In single sideband, the transmitter filters out the basic carrier frequency leaving just one of the modulation sidebands. The BFO serves to restore the carrier sinewave, in effect returning the sideband signal to its original amplitude modulation.

During detection, the audio signal passed on to the loudspeaker is the difference between the IF frequency and the BFO frequency. For example, when listening to CW signals, the IF frequency might be 9.000,000 MHz. The BFO frequency might be 9.000,**700** MHz. What you hear in your headphones is a musical tone of the difference frequency, 700 Hz. If that pitch is too high for you, adjust the BFO frequency to say 9.000,500 MHz to produce a musical tone of 500 Hz. For the musical tone to stay constant, the BFO oscillator must be quite stable. Therefore, we use a crystal oscillator and pull the frequency up or down using a variable capacitor, just like we did in the crystal controlled QRP in chapter 6.
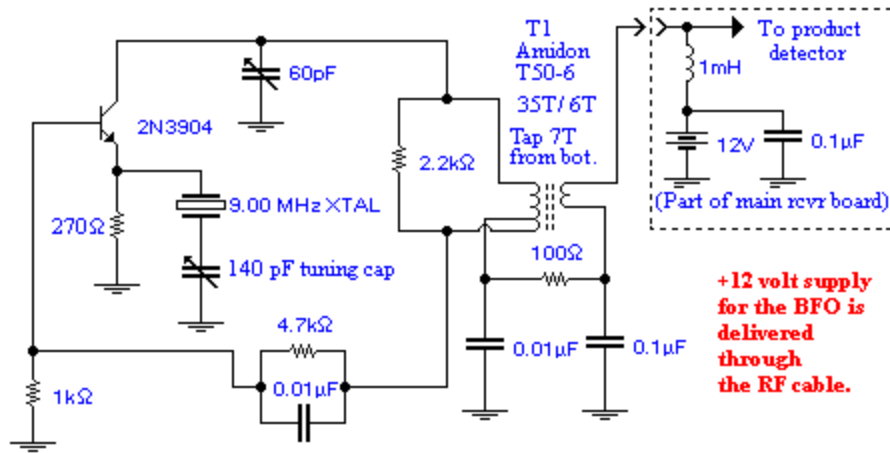
The Beat Frequency Oscillator

This BFO is from the W7ZOI and K5IRK receiver in the 1986 ARRL Handbook. Its unusual feature is that its DC power supply rides on the same line as the RF output. This makes it easy to install the BFO in a little metal box up on the front panel remote from the main receiver board. A variable capacitor on the front panel "pulls" the BFO crystal frequency above and below the nominal frequency. The BFO, together with the crystal filter, allow you select upper or lower sidebands. The BFO is connected to the main board with a length of thin coax jumper cable. If you wish to use this oscillator for matching 9 MHz crystals for filters, I suggest you install the BFO crystal in a small socket.

The Beat Frequency Oscillator (BFO) module.

The BFO frequency tuning range should extend above and below the bandpass of your crystal filters. *When the BFO frequency is below the center of the filter bandpass, you are listening the upper sideband. When the BFO is tuned above the filter bandpass, you're hearing the lower sideband.* Tuned to the upper sideband, when you tune down the CW band, the whistle pitch of a signal will start high, drop down to a low pitch and then disappear. When

tuned to the lower sideband, when you tune down the band, the pitch will start low then climb up high and disappear. When the BFO is tuned to the center of the filter bandpass, the tone will start at a medium pitch, drop to a low pitch, then climb back up to medium pitch, then disappear.

When tuned to sideband phone signals, the signal is harder to make understandable if you select the wrong sideband. Consequently, it will be important to calibrate the BFO tuning knob so that you will know when you are listening to upper or lower sideband.

Ladder filters

Building crystal filters was easy, once I figured out how. Most commercial tranceivers use modular crystal filters that have specific bandwidths and are sealed in little cans, something like an integrated circuit. I made my filters from discrete crystals.
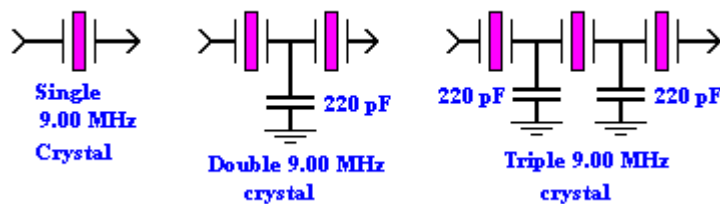
One, two, and three crystal "ladder filters."

A ladder filter is just two or more simple crystals in series with capacitors bypassed to ground at the nodes. The bandpass width is inversely proportional to the number of crystals and the capacitance to ground. ***In general, the lower the capacitance on the nodes, the wider the bandwidth.*** Large capacitors, like 50 ohms reactance, will give narrow bandwidths and higher attenuation. Long "ladders" of course produce even narrower bandwidths and more attenuation. If all the crystals are identical, then the "skirt attenuation" on either side of the peak passband becomes steeper and steeper as more crystals are added.

Crystal filters with two or three crystals are sophisticated enough for "CW after dinner." By that I mean, you can work the busy CW bands early in the evening with adequate signal separation. A single crystal filter made from just one 9 MHz crystal is perfect for single sideband phone (SSB). With three or four crystals, the bandwidth is so narrow, SSB is totally unintelligible. With strong CW signals and lots of QRM, triple or quadruple crystal ladders are extremely useful. If you tune down to the bottom of 20 meters in the evening, you'll usually hear storms of CW stations all trying to work the same 5 or 6 DX stations in exotic countries. With only one crystal switched in, you'll hear practically everyone at once. Switch in two and three crystals and suddenly, you're not only listening to one clear station, but most of the background noise has gone too.

How many crystals can you use in a ladder?

One limit on how many crystals you can use in series depends on the precision with which you match the crystals. I didn't match my first set of filters and they produced more attenuation than filtering. I then proceeded to waste time getting more gain out of my IF amplifier. Then, after I achieved the gain, the selectivity wasn't much better than single crystals. Finally, I tested my crystals one by one by putting them in the BFO and measuring the frequency with a frequency counter.

I didn't expect that the frequency filtering characteristics would be exactly the same frequency as when a crystal is used in an oscillator. However, I figured I could at least select sets of crystals that were similar. When I ran them in the oscillator, I was shocked to discover that the crystals were as much as 2.5 KHz different! No wonder it worked so poorly. I had put 9.001 MHz crystals in series with 9.003 MHz crystals. I had built a "crystal barrier," rather than a crystal filter.

Luckily I had bought twenty 9.000 MHz microprocessor crystals. That sounds extravagant, but they're under $1 each at Digi-Key or Mouser. Because I had a wide selection of 9.000 MHz crystals, I was able to match up two crystals that were within a few Hz of each other. And I was also able to match up a group of 3 crystals that were within 50 Hz. This time when I put matched crystals in my ladders, the improvement was dramatic. When I switched from a single crystal to a double crystal, the signal strength barely dropped. With three crystals, the signal strength just dropped slightly more.

In theory, you can make perfectly matched crystals by placing trimmer capacitors in parallel with each crystal. Then you would trim the crystal and capacitor assemblies in the oscillator one at a time so that each crystal/capacitor assembly oscillates on precisely the same frequency.

Another limit on the number of crystals in a filter is the shielding and RF isolation between the mixer and the IF amplifier. If the shielding is poor, your IF amplifier will "hear" the signal from the mixer without the signals ever passing through the crystal filters. In my receiver, 5 or 6 crystal ladders aren't worth building.

220 pF (3)
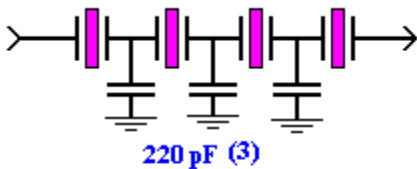
Four matched 9.000 MHz crystals

Switch in your filters with a rotary switch

I first built my filters as "plug-ins," but I soon discovered it was too hard to change them in the middle of a QSO. Eventually I wired them to a rotary switch in a shielded box. As I became more experienced with using the filters, I began to use the triple filter more and more. Finally I built a quadruple filter and now use it routinely. I find it works well with the S-meter (strength meter) as a way to tune my transmitter in to zero beat with another ham's signal. I just sweep the transmitter VFO across the band until the S-meter jumps up to maximum. This occurs when the VFO frequency converted into the IF matches the frequency of the four matched crystals. The offset of the BFO and the tone of the Morse code signal take care of themselves. That is, if the fellow is on the upper sideband, then the S-meter only responds to my VFO when I am on the same BFO offset that he is using. This happens because only one sideband is audible at a time with 3 or 4 crystal ladder filters.

By the way, one of my 20 crystals behaved erratically. While I watched, the frequency wandered about +/- 200 Hz. Consequently, I didn't use it. With my bare board oscillator, I

found that **all crystals wandered about 2 to 5 Hz.**   This implies that ideally, all crystal oscillator circuits should be treated with the same respect needed for a stable VFO. In other words, crystal oscillators should be housed in metal boxes with regulated power supplies. Building a stable VFO is hard enough. There's no need to add an additional 5 Hz of drift if it can be avoided.

Series and parallel cut "XTALS"

There are two kinds of simple crystals, series and parallel cut. As I understand it, the difference is the oscillator circuit for which they are designed to be used. For example, a series-type crystal is intended to be used in series with a specific capacitance in an oscillator. When this exact capacitance is used, it will oscillate at the rated frequency, for example, 9.000 MHz. In contrast, if you use a parallel cut crystal in the same circuit, it might oscillate at 9.004 MHz. You may use either kind of crystal, but your filter frequency may not be exactly 9.000 MHz. If you like, you may place trimmer capacitors in series or parallel to get exactly 9.000 MHz.

All 9.000 MHz crystals aren't equal

In my experience larger crystals, size HC49 or bigger, work well. The tiny surface mount or half-size HC49 crystals need more signal strength from the mixer output to push the signals through the filter. The broadband "optional" amplifier shown below will give you extra gain if you need it. It's the same design that will be used later as a RF amplifier for the higher HF bands.
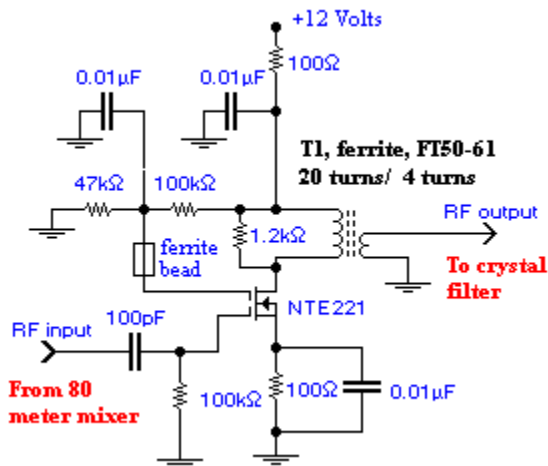
Broadband RF amplifier   Place between RF mixer and the crystal filter.

I also observed a difference between different brands of crystals. My crystals from the ICM company were extremely similar to each other. For ladder filters, this would be the brand to buy. My crystals from the ECS company had much wider frequency variation from one crystal to the next. This isn't helpful for building ladder filters, but if you need crystals that are slightly different from each other to build wider pass-band filters, or perhaps SSB oscillators that must operate 2.5 KHz above and below the nominal frequency, then buy the ECS crystals. I found them both useful.

By trial and error I found that the untuned impedance step-down transformer (T1) shown

in above circuit performs better than leaving the transformer out. In other words, this implies that the crystals look like roughly 50 ohms, but must be matched to the high impedance output of the MOSFET transistor. There's a design in my ARRL handbook that uses impedance step-up transformers to match the filter. I find it hard to believe that design is optimum unless the crystals they used behave differently than mine.

The second input gate in the above amplifier is used to set the DC bias and make the amplifier class A. A voltage divider delivers about 4 volts DC to the gate. The "*ferrite bead*" is a tiny inductor (RF choke) that helps insure that the MOSFET doesn't oscillate. The ferrite bead is literally a 1/8 inch cylinder with a tiny hole through the center. For example, you could use a CWS type (Amidon) FB43-101 bead. The type isn't critical. I used several different kinds of beads and have had no trouble with oscillation. If does oscillate, remove the 0.01 µF bypass cap from the 100 ohm source resistor. The resulting negative feedback should kill the oscillation at the expense of a small amount of gain.

The IF amplifier

The IF amplifier is another tricky part of a superhetrodyne. It's a high-Q amp that must handle signals with a range of 100 dB or more without oscillation or noise. This is a huge dynamic range. The gain on the IF amplifier stages should be adjustable using an IF gain control. Too much gain and you will have noise and squeals. Too little gain and you can't hear those feeble DX stations.

Moreover, if you used miniature half-size HC-49 crystals to build your bandpass filters, you will need even more gain to stuff signals through the significant attenuation of the filters. In the last section I described a simple RF amplifier that can be placed between the mixer and crystal filter to overcome this difficulty.

Oscillations in an IF amplifier come in several flavors. As you tune the LC circuit of an IF amplifier stage you will hear squeals, harsh roaring, silent dead spots, and gentle static. The setting that brings in the loudest signals is surprisingly noise free. The first time I turned on my receiver, I quickly learned that *most of the receiver noise is coming from the mixer and IF amplifiers*, not from the outside world. The noise comes from a maladjusted mixer or too much IF amplifier gain.

Although I was able to tune up my 80 meter receiver using a signal generator, real 80 meter ham signals worked the best for me. There's no point in simulations when you have the real thing. A problem with tuning up the IF on 80 meters is that 80 may be dead during the day. During the summer, 80 may not be so hot in the evening either. As a result, you might consider building a converter for 20 meters early in the project. 20 meters is usually full of signals anytime, day or night, all year long. Since your 80 meter receiver may not yet be working, you can adjust your converter by feeding the output into a commercial receiver tuned to 80 meters. Then, after you have the converter working, you'll be confident that there are lots of real signals for your 80 meter receiver to hear.

Impedance matching the crystal filter to the IF amplifier

Looking at examples on crystal filter circuits in handbooks from various years, I found circuits that seem to assume the filters are low, medium or even high impedance. In most of my attempts, I seemed to get the best gain when my filters were assumed to be relatively low

impedance, say 50 to 100 ohms. That's why the optional amplifier described above used a step down transformer output. I tried step-up, step-down and no transformer to feed the signal into the IF amplifier shown directly below. Step up worked best as shown.
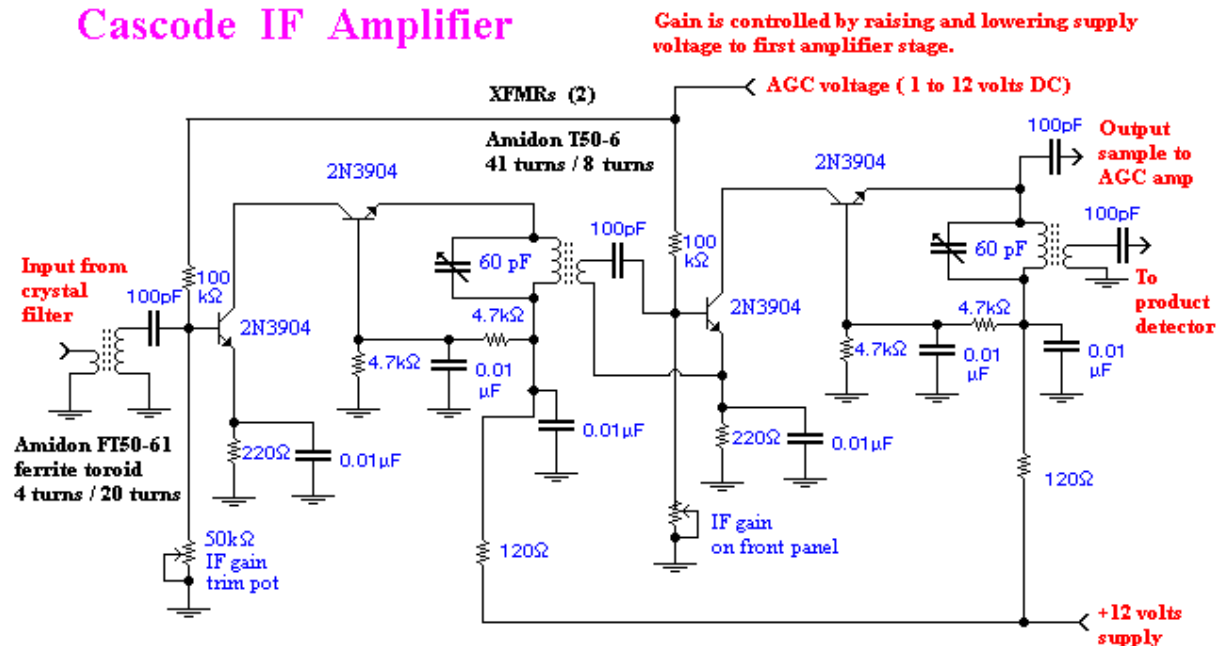
An IF amplifier using bipolar cascode amplifier stages

Cascode amplifiers - variable gain with constant Q

I had heard of *cascode amplifiers* but didn't have a clue why they were wonderful. I built two other IF strips before I settled on the circuit shown above. The previous versions used dual gate MOSFET amplifiers, similar to the crystal filter preamplifier described earlier. The gain of each MOSFET transistor could be controlled by varying the DC bias on one of the two control gates. This control voltage can be generated by either the IF gain knob or by the automatic gain control circuit. In short, the dual gate MOSFET looks ideal for IF stages. Unfortunately, I had lots of trouble with squeals and noise and I always had insufficient gain.

Reading in an old handbook, I spotted the IF amplifier shown above. The handbook said that simple transistor amplifiers were poor for IF amplifiers because, when you tried to change the gain of a single transistor, the Q of the output tank circuit changes and you get squeals and noise. "Yes!! Yes!!" I hollered. "That's my problem!" The above circuit uses two bipolar transistors in each stage in a "cascode" configuration.

The input transistor is wired as an ordinary grounded emitter amplifier with its high input impedance. The clever part is that the second transistor is wired to the first in a grounded base configuration. This gives the amplifier a super-high output impedance which supposedly makes it immune to changing the DC bias on the first stage. Besides the phrase "cascode amplifiers" sounds cool and I wanted to use some. This cascode amplifier worked well for me. It produces more signals and less noise and oscillation than my previous efforts.

It's interesting to see what happens when one tunes up an IF amplifier with a scope probe on the IF amplifier output. As expected, the audio signals ride on the IF frequency signal, much like amplitude modulation. When the amplifier is tuned for optimum signal reception, the scope shows that the amplifier is producing the most modulation on the IF signal. But when the output is tuned slightly differently to produce the largest 9 MHz signal, the reception is OK, but not the best. I had not realized that these two attributes aren't the same thing.

Automatic Gain Control (AGC) is not a luxury

The automatic gain control is a receiver feature that holds the signal level relatively constant while tuning in signals of varying strength. Before I built one, I thought an AGC was in the same category with digital readouts and beautiful cabinets. Why do I need one? Am I too lazy to turn the IF gain up and down? It turns out that an AGC has many advantages. The main one is that it helps you achieve the gigantic signal strength dynamic range (100 decibels) that you need in practical ham receiver. After I built an AGC, I realized it was it was also a big help in getting rid of the noise and oscillations.

Although I had been happy with the performance of my IF without an AGC, I could never get rid of the "noise zone" in my IF gain control. That is, I had to keep the IF gain below a certain level, or it would produce a roar of receiver-generated static. Apparently, IF amplifier stages are only happy when they are processing signals of a limited range of amplitude. Noise and oscillations happen when the signals in the final IF amplifier are too large. With an automatic gain control, it was easier to tune the IF so that the IF gain control acts like a "volume control" without a noise zone.

The S-meter and other uses for the AGC

A benefit of an AGC is that, when I switch in higher selectivity crystal filters, the AGC compensates for the filter attenuation to a large degree. Also, when you put a meter on the AGC signal level, you have made an *S-meter* - in other words, a "strength meter." The S-meter taught me that what you hear in the headphones doesn't always correlate with the signal strength in the IF strip. In other words, the S-meter is reacting to big IF frequency signals, not the level of modulation on those carrier signals.

One nifty use for an S-meter is to tune the transmitter VFO to match the receiver. In other words, if you are answering a CQ, you can tune your transmitter right in on top of the fellow you want to call. First, you need to switch in a 3 or 4 crystal filter. Then, as you slew your transmitter VFO across the frequency, the S-meter will soar when you are lined up right on top of him. Without using this technique, "zero beating" the VFO is time consuming. Modern transceivers don't have this synchronization problem because the receiver and transmitter and using the same VFO.

I originally used a digital bargraph S-meter that looks very racey. Unfortunately, like almost everything digital, it makes a hissing radio noise when it changes level and I don't need that. I tried hard to filter the bargraph circuit, but as usual, I couldn't get rid of the hiss. I finally replaced it with an old-fashioned analog meter and the noise vanished.

Automatic Gain Control (AGC)
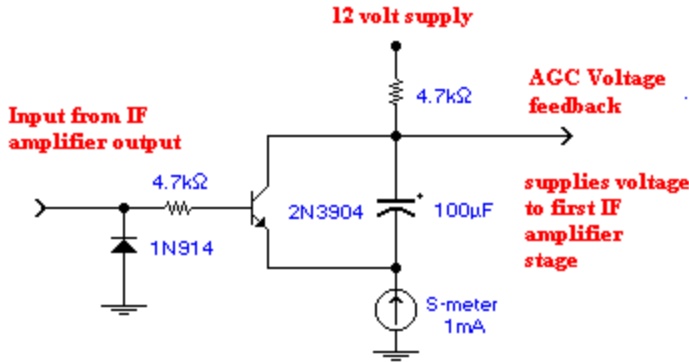
An AGC works by sampling the output level of the last IF amplifier stage. Signals are detected like a crystal set using a diode and averaged with a capacitor to produce a DC level proportional to the IF signal strength. This DC level is then amplified and used to bias the IF amplifiers. For example, the above circuit can deliver the positive voltage bias on IF amplifier stages made from dual gate MOSFETs. Or if the IF amplifiers are made from bipolar transistors, the same circuit can put Class A bias current into the bases of the transistors. For big signals, the AGC automatically turns off the bias and runs the transistors "Class C." Then when signals become weak, the bases are biased "ON" so that the signals don't have to exceed the 0.6 volt input barrier.

The product detector
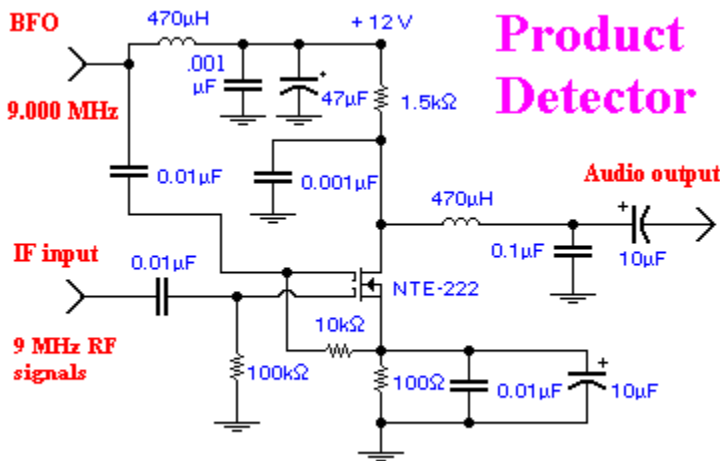
My product detector is basically the same circuit I used as my mixer. Product detectors are "direct conversion mixers" that mix an RF "beat frequency" (BFO) signal with the IF frequency to produce a difference frequency which is the audio signal. A 470 microhenry RF choke keeps the RF out of the audio output. To say it another way, the choke keeps the .1 μF cap from shorting out the RF while letting audio frequencies pass on to the AF amplifier.

Notice that the 12 volt DC power supply for the BFO oscillator passes through another choke and goes out to the BFO oscillator box on the front panel. That is, the DC power input for the BFO and 9 MHz RF output from the BFO share the same wire. The 470 microhenry choke

prevents the 9 MHz signal from shorting to the power supply line.

Product detectors are exactly what's needed for CW or SSB. However, when you tune in an AM broadcast station, it will have a whistling overtone on it until you tweak the BFO perfectly to get rid of the whistle. If you plan to listen routinely to short wave AM broadcast stations, you'll probably want to replace the IF crystal filter with a short circuit. Otherwise, the 2 KHz width of a single crystal will be too narrow and the sound will be "low-fidelity." Another change you might consider is to put in a switch to bypass the product detector and use an ordinary diode detector for AM signals. Any of the four dual gate MOSFET transistor types mentioned earlier will work fine, including the NTE221.

With product detectors, anything works at least a little

In my experience, receiver RF mixers that produce an IF output are extremely finicky and are often plagued with low sensitivity and oscillations up and down the band. In contrast, a product detector is amazingly uncritical. I haven't tried to make one out of wood shavings or pebbles from the driveway, but I wouldn't be surprised if I would still hear signals.

For example, I built a new IF strip and product detector in hopes of improving the noise problem. It worked, but I was disappointed with the sensitivity. I was inspecting my dual gate MOSFET product detector when I realized that I had soldered the MOSFET in 90° out of alignment. In other words, the drain was connected to the RF input gate, the source was connected to the drain circuit and the BFO input was connected to the source. Delighted that I had discovered my problem, I correctly soldered in a new transistor. When built properly, it worked better - but not dramatically better.

In another experiment I disconnected the RF input so that the input to the product detector was just stray coupling from the IF strip. Signals were weak, but it still worked amazingly well! Finally, I disconnected the BFO input. I was relieved to confirm that it no longer tuned and received ham-band signals. Instead it worked like a crystal set and received the loudest signals on or near the ham band input. For example, on 17 meters, it brought in the Deutshe Welle (Radio Germany) loud and clear.

The AF amplifier
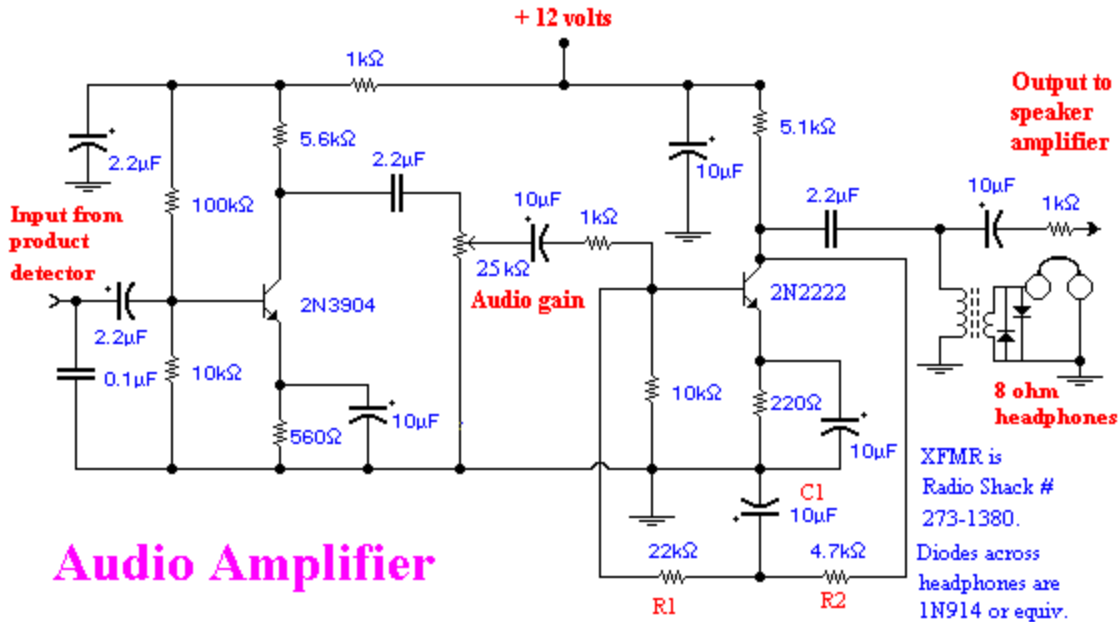
Audio Amplifier

The output from the product detector is an audio signal that needs to be amplified before it goes to the earphones or speaker. Most ARRL designs use integrated circuits marked "audio amplifier." The LM386 is a typical one-chip audio amplifier. I've used these and they usually work great. But of course I didn't learn anything from the experience. So this time I built my audio amplifier out of discrete parts from an example in my 1986 handbook. It looked like two straight-forward "R-C coupled amplifiers" in series. But the design had extra filter components I didn't quite understand. Every part that I didn't understand, I left out. That was my education. The audio amplifier was dead as a doornail when I first turned it on.

An audio Automatic Gain Control (AGC)

I was particularly puzzled by the low frequency feedback link, R1, R2 and C1. I couldn't understand what sort of "low frequency filtering" the designer was trying to accomplish. But, when the amplifier seemed completely dead, I put these mysterious components back in the circuit. Voila! The earphones came to life. It turns out that this loop biases the amplifier "on" for weak signals and biases it "off" for loud signals. It's a sort of audio AGC circuit.

Remember that for a bipolar transistor to turn on, the input signal must be greater than 0.6 volts or no current will flow into the base. In a "Class A" amplifier a DC signal is added to the base. This increases the base voltage above 0.6 volts so that it's always turned on. In this way a class A amplifier can amplify signals much smaller than 0.6 volts. The low frequency feedback adjusts the bias for weak and strong signals. When the signals are weak, the second transistor is turned off, so it's collector voltage is high and unchanging. This big collector voltage is leaked into C1 to provide a forward bias for the same transistor, biasing it on and raising its sensitivity. Conversely, when the signals are strong, the collector has a big current flowing but a low average voltage from the collector to ground. This lower voltage biases the transistor more "off."

Protecting your ears from strong signals

The audio amplifier is able to blow your ears off when you encounter a strong signal.

Therefore it's essential to add a clamp circuit to limit the voltage to the headphones to less than about a volt. I first did this with back-to-back 5 volt Zener diodes across the headphone jack. In practice, with sensitive, modern 8 ohm headphones, I found that less than one volt peak is plenty of volume for me. Eventually I put in two ordinary silicon 1N914 diodes "shorted" across the headphones. This limits the positive and negative sound peaks to just +/- 0.6 volts and my ears haven't been blasted since.

How Hi-Fi should it be?

The original circuit was also sprinkled with 0.1 microfarad bypass capacitors as if the designer were trying to kill all higher frequency sounds and shunt most of the audio to ground. Since I was always trying to get more gain, I left out the bypasses. The amplifier worked well without them, but the sound of the static had an obnoxious, piercing, high pitch that irritated my ears. I put the bypasses in and, as I expected, the audio sounded more "base" and became somewhat weaker. However, getting rid of that piercing, hissing static was well worth the loss of gain. Experiment!

The original design also had no emitter bypass capacitor, the 10 microfarad capacitor across the 220 ohm resistor. Not having this bypass capacitor reduces the gain because some of the audio voltage signal is wasted across the 220 ohm emitter resistor. Since I needed gain, I put in the capacitor and my gain jumped up noticeably. This bypass has no disadvantage that I could detect.

Audio filtering

Many receivers have audio filters that limit the audio frequency of signals passed onto the headphones. This can be useful for separating CW signals that are nearly on the same frequency. If I didn't have my multiple crystal filter selections, I would definitely want audio filters. But in practice, when QRM (interference) happens to me, the guy that is interfering usually has the same audio tone pitch as the fellow I'm trying to listen to. Obviously in this case an audio filter would not help. But if you want to add one later, it is never too late. Unlike IF crystal filters, audio filters can be added later, external to the receiver.

Driving a speaker

If you don't need a speaker, you don't need a third amplifier stage. By the same token, an 8 ohm speaker plugged into the 8 ohm headphone output is much too faint. Also, 0.6 volts peak is not nearly enough to drive a loudspeaker.

In the original handbook AF amplifier design, the third stage was an emitter-follower for driving either a speaker or low impedance headphones. The advantage of this design was that the emitter-follower drove the speaker directly and needed no high-to-low impedance transformer. The speaker was located between the emitter and ground while the collector was connected to the positive supply. It looked straightforward to me, so I tried it. Unfortunately the emitter-follower distorted the sound and "motorboated" on strong signals. That is, the sound ran in "putt-putt" bursts. I tried several modifications to solve these problems but was never able to fix it. I gave up on the emitter-follower and used another impedance stepdown audio transformer to drive the low impedance earphones. I happened to have a handful of tiny speaker transformers in my transformer junk box, so for me this was an easy solution.
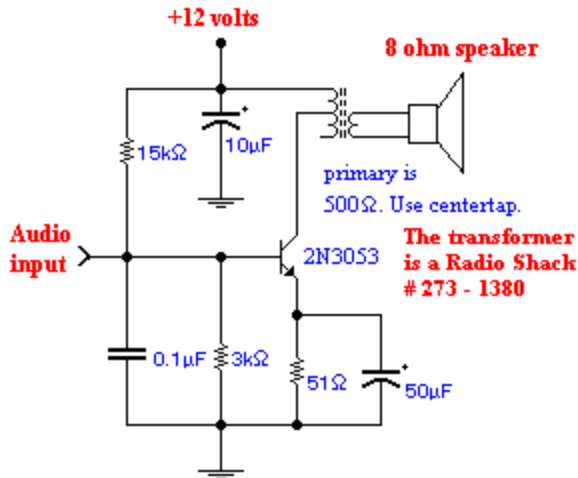
An optional extra amplifier for driving an external speaker

You'll find that a big speaker sounds much better than a little one. A speaker small enough to fit in the receiver itself will sound "tinny." I eventually wired my speaker output to a remote, 12 inch wide speaker.

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Converters for the other HF bands
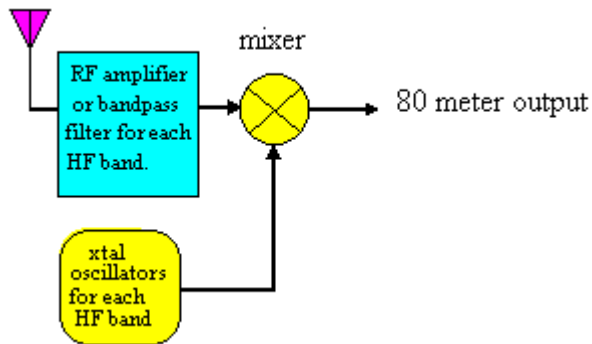
Block diagram of a converter for an HF hamband

I used the RF amplifiers and crystal oscillators out of the W7ZOI and K5IRK receiver. I built these modules close to what was in the handbook and they worked right away. For my mixer module I used the same dual gate MOSFET circuit I developed for the 80 meter receiver. I had some difficulty with the low frequency preselector filters, so I used other designs as will be described.

In my receiver all converters for bands other than 80 meters share the same dual gate MOSFET mixer. Band switching would be easier if each converter had its own mixer. On the other hand, those dual-gate MOSFETs are pricey transistors, so do what you like. Each band needs its own crystal-controlled oscillator and a pre-tuned bandpass filter or "preselector" to limit the input to the desired band. Bands above 30 or 40 meters need an RF amplifier. Below 20 or

30 meters, the signals and noise are stronger and an RF amplifier on the antenna input shouldn't be needed. I have had some trouble with weak signals on 30 meters, so maybe I should have added an RF amplifier on 30 meters after all. On the other hand, maybe the signals are just plain weak.

Each ham band needs its own HF converter

In the old vacuum tube days, tubes were big and it would have been extravagant for a homebuilder to use a separate converter for each band. My old homebrew vacuum tube receiver, had a single multi-band converter that had to be tuned manually for each upper band. Every time I tuned in a weak station, I tweaked three variable capacitors and three separate gain controls.

Transistors and powdered iron cores are tiny, so today we can easily house a complete HF converter into a few cubic inches. Moreover, each converter runs on just one low DC voltage. This simplicity means that the power can be routed to the converter using the same coaxial line that receives the output from the converter. Since each converter is optimized for just one band, it can be tuned up once and forgotten.
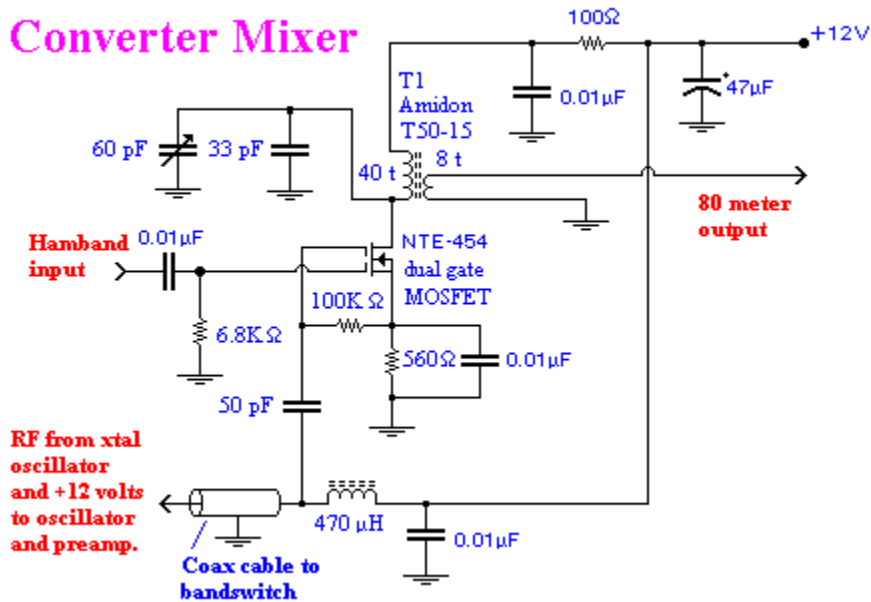
The converter mixer shown above is shared by all my converters. A rotary bandswitch brings in the filtered and amplified hamband RF signal on the upper input. The lower input takes in the RF from the local crystal oscillator for each band. In addition, the lower "input" is also an output that delivers 12 volt power to the oscillator and the preamplifier for that band.

Hamband Converter Preamplifier
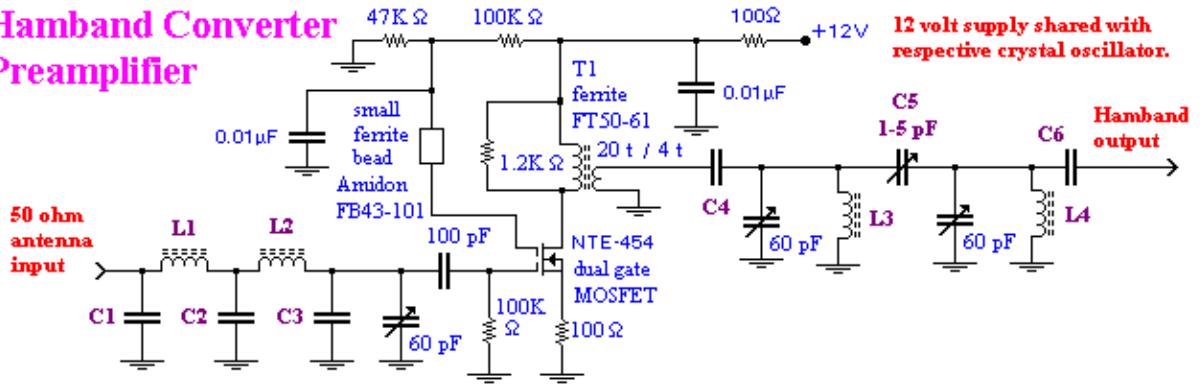
Table of values for converter preamplifier and filters

Hamband	C1	C2	C3	C4 C6	C5	L1	L2	L3 L4	
	(pF)	(pF)	(pF)	(pF)	(pF)	(µH)	(uH)	(uH)	
30 meters	300	680	33	33	4.1	0.68	3.36	1.16	
		T50-6 CWS (Amidon) toroids					**(13t)**	**(29t)**	**(17t)**
20 meters	220	500	22	27	4	0.58	2.50	1.16	
		T50-6					**(12t)**	**(25t)**	**(17t)**
17 meters	180	390	none	22	3.9	0.40	1.94	1.44	
		T50-6					**(10t)**	**(22t)**	**(19t)**
15 meters	150	330	none	20	3	0.40	1.60	1.44	
		T50-6					**(10t)**	**(20t)**	**(19t)**
12 meters	120	200	none	12	2.1	0.26	1.44	0.58	
		T50-6					**(8t)**	**(19t)**	**(12t)**
10 meters	110	250	none	12	1.6	0.26	1.16	0.40	
		T50-6					**(8t)**	**(17t)**	**(10t)**

Preselectors for the lower hambands

As explained earlier, hambands lower than about 30 meters shouldn't require an RF preamplifier. The only purpose of the preselector is to limit the input signals to the particular hamband. This design shown below is the one recommended by W7ZOI and K5IRK .

Hamband Preselector Filter
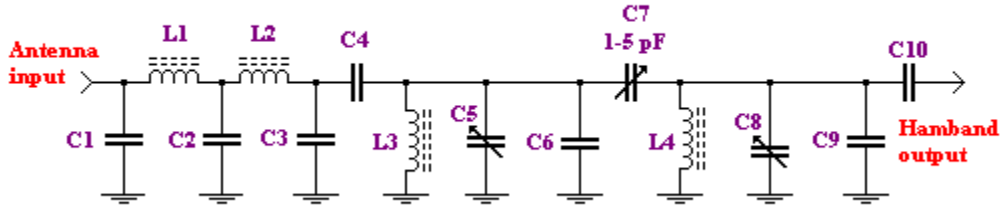
Table of values for preselector filter (without amplifier)

Hamband	C1 C3 (pF)	C2 (pF)	C4 C10 (pF)	C5 C8 (pF)	C6 C9 (pF)	C7 (pF)	L1 L2 (μH)	L3 L4 (uH)
30 meters	300	600	32	180	50	4.1	0.68	1.16
		CWS (Amidon) T50-6					**(13 turns)**	**(17 turns)**
40 meters	430	860	42	180	50	4.6	1.16	2.50
		CWS (Amidon) T50-6					**(17 turns)**	**(25 turns)**
160 meters	1720	3440	none	250	120	20	4.64	30
		CWS (Amidon) T68-2					**(29 turns)**	**(79 turns)**

My 160 meter filter is similar to the original handbook design and was extrapolated from their 40 meter values. For 30 and 40 meters I used the following filter design that I adapted from an article in QEX:
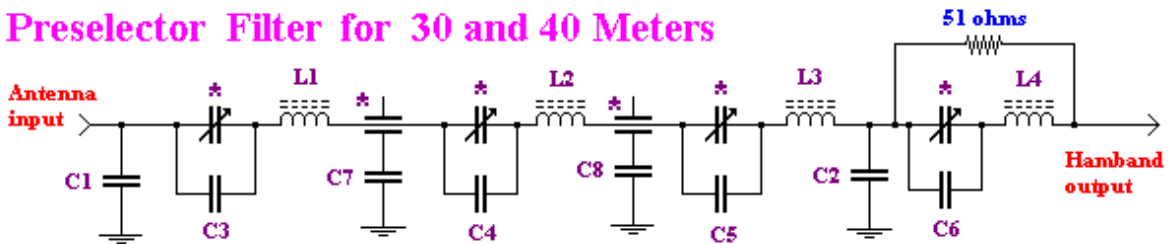
Table of component values for alternate preselector filter

Hamband	C1, C2 (pF)	C3, C4, C5, & C6 (pF)	C7,C8 (pF)	L1,2,3 (μH)	L4 (μH)
30 meters	710	33	2000	3.5	4.6

			CWS (Amidon) T50-6	**(30 turns)**	**(34 turns)**
40 meters	1000	47	3000	5.0	6.6
			CWS (Amidon) T50-6	**(35 turns)**	**(41 turns)**

The above design is a series of 4 series LC circuits, each in its own egg carton compartment soldered onto the PC board. The signals are fed from one little chamber to the next using .001µF feedthrough capacitors. Extra capacitors were soldered on bring the values up to the values listed above. These filters tuned up well and I have no complaints about the receiver performance on 40 meters and above. 80 and 160 meters are more difficult, as discussed earlier and below.

160 meters is hard

160 meters presents two problems. First, standard broadcast signals are huge and just below 1.800 MHz. If you don't attenuate the broadcast band signals, you may be plagued with the loudest local AM stations appearing in your IF. You may find the AM broadcast filter described in chapter 7 useful. It worked best when placed in between the 160 meter preselector and the input to the 80 meter receiver board. It was not so helpful in series with the antenna jack outside the receiver. My 160 meter preselector was primarily a high pass filter.

The second problem with 160 meters is its proximity to 80 meters. When I first got my 160 meter converter working, I immediately heard hams and thought I was successful. It was a several evenings before I discovered that some of those hams were actually on 80 meters. Oops! When I tuned in a ham, I then switched to 80 meters to see if he was still there. If he disappeared, then I knew he was on 160 meters. Not really up to snuff. Since my core receiver is designed for 80 meters, the bandpass filtering on the 160 meter converter must be quite selective to keep out both the broadcast signals <u>and</u> the 80 meter signals. I'm still not satisfied with my present filter. As mentioned elsewhere, 80 and 160 meters work much better when you listen to them using your transmitter "T-match" antenna tuner.

It can be hard to find an appropriate, cheap crystal for 160 meters. 5.5 MHz is available as a standard frequency and looked ideal. Unfortunately, this produces a large whistling artifact on 2.00 MHz. 5.6 MHz worked OK because the artifact is now on 2.1 MHz, completely out of the 1.8 to 2.0 MHz ham band.

A difficulty with 160 meters is that, if you build a multistage filter like those shown for 40 and 30 meters, the variable capacitors will be physically quite large. I didn't have room for such a large preselector, but if you started out with a big enough chassis that shouldn't be a problem. To scale the 40 meter filter to 160 meters, multiply the value of each capacitor and inductor times four. Good luck!

Crystal oscillators for the converters

These oscillators are nearly identical to the BFO oscillator described earlier. The 12 volts power for each oscillator is delivered via the cable from the bandswitch.

Converter Crystal Oscillator(s)
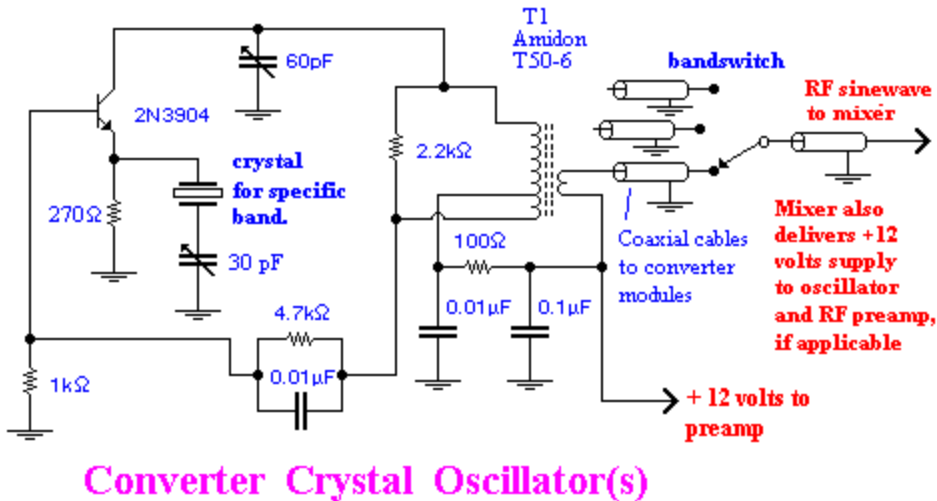
Data table for crystal oscillators

Hamband	Crystal freq.	T1 primary	Primary tap	Secondary
	(MHz)	total turns	turns	turns
160 meters	5.600	39	8	7
40 meters	11.000	30	7	6
30 meters	13.800	26	6	5
20 meters	18.000	28	5	4
17 meters	21.900	20	4	4
15 meters	25.000	20	4	4
12 meters	24.800	17	4	4
10 meters	32.000	14	3	3

All toroids are CWS (Amidon) T50-6 powdered iron

Since I am converting to 80 meters, my receiver uses the same local oscillator frequencies I used in my CW transmitter, which uses an 80 meter VFO. For most bands I use microprocessor crystals cut for frequencies 4.0 MHz above the bottom of the desired ham band. For example, I used 11 MHz for 40 meters, 18 MHz for 20 meters, 25 MHz for 15 meters and 32 MHz for 10 meters.

You could also use local oscillator frequencies below the desired band. For example, to cover 15 meters, you might use a 17.5 MHz crystal oscillator. This will convert the 15 meter band to range from 3.5 MHz to 3.95 MHz. Notice that the direction of VFO tuning is reversed from using local oscillator frequencies above the desired band. Whatever you do, it's good to be consistent so that direction of tuning and the calibration can be consistent. Also, if the local oscillator frequencies are round numbers, like 11, 18, 25. and 32 MHz, then decimal calibrations on the VFO will be identical. Unfortunately, to get quality crystals for the WARC bands that didn't drift, I eventually had to have custom crystals ground for me. Maybe cheap isn't so

important after all.

Mechanical construction of converters

I built my converters on two-sided PC board material. Strips of PC board were soldered onto the main board to provide the walls and partitions in the egg carton construction. A folded aluminum, press-on cover keeps out most stray RF. The assembly shown below contains four converters for 20, 40, 30, and 12 meters. It looks daunting, but I built them one band at a time over several months. I only built another converter when I was ready to listen to a new band.

Converter modules for 20 meters, 30 meters, 40 meters, and 12 meters

This module contains converters for 160 meters and 17 meters.

Band switching

The very first module in my receiver that worked properly was the converter for 15 meters. I checked it out by using it with my old receiver tuned to 80 meters. I immediately noticed that it worked better than the old receiver tuned to 15 meters. Later, when the new 80 meter receiver began to work, I was able to listen to 15 meters by plugging the 80 meter receiver to the 15 meter converter directly with phono plug cables. Next I built a converter for 10 meters and 40 meters. Whenever I switched bands, I moved my cables around like plugs on an old-fashioned telephone switchboard.

Eventually, as I built more and more converters, this process became increasingly cumbersome. I finally gritted my teeth and spent a Saturday afternoon wiring up the bandswitch shown above. To switch from one band to another, a rotary switch selects the desired input filter/ RF amplifier and local oscillator for each band. Like the BFO design described earlier, the 12 volt power for each local oscillator and RF preamplifier arrives riding on the local oscillator RF signal to the mixer. In other words, a single switching circuit carries both the local oscillator signal and the 12 volt power. Even with this reduction in complexity, the 9 band rotary switch becomes a confusing pile of RG-174 coax spaghetti. Be sure to label each plug and socket. I used a fold of white plastic tape on each cable and labeled it with a fine-point permanent marker pen.

Receiver muting

While transmitting, it is extremely distracting to hear your own signal blasting your ears in the receiver. Even with the antenna switched over to the transmitter, the receiver will still be overwhelmed by your own loud signal. A CW signal will usually sound distorted and will interfere with your sending. I have found it best to turn the receiver off altogether while transmitting. That is why I built a Morse code sounder into my electronic bug so I would have a clear tone to listen to while I am sending.

Turning the receiver off by hand is too slow, so you will need to build a muting circuit. I trigger mine with the same transmit/ receive signal line used to turn on the transmitter. I have

found that the simplest solution is turning off some or all of the power supply lines. I tried just turning down the audio and IF gain pots by pulling the pot wipers down to ground using the collectors of transistors. This was inadequate, so I have since gone to keying the receiver power supply on and off, just as I did in the transmitter. I leave the receiver VFO supply on constantly to prevent any drifting due to having the VFO circuitry cool off and warm up repeatedly.

Receiver power supplies

The VFO power supply used in the receiver is the same one described in chapter 10. You could also use the line powered regulated supply described in chapter 8. I run my station on a 12 volt battery, so I just needed the low drop-out regulator shown below. The power supply requirements for the receiver are similar to the low power stages of the transmitter. I used the same supply that I developed for use with my QRP modules in chapter 8. This supply is over-designed for a receiver and can supply at least a few amperes.

The mute capability was implemented using an unused op-amp as a comparator. The mute input lead comes from the transmitter. Or in my case, it comes from the transmit/ receive switch on my homebuilt bug. During transmit, the mute line is pulled low to ground. During receive, the 12 K and 47 K resistors pull the mute line up to 12 volts.
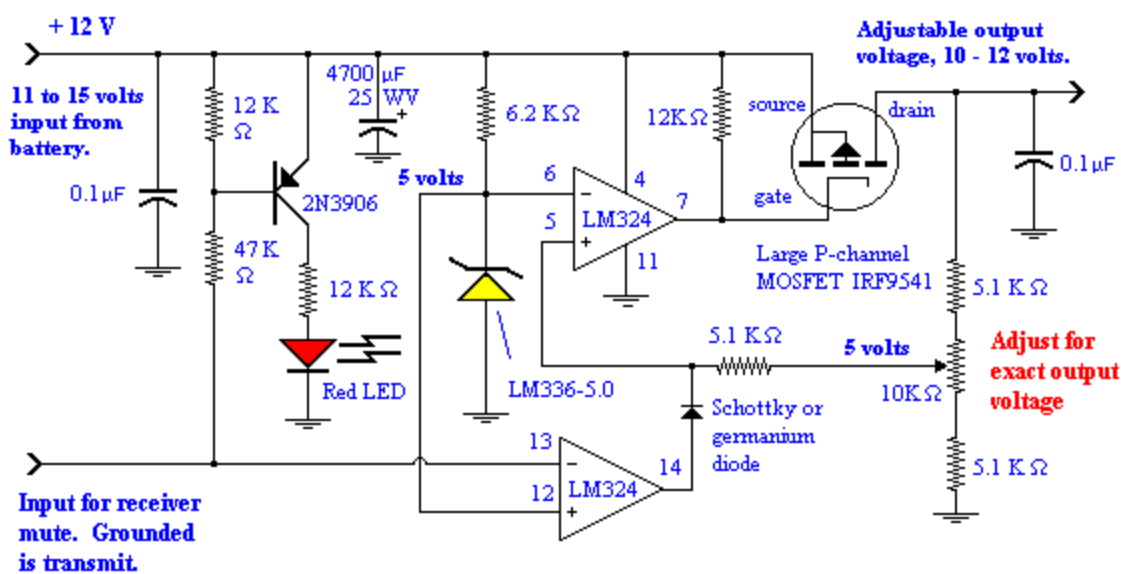
Low Dropout 12 Volt Power Supply with Mute Capability

Referring to the lower op-amp, when the positive input wired to the 5 volt reference is higher than the mute line, the op-amp output, pin 14, rises up to 12 volts. This causes current to flow down through the diode to the positive input of the upper op-amp, pin 5. When the positive input (pin 5) is higher than the 5 volt reference on pin 6, the upper op-amp output (pin 7) rises to 12 volts, thereby turning the power MOSFET off and shutting off the current supply to the receiver.

Red mute indicator light

While the receiver is being muted, the base of the 2N3906 transistor is pulled down

thereby turning on the transistor and lighting the red LED. My LED was an extra bright type that only needed 1 milliampere to be adequately bright. You may need a resistor smaller than 12 K for good brightness.

Use linear regulators, not switching regulators

I tried to use switching supplies for this receiver, but reception was always impaired by switching supply noise. Switchers cause buzzing and hissing on every hamband. RF filtering was a great improvement, but it was never good enough. Building a low-noise receiver is hard enough without fighting a built-in noise generator.

In summary,

If you've already built homebrew transmitters, you'll find that building a receiver is easier than building your multiband, VFO-controlled CW transmitter. The hardest parts are the 80 meter pre-selector, the 80 meter mixer and the IF amplifier. After that, it's pretty straightforward. Receivers don't need RF power gain stages, so the currents are low and the circuit board layout is forgiving.

In closing, remember that when you build a transmitter, you will hear no end of complaints about your signal until you get <u>all</u> the bugs out of it. But when you're on the air with your homebrew receiver, your contacts never complain about your receiver. Or at least you can't hear them complaining.

CRYSTAL SETS TO SIDEBAND
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Chapter 14
VACUUM TUBE RECEIVERS AND TRANSMITTERS

My old-tech QRP project began the day I acquired an ancient type 216A vacuum tube. It's a wondrous Jules Verne-looking device with a round glass ball mounted on an elaborate nickel-plated brass base. It's the simplest three-element "triode" with all its guts in plain view. It has the filament in the center with a wire "grid" and a plate on each side of the filament. The base is imprinted with several patent numbers dating from 1907 to 1918. I decided I would use it to build a one-tube, crystal-controlled transmitter, just like the old days. As you'll see, there were problems with this dream.

The transmitter described in this chapter uses the most ancient vacuum tube technology I could, while still sounding pretty good on the air. Some of the parts I used were rare and unobtainable as new parts. However, if you can't find similar components at local swapfests, you can always buy them on-line. It's also possible to substitute more modern vacuum tubes that are still available.

How old can you go?

I got a huge kick out of building the spark gap transmitter and crystal set receiver. My only regret was that I couldn't use them on the air. I wondered how old fashioned a rig can still

be used today. About 1920 hams began to replace their spark gap transmitters with single tube LC tuned oscillators. In principle, these VFOs weren't that different than the VFOs described in chapter 10. Unfortunately the old VFOs were crude and drifted several kilohertz per minute. Obviously one of those state-of-the-art 1925 transmitters was not going to be acceptable today.

Spark gap transmitters were totally banned in 1927 because they splattered all over the band and wasted spectrum. After the international reorganization of the ham bands in 1929, the hams were confined to what were then considered "narrow" portions of the spectrum. Crystal control for hams was first introduced in QST magazine in 1927. The May 2001 QST had an article on ham transmitters used in the 1920's. The article warned that these early machines shouldn't be used on the air. That's no fun! In my local ham newsletter Yardley Beers, WØJF, described a transmitter he built in 1930 that sounded promising. It was a 10 watt, one tube oscillator with a type 210 triode. I figured that a triode oscillator with crystal control should be about as old-tech as I can go.

Why bother with tubes?

A homebuilder who has never built with vacuum tubes has missed an adventure. I told my electrical engineer nephew that I was building a vacuum tube transmitter. There was silence on the phone. "Why?!" he finally blurted.   I was startled. To us geezers, "why" is obvious.

Let's use trains as an analogy: I once had the privilege of riding on the French TGV (Le Tran Gran Vitesse) that translates to something like, "The Really Fast Train." At 240 kilometers per hour the TGV is indeed speedy. When it passes another train on the adjacent track, the whoshing roar lasts less than two seconds. When TGV crosses a trestle, the ground drops away under you so quickly you feel as though you were taking off in a rocket. Modern ham equipment is like the TGV. Its attractions are sophistication and high performance.

Every summer narrow gauge steam trains chug up and down Colorado canyons. These old-time anachronisms are packed with tourists. Steam trains aren't popular for their performance, but rather for their sound and appearance. Vacuum tube transmitters, especially ones from the 1930's or 40's, don't have impressive performance, but their visuals are great! Transmitters back then had great big coils, "bread slicer" variable capacitors and wondrous glass vacuum tubes. Their plate current meters look as though they belong in a power plant.

Vacuum tubes have the same function as transistors. They are constructed like filament light bulbs. Inside an evacuated chamber, usually glass, they have glowing filaments and intricate metal screens and plates. The lightbulb-like filament is heated to incandescence to drive electrons off its surface. The metal mesh, called the control grid, regulates the relatively large current passing through the vacuum between the filament (the cathode) and the metal plate. The grid is analogous to the base of a bipolar transistor or the gate of a field effect transistor.

Vacuum tubes were the first practical signal-amplifying device. They dominated electronics for over 50 years. Most sophisticated analog circuits and even computer circuits were first implemented with tubes. When transistors became available, it was relatively easy for vacuum tube engineers to redesign the old circuits using transistors.

If tubes are so easy, why did my first two transmitters fail?

I've always been curious why my first two home-built transmitters did not succeed 45 years ago. My first transmitter was a 7 watt 80/40 meter rig built with plans in the 1957 ARRL handbook. It worked well around town, but hardly anyone heard me outside of town. Now that I've built modern QRPs and receivers, I realize that the average ham receiver back then was so poor that hardly anyone could hear a QRP. My second homebuilt transmitter was supposed to put out 30 watts but never worked properly. I lacked the test equipment and knowledge to find out why. Eventually I bought a commercial transmitter kit, just like all the other novices were using.

In the transmitter described below, the power supply turned out to be my biggest obstacle. I'm convinced that was also my biggest problem back in 1957. Yes, my power supply was able to supply the required power, but now as then, my power supply was too weak or "soft" to supply the needed power without a significant voltage drop. Whenever the transmitter drew current from the supply, the voltage crashed causing the transmitter to run in bursts called "motor-boating." Since I didn't have a high frequency oscilloscope back then, I couldn't see what was happening.

The power supply

Vacuum tubes work by conducting electrons across a vacuum. Personally, I'm amazed that's even possible. But once you get past that, it shouldn't be a surprise that a vacuum tube has a relatively high resistance. So if you want to pass big currents, you need big voltages to push the current across the void.

Power = Voltage x Current

To get big power you need either big voltage or big current, or both. The transmitter

described here needs at least 250 volts to deliver 5 watts output. And because of its low energy conversion inefficiency, plan on supplying 15 watts DC power instead of just 5 watts. For example,

15 watts = 250 volts x 60 milliamperes

High voltage power supply safety

The chief disadvantage of high voltage is the danger of burns and shock. Vacuum tubes almost always operate at high voltages, typically over 100 volts. For high power ham band amplifiers the plate voltage can be 1000 volts or even 3000 volts DC. The bad news is that this can cause a severe jolt and burn when your finger touches the **DIRECT CURRENT** supply. The good news is that, although high DC voltage may knock you across the room, badly burn you and scare the heck out of you, high DC voltage rarely kills anyone. It <u>can</u> kill, but usually doesn't.

Shock

Technically, the word "shock" means electrocution, so DC voltage usually doesn't "shock" hams. On the other hand, a 1000 volt DC power supply has 1000 volts of **ALTERNATING CURRENT** on its rectifier. If you get your hands across that, death is quite possible, even likely. Any power supply that plugs into the AC mains will have at least 120 volts AC on it and that's plenty to kill you. All power supplies are potential killers if you touch high AC voltage. In contrast, when 60 Hz AC voltage is below about 20 volts, it approaches being "safe." However, if you wet both hands, grip the two leads firmly so that 20 milliamperes of AC current passes through your chest, even 12 volts AC can kill you. In summary, it pays to be extremely cautious with AC voltage. Whenever possible, unplug the power supply before you work on your line powered equipment.

RF burns

Another safety issue is RF burns. High frequency, high voltage, radio frequency AC voltage doesn't shock you because your nerves can't respond fast enough to be polarized by the changing voltage. However, RF voltage can burn large holes in your hand. If you touch the plate circuit of your vacuum tube transmitter, you can expect at least a small hole in your skin. And, the higher the RF power you are running, the bigger the hole it will make. In summary, any voltage, AC, DC or RF, higher than roughly 50 volts deserves great respect. Your first lesson on working with vacuum tubes should be "***don't touch anything until the power is turned off.***" And, after the power is turned off, ***be wary of large capacitors that may be charged to a high DC voltage.***

****

The Vacuum Tube QRP Transmitter

Once I began planning my tube QRP, reality began to sink in.

* First, I only have one 1918 tube. I'd hate to break it.

* Second, this tube has no cathode. It just has a simple filament. This means that the electrons come directly off the filament. A simple tungsten or carbon filament gives off electrons reluctantly, so these early tubes had low operating currents. That meant that my QRP transmitter

would be extremely weak, like a few milliwatts. There was a good reason that hams used spark-gap transmitters until 1927. They couldn't buy power tubes until the 'twenties. It was hard to generate any significant power output until tubes were developed that that could handle hundreds of milliamperes of current, instead of just a few milliamperes. Also, I'll bet power tubes back then cost a fortune.

* According to my 1979 ARRL handbook, "it is almost impossible to build a one tube CW transmitter that doesn't chirp to some degree." I guess chirp was normal in the old days. But today your signal will be roundly criticized if you dare to chirp at the modern hams who rule the airwaves today. So much for a one-tube transmitter.

* A related problem is that, the better a keyed oscillator sounds, the less output power you will get from it. In other words, a keyed oscillator that sounds good, puts out little or no useful RF power. I began to understand that my 100 milliwatt transmitter might easily end up as a 20 milliwatt transmitter.

In my opinion, 1930's technology is about as early as you can go and not embarrass yourself today. I eventually built my transmitter using tubes that I had salvaged from old radios built during the 1930's. I like tubes from that era because they are big and spectacular. More modern tubes from the 40's and 50's are only large if they handle high power. Moreover, their glowing filaments are mostly hidden by their cathode sleeves.

In the design described below I used a simple triode as a final amplifier. I believe the filament has been treated with thorium so that it emits electrons readily. Triodes have relatively low gain and were not very linear in their amplification characteristics. The tubes I used were type 68 and type 71. If you can't scrape up some old tubes, the more modern 6L6 is still available. To eliminate the chirp, I used two more tubes to drive the final. So my single tube QRP ended up a 3 tube transmitter. And all I get out of it is 5 watts! The oscillator runs at very low power and can be keyed with little chirp. The oscillator is followed by a "buffer" amplifier, which amplifies the tiny oscillator signal up to the level where it can drive the final. My oscillator and buffer are type 41 tubes, which are small power pentodes. They look ancient, but were made in the 1930's and are equivalent to the more modern, and still available, 6V6 or 6K6 tubes. 6V6 and 6K6 were manufactured during the 1940's and 1950's and can still be bought from RF Parts Company and other companies.

Vacuum tube amplifiers
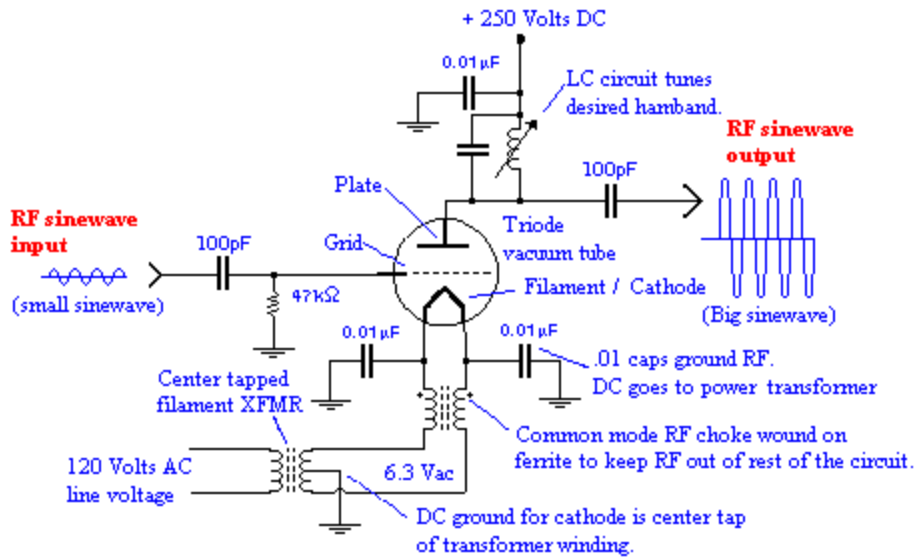
A vacuum tube RF amplifier

The simplest tube is a three-element device. The "control grid" is analogous to the gate or base of a transistor. The "plate" is analogous to the drain or collector and the glowing filament is comparable to the source or emitter. Tubes are principally voltage-controlled devices, although there is a small current that flows into the control grid. The control grid modulates the much larger current that flows from the filament to the plate. So as you would expect, the input signal is placed on the grid and the output signal is the current passing through a load resistor or load inductor, as shown above.

Filaments - three circuits in one

Referring to the diagram above, what is all that stuff wired to the filament? This is the kind of complexity that drives beginners in electronics into other lines of work. Actually, once you unravel the parts, it isn't so bad. The difficulty with using an ancient filament tube is that the filament has three jobs to do simultaneously.

Signal cathode function First, the filament serves as a "cathode" to launch our radio frequency current from the chassis ground toward the plate. That is, it serves the same role as an emitter in a bipolar transistor or a source in an FET. RF conducts easily through 0.01 microfarad capacitors, so they conduct RF up from ground into the filament. The common mode RF choke keeps the RF out of the filament transformer.

Heater function Second, the filament must be heated in order to boil the electrons off the filament and into the vacuum. The filament heat function is provided by a 6.3 volt, high current AC signal. So it's necessary to pass a big, low voltage AC current through the filament to warm it up, just like toaster element. On the other hand, we don't want 60 Hz AC impressed on the signal we are trying to amplify. If we didn't take special steps to prevent it, the guys we are talking to would hear a big hum on our signal.

To keep the AC out of the radio frequency signal, the single loop of filament is powered by AC voltage that is referenced to ground in the center of the filament winding. That is, one

side of the filament is connected to 3.15 volts AC, while the other half of the filament is connected to 3.15 volts AC with the opposite polarity. In the center of the filament, the voltage gradient passes through zero volts. The 60 Hz AC filament current biases the current flowing across the vacuum. However, because of the grounded tap on the transformer winding, half of the filament is shedding extra electrons, while the other half is shedding fewer electrons. As a result, the 60 Hz signal is cancelled and the RF signal the amplifier produces is not modulated with 60 Hz. Whew!

All this filament complexity is a nuisance, so newer tubes like the 6V6 and 6L6 have a metal tube surrounding the filament that is heated by the filament. When hot, it is the cathode that gives off the electrons. In that way, the heater function is electrically separated from the signals on the cathode.

DC bias function Third, every tube or transistor circuit has an optimum direct current operating point for the kind of amplifier you are trying to build. For example, if you want a high fidelity audio signal amplified with as little distortion as possible, the bias of a tube is turned half way *ON* at rest. That is, it is biased to operate class A. In class A, as the audio signal goes positive and negative from the resting point, the amplification will be equal for rising and falling voltage levels. If the operating point were wrong, the upper of lower half of the signal might be amplified more than the other, or perhaps cut off all together. Any distortion would ruin the sound of the music. Unlike bipolar transistors, the tube is already half-turned-on with no forward bias resistor going to the grid from the plate voltage.

In the case of a CW transmitter RF amplifier, the bias for a tube is simple: We just ground the DC on the cathode to provide the correct bias. In the case of a vacuum tube CW transmitter, we use this ground connection to turn the amplifier on and off. To send Morse code the telegraph key is used as a switch between ground and the center tap of the filament winding on the transformer.

The RF sinewave oscillator

Modern radio began with the vacuum tube sinewave oscillator. An RF oscillator consists of an RF amplifier that amplifies its own output. That is, a bit of feedback from the output is returned to the input causing the tube to produce a large sinewave output signal. Tube RF oscillators operate on the same principles as the transistor RF oscillators discussed in chapter 6 and chapter 10. If building an adequate transistorized VFO is difficult, you really don't want to use a tube VFO on the air today. I tried it and the criticism wasn't pleasant. Consequently, my old tech QRP uses crystal control.

Quartz crystals

While building my transmitter, I discovered that the old crystals in my junk box no longer oscillated. When new, crystals are so reliable that it never occurred to me that old crystals might not work. My crystals ranged in age from 20 to 50 years and hadn't been used in decades. The ones that still oscillated did so only under extreme stimulation. Fortunately for me, they were large, old-style FT-243 crystal holders that can be disassembled. I took them apart and cleaned the parts with alcohol. Two of them began to oscillate again, but the others remained inert. I suspect the rubber gasket gives off a vapor that condenses on the crystal and literally gums up the vibrations. In summary, if you try to use old crystals and the oscillator doesn't work, or if it only

delivers a tiny signal, you need to clean the crystal or buy a new one.

Triode and pentode oscillators

To be "old-tech," I started with triodes without cathodes. The oldest power tubes I had in that category were the type 68 and 71 tubes. I quickly re-learned that one reason triodes lost their popularity is that their output signal varies with the power supply voltage. Those other grids in tetrode and pentode tubes make the amplified signal relatively independent of the power supply voltage. To say it another way, a pentode tube has V/I characteristics that resemble NPN or N-channel transistors. This was particularly important for the crystal oscillator. The supply voltage sags slightly when the key is depressed and causes chirp. When using a triode, I could never quite eliminate the chirp, so I ended up using a type 41 pentode. Pentodes work fine.

Old tech circuit boards

I used a genuine old-tech circuit board made from a pine tree. A wooden board lets me move parts around inside the metal chassis and swap parts with little effort. Since 6-pin and short 4-pin 4 tube sockets aren't available anymore, I had to make my own tube sockets by drilling holes into a fiberglass perf-board. To grip the tube pins, I wrapped solid copper wire around them. This worked much better than I expected. I can even unplug and replace tubes.
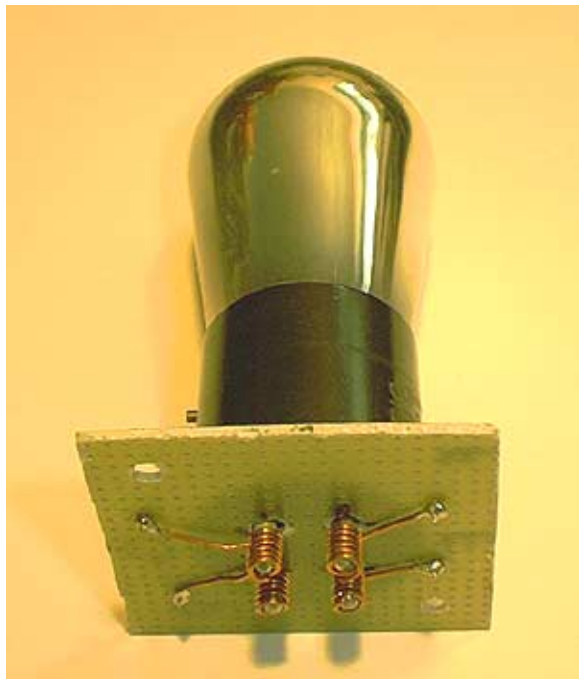
The best oscillator circuit

There are several different vacuum tube oscillator circuits. The one below is the easiest to understand and produces the biggest output signal. The crystal, which is usually wired in series with a capacitor, is connected between the plate (the output) and the grid input. This puts big voltage on the crystal and produces an extremely strong oscillation. I was able to get 10 watts out of this oscillator with a 300 volt supply. That would be great, but this oscillator is difficult to key on and off for Morse code. Mine started up so slowly, it was only able to generate dashes. The oscillator simply would not start in time to send "dots." It sounded more

like a sick bird than Morse code. Its chirp was beyond "bad."
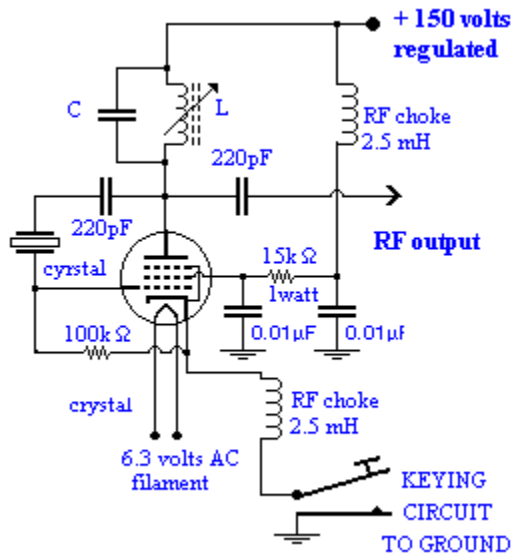
A better tube oscillator for CW

The oscillator below is the circuit used most often in old vacuum tube transmitters. The first question you probably have is, "Where's the feedback?" There is no visible connection between the input grid and the output plate. However, there is feedback between the cathode and the grid by means of the 100K resistor. There is also feedback by stray (accidental) capacitance between the grid and plate. Remember that a vacuum tube is already turned halfway "on," even when the grid voltage is zero. If there is any random change in the plate voltage (and/or cathode voltage), a tiny voltage will be coupled to the grid. When this change in voltage appears across the crystal, the crystal will respond, thereby reinforcing an oscillation at the crystal resonant frequency. The advantage of this oscillator is that it keys well and makes good Morse code. The bad news is that the output signal is small. Mine only put out 6-volt peak sine waves. This compared with 30 volt sinewaves when I used plate-to-grid feedback. As seen in the diagram, I eventually settled on using regulated 150 volts plate voltage.
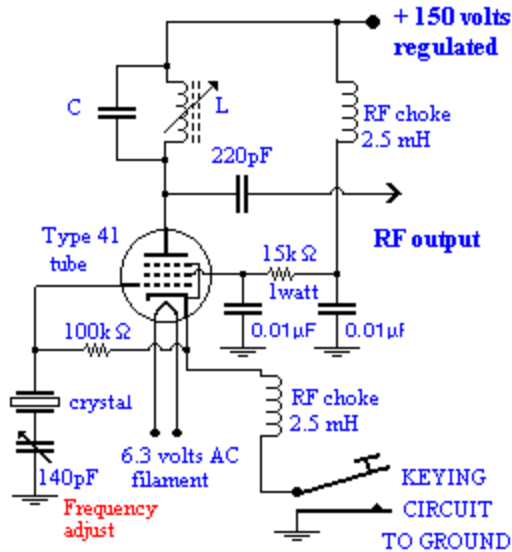
Old time voltage regulation

My tube oscillator was powered by a simple, line-powered transformer high voltage supply. When the oscillator was in "standby," the plate voltage on the filter capacitor rose to a level proportional the height of the power line sinewaves. Then, when I pushed down on the telegraph key, the voltage crashed to a lower steady state. This caused a noticeable "chirp" in the tone.

To fix this I used a 150 volt regulator tube. These tubes are the old-time equivalent of a Zener diode. Regulators are simply glass vials containing low pressure inert gas. They have two electrodes. A central wire "cold cathode" runs down the center and a cylindrical plate collects the electrons from the cathode. When voltage is applied across the two electrodes no conduction occurs until the voltage reaches a threshold voltage where the inert gas ionizes into a glowing plasma. As the current through the gas increases, more and more gas is ionized and the voltage across the tube remains approximately constant. By designing tubes of different dimensions and using different mixtures of gases, the tubes regulate at different voltages. To regulate my oscillator supply I used an 0D3 tube which regulates at 150 volts. This trims the ripple off my supply voltage and greatly improves the sound of the CW. The regulator glows with a lovely violet color.

The travails of tubes

After building my own rig, I now suspect that "normal" signal quality was really low back then. Yes, I was able to build a one-tube, crystal-controlled oscillator that keyed well and wouldn't be criticized for key clicks, chirps, drift, sag, or any of the other vacuum tube diseases. Unfortunately, it only put out 300 milliwatts. As the ARRL handbook said, it's almost impossible to build a one tube transmitter than doesn't chirp. I think they're right. I needed at least a two-stage transmitter.

The final amplifier

I still wanted to use the type 68 triode as my final. 68's have a simple, rounds shape like

tubes from the 1920's and they have a big, open filament that looks like an orange, glowing bread toaster element. You can almost imagine dropping little Pop Tarts down in there for breakfast. The type 71 worked as well as a 68, but the glass has the newer, double-curved shape. Unlike more modern tubes, all three elements of these triodes are plainly visible. In order to operate a triode filament as a "cathode," the filament transformer winding must be insulated from ground and the DC taken off through a centertap. Since both sides of the filament are DC inputs for the cathode function, the cathode choke should be a common mode design. I used a modern ferrite toroid core. Oh, well, close enough. They had pretty good powdered iron cores back then.
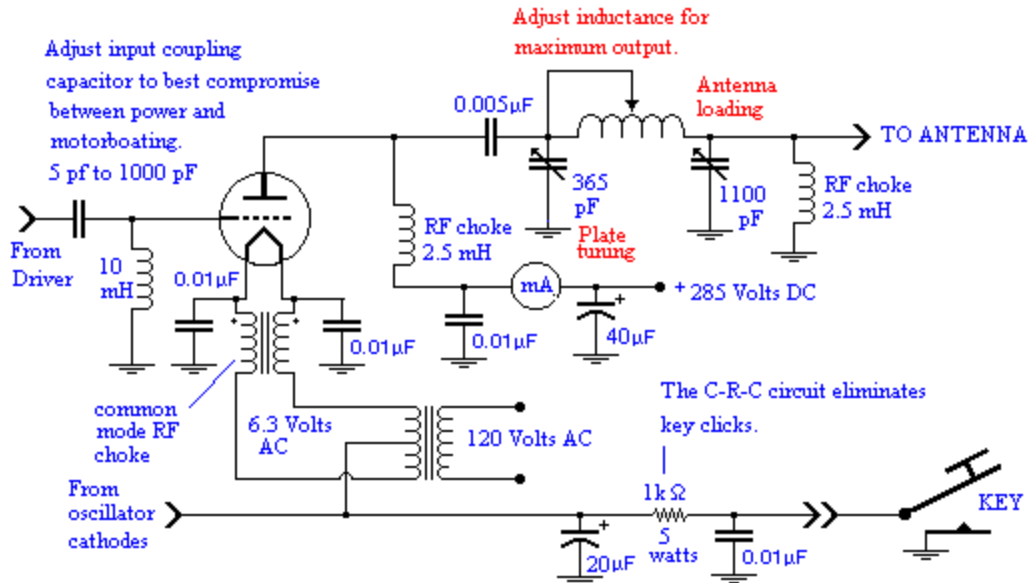
My triode final is shown above. Rather than amplify the input signal, the triode preferred to oscillate all by itself. When it wasn't self-oscillating, the drive from the puny oscillator was insignificant to get any useful power out. I wondered how typical novice transmitters 40 years ago managed with only two tubes. I thought, "It must be those high gain pentode finals!" I threw together a 6L6 final and tried it out. No change. The 6L6 had the same gain as my ancient triodes. If this was going to work, I needed more grid drive. I finally concluded that those old Heathkits, Knight kits and Viking Rangers were just darn well engineered. They achieved amazing performance from very few parts.

Key clicks

Notice the C-R-C filter in the keying circuit. That's what I had to do get rid of the key clicks. Key clicks are sharp, unpleasant clicking sounds on the Morse code caused by the dots and dashes turning on and off too rapidly. Although my transistorized CW transmitters seem to have rise and fall times just as abrupt, my transistorized rigs have had practically no problem with clicks. I don't understand this, but the C-R-C filter in front of the key causes the tubes to key on and off gently and the tube transmitter no longer clicks.

Buffer amplifiers

After struggling for a few hours, I eventually added a "buffer amplifier" made from another type 41 pentode between the oscillator and the final. Now I had enough drive for the

triode final. So that's what buffers are for!
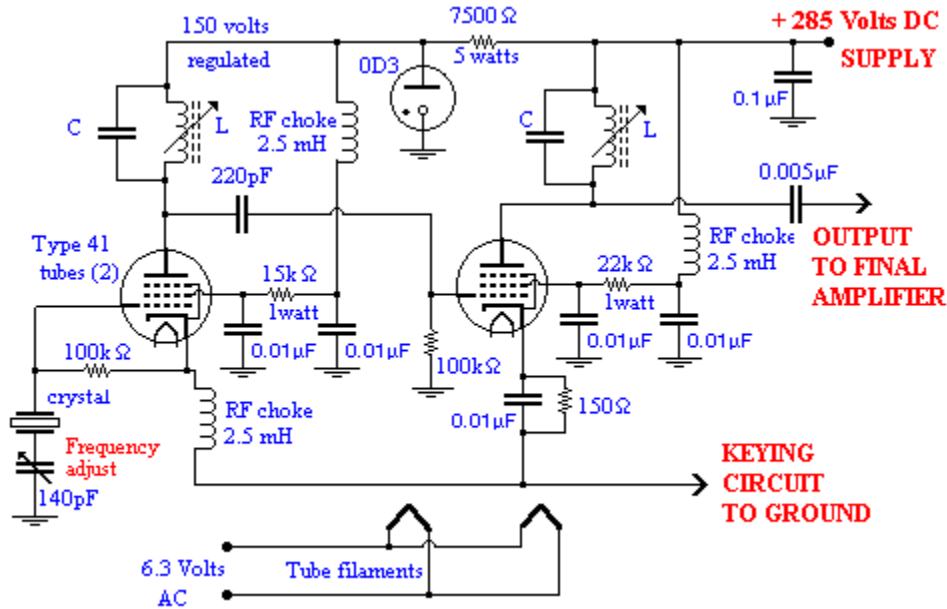
Oscillator and buffer stages

The oscillator tube drives a buffer amplifier to increase the drive to the final. Notice the 0D3 regulator tube for the oscillator plate supply. A 7500 ohm resistor drops the 285 volt supply down to 150 volts while the regulator tube holds it at that level.
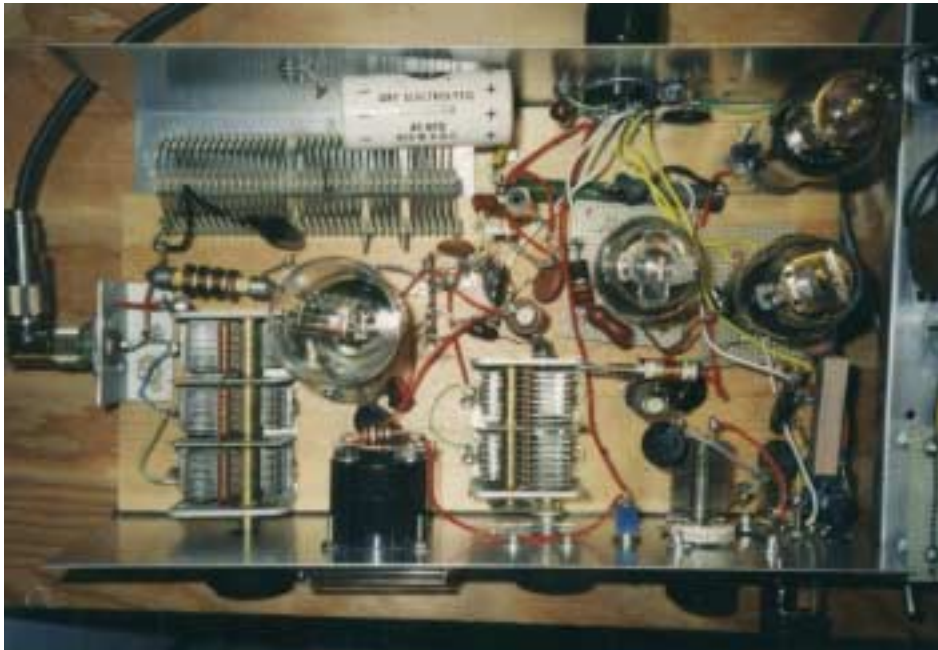
The completed 40 meter transmitter

The final amplifier is on the left. The oscillator, buffer and regulator tube are at the right rear. The plate coil is the long, tapped coil at the rear. In theory it was supposed to work on several bands, which is why the coil has the multiple sections. However, so far I have only

gotten it to work on 40 meters. The plate coils for the oscillator and buffer were wound on slug-tuned coils, which were the popular way to do it back in the vacuum tube days.

Triodes chirp

While up to my ears in vacuum tubes, it dawned on me that those homebrew "kilowatt linear amplifiers" in the old ARRL handbooks made from triodes cannot be linear. The output voltage of a triode varies with the supply voltage, not just the grid voltage. Well, they could be linear, but the operating range along the load line would have to be really narrow and the supply would have to be perfectly regulated. I doubt those designs meet either of those criteria.

THE POWER SUPPLY

An inadequate power supply made from old-fashioned parts

Before I could try out my QRP transmitter, I needed a power supply. I first tried to use a power supply salvaged from a junked 1935 radio. Unfortunately this power supply didn't deliver enough power for a QRP transmitter but, as always, it was educational.

A power supply made from parts salvaged from an ancient radio.
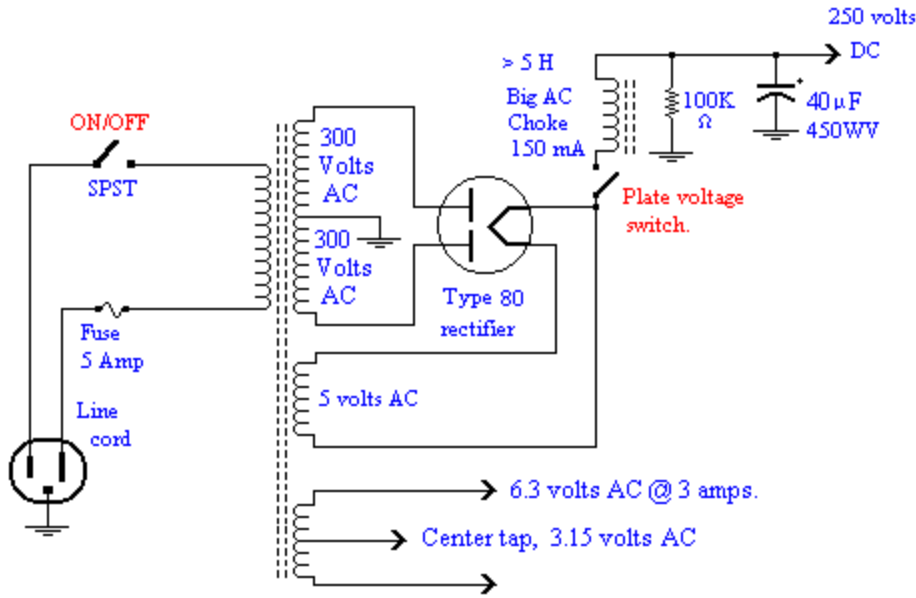
Schematic of the 1935 power supply

The AC power from the wall comes into the supply and first encounters a 5 ampere fuse. In case the supply is shorted, the fuse can blow and prevent further damage. Five amperes is a larger fuse than needed, but it's within electrical standards for small appliances. A switch connects the power transformer primary winding with the AC line. The transformer is equipped with three secondary windings. A high voltage winding puts out about 300 volts at 30 milliamperes. A filament winding puts out 5 volts at about 2 amperes. This winding is used exclusively to run the rectifier tube. A second filament winding puts out 6.3 volts at about 3 amperes.

The 6.3 volt winding is center-tapped. This means that actually, it is a 3.15 volt winding in series with a second 3.15 volt winding. The center tap is essential if you wish to use an ancient tube that has no separate cathode and must use the filament as a cathode. The center tap offers balanced access to the filament circuit to complete the main circuit between the plate and filament. Without a centertap, 60 Hertz power line noise will be impressed on the current and will appear in the transmitted signal.

Tube rectifiers

Before the high voltage can be used, it must be rectified and converted to DC. Vacuum tube rectifiers are a kind of diode and only conduct electricity in one direction. Specifically, they conduct electrons from the filament (or heated cathode) to the plate. The round circle symbol with the single filament and two plates is a dual, "full wave" rectifier. It converts both halves of the AC signal into a single DC signal in which both rectified halves of the sinewave have the same polarity. Both sides of the high voltage winding are connected to the two plates so that, at any moment, one side is always conducting while the other is not. The two positive voltages are added together at the filaments for a single, continuous, positive output.

Ripple filtering

In order for Morse code to sound clear and pure, the voltage driving the transmitter must

have no ripple left over from the sinewave. This is done with an "L" filter. An inductor and a capacitor make the two arms of the "L." The choke, being a large, 5 Henry inductor, doesn't allow the current flowing through it to change rapidly. This prolongs the charging period of the capacitor and helps smooth out the ripple. Many designs add a second big filter capacitor on the input side of the choke. This practice causes big surge currents to flow into the first capacitor and may saturate the transformer. The saturation in turn causes the transformer to heat and probably isn't as effective as putting both capacitors on the downstream side of the choke.

So much for theory. In practice, a receiver needs far less DC current than even a small transmitter. One difficulty was that the old-fashioned type 80 tube rectifier cost me 50 volts drop all by itself. Another was that the L and C filter were insufficient to prevent the ripple from making the Morse code sound rough and harsh.

But worst of all, the transmitter drew so much current that the voltage dropped precipitously and it tended to run in "bursts" called ***motorboating.*** One cure is to use the smallest input coupling capacitance to the grid of the final amplifier. With luck, this can stop the motorboating and still give good output. With a soft (sagging) power supply the coupling cap may need to be as low as 5 pF on 40 meters. I also tried to use an ancient type 83 mercury vapor rectifier tube. This is a vacuum tube rectifier that contains a touch of mercury vapor gas inside. This lowers the resistance of the tube and raises the current capacity of the power supply. The type 83 was a big improvement, but still not adequate for on-the-air use. I've had quite enough bad signal reports, thank you.

Checking out an old transformer

Big power transformers have always been costly. That's why my 1957 novice transmitter power supply was so wimpy - I thought I couldn't afford a bigger one. The old ham radio handbooks suggested using power transformers from vacuum tube TV sets. However, junk vacuum tube TV's are rare today. If you have such an old TV, remove the transformer from the chassis carefully being sure to label which pair of wires (usually black) go to the AC line.

Suppose some buddy from your ham club gives you a power transformer and assures you it is "perfect" for building a transmitter. He hands you a 5 pound lump of iron with a nest of unmarked black wires protruding from the bottom of the transformer. You think to yourself, "Now what?"

The first step in checking out an old transformer is to strip the ends of the wires so you can measure the resistance of each winding. If you're lucky, you will find that, once you clean off the dirt and tar, the wires are color-coded. The most common color codes are as follows:

two black wires - the 120 volt primary winding.

two red wires - the high voltage secondary for the plate supply, typically 1000 volts centertap
   for a 50 watt transmitter.

one yellow and red stripped wire - the center tap of the high voltage winding. This wire will be grounded in a "full wave" rectifier circuit.

two yellow wires - a 5 volt filament winding is usually good for 1 or 2 amperes. This is used exclusively for the rectifier filament.

two green wires - a 6.3 volts filament winding. This supplies the filament current for the

transmitter tubes.

one yellow and green stripped wire - This is the center tap for 6.3 volt winding. You'll need this if you use an old-time triode vacuum tube final amplifier. If you use a more modern tube with a separate cathode, then just tape off the end of the centertap wire and fold it up neatly. Don't cut it off. Someday you may want it.

Often there are no visual clues telling you which winding is which. Or sometimes the windings are just solder eyelets mounted on the edge of the transformer. Using your ohm-meter, measure the resistances of the windings picking them out one by one. Label them with tape and write down the resistances. The highest resistance winding will be the high voltage winding. For example, it might read, say 40 ohms. And the high voltage center tap will have half as much resistance as the whole measured end to end. The 120 volt primary winding will have the next highest resistance. The lowest resistance windings will be the two filament windings. These will be an ohm or two at most.

Once you think you have the windings figured out, you need to test them before bolting and soldering the transformer into your transmitter. If this isn't going to work, you want to know as soon as possible. Now that you are considering plugging it in, you now have a great opportunity to electrocute yourself, trip circuit breakers and start fires. But if you're careful and proceed thoughtfully, testing a transformer can be done safely. The idea is to limit the current that flows into the transformer. That way nothing terrible will happen even if you screw up or if the transformer is internally shorted.

Testing a power transformer

To test the transformer you must connect the winding you believe to be the primary to a source of 60 Hz voltage. How safe you want to be is your decision. But AT VERY LEAST don't plug the test transformer into the power mains without soldering a 10K ohm (or higher) resistor in series with the primary winding. That way, even if the primary is a dead short, little current will flow and nothing bad will happen.

Measure the open circuit secondary voltages with your multimeter set to AC voltage. Then you measure the AC voltage across each pair of windings you isolated earlier. Connect your voltmeter to the transformer secondaries using test clips. Don't just try to press the wires against test probes. You might slip.

Go through the windings one by one and you should be able to confirm the guesses you made from the resistance measurements. Whatever you do, don't just connect it to a line cord and plug it into the wall. Ideally, you could build a special test fixture equipped with an ON/OFF switch, isolation transformer, fuse protection, insulated test leads and a variable impedance between the AC source and the test winding you believe to be the primary.

An adequate tube QRP power supply made from modern parts
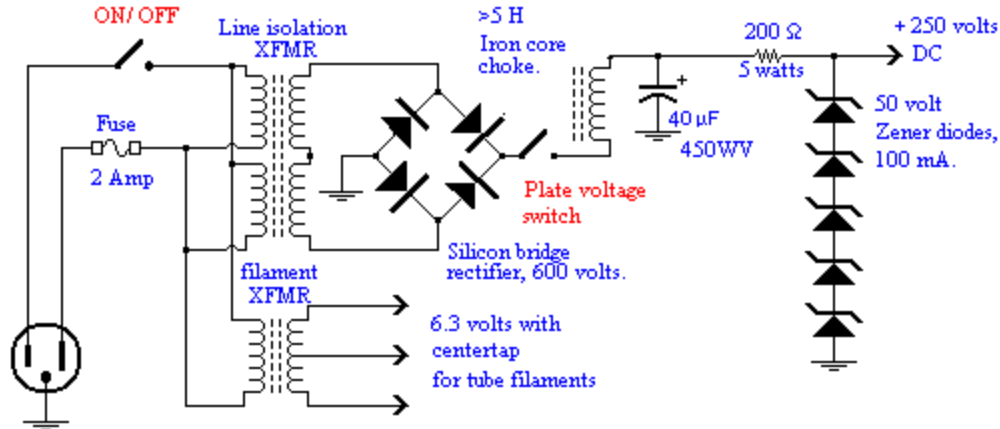
When my first supply worked poorly, I built another made from modern transformers and semiconductors. This supply was adequate to run the vacuum tube transmitter. Ideally it produces 250 volts at 200 milliamperes. This time there was no significant voltage drop across the modern bridge rectifier and the modern Zener diode string clipped off the ripple and gave me a pure CW tone.

I only needed 60 milliamperes, so the extra 140 milliamperes made it "stiff." That is, this supply behaves like a good voltage source over a wide range of current. The other power requirement for vacuum tubes is a 6 volt supply to light the filaments. Each tube filament needs about 0.5 to 1.2 amperes of current. Notice that roughly 5 watts is expended just to heat up each tube! Tube transmitters are inherently inefficient.

I couldn't find an adequate, triple-winding transformer, but there are alternatives. Magnetek makes a isolation transformer that can isolate an appliance from ground for shock protection. (Magnetek / Triad part # VPS230-350 sells for about $30.). It has four 120 volt windings. Each winding is rated at 350 milliamperes - plenty "stiff." These two pairs of windings may be connected in series or parallel. For this application you could put two windings in parallel for a 120 volt primary. The secondary windings can then be connected in series to give you a 240 volt secondary rated at 350 milliamperes. Notice the dot markings on the windings. These tell you the phase direction of the sinewave voltage. On the primary side, you must connect the leads so that the dots should be connected together. That way, the two windings will work together.

On the secondary side, the dotted end of one winding goes to the un-dotted end of the other winding. Notice that if you connect the secondary windings so that the two dotted ends or the two non-dotted ends are tied together, the voltages will cancel each other instead of add. Instead of 240 volts you will get zero volts.

I used four modern silicon rectifier diodes rated for 600 volts peak inverse voltage and arranged as a bridge rectifier. Since you aren't using a tube rectifier, you won't need a 5 volt filament winding like the one shown earlier in the 1935 power supply. You will need a separate 6.3 volt filament transformer for your transmitter tube filaments.

My supply made from modern parts can put out 42 watts and that's sufficiently "stiff" to deliver my measly 10 watts without sag. Using the modern silicon rectifiers I got 4 watts out of my transmitter. To regulate the output voltage I used five 50 volt Zener diodes in series.

A power supply for the tube transmitter constructed from old style parts

Although I now had the rig working, I still wanted to use old parts exclusively. Unfortunately, to use an old tube rectifier with full-wave rectification, I needed 480 volts centertap. So I added a second transformer. This worked, but the extra voltage drop across the type 83 tube rectifier cost me half my 4 watts!   Finally I added yet another transformer and got the average, well-regulated DC voltage up to about 285 volts.

I tried using gigantic filter capacitors, but they weren't available in 1935 and they caused long-term sag. I was surprised to discover that a total of two 40 microfarad caps were plenty when used with voltage regulators. To regulate my 285 volts DC I used one 0A3 (75 volts) and two 0C3 (105 volts) gas tube voltage regulators in series. 0A3s glow with a spectacular orange color while 0C3s glow violet.

In order to regulate while the transmitter is keyed, the voltage regulator tubes should be at least slightly glowing at all times. For best regulation, you may have to reduce the 200 ohm current limiting resistor to 150, 100 or even zero ohms. You will probably find that the regulators only stay lit while the key is down when the transmitter is perfectly tuned to the antenna. When it is out of tune, the transmitter draws too much current and regulator tubes will be extinguished and essentially take themselves out of the circuit.

I have seen these old gas regulator tubes offered for sale at as much as $30 each! Hopefully you can find some at a swap fest. Notice that I could have used six teeny 100 mA Zeners at less than $2 each. Anyway, when all was said and done I had 5 watts of pretty good sounding CW. Behold! I have created the world's most inefficient transmitter!
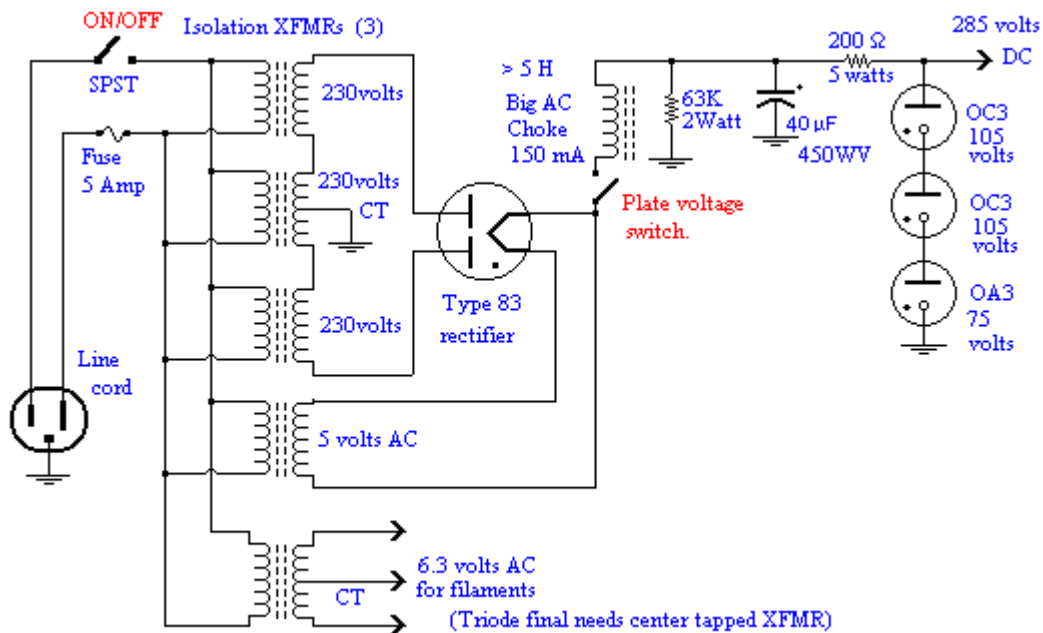
Schematic of the regulated QRP supply made with old-style parts

It isn't that you can't build modern high tech stuff with 1935 parts, it's just that the assembly becomes huge and expensive. Meeting modern specs with old parts reminds me of a scene in the movie Back to the Future. "Doc" replaced a burned up integrated circuit with a tube circuit the size of a laundry basket. It must have been a low scale integration chip!

Old-tech QRP

A happy ending

In conclusion, old parts aren't efficient in any way. However, you get to use a whole lot of them to accomplish very little and they look terrific. The voltage regulators glow orange and violet, but when you key the transmitter the glow flashes on and off inversely with the CW.

When I first turn the mercury vapor rectifier on, mercury condenses on the glass in a silver-white fog. Then as it heats, the mercury evaporates and the tube runs with a glorious blue glow with bright orange filaments. Great show biz! Oh, yeah. I forgot to mention the "mercury vapor rectifier hash" that you get to listen to on receive. Oh, and another thing - don't place your transmitter supply tranformers close to your receiver. The receiver may pick up a 60 Hz hum. You'll probably have to turn off the transmitter high voltage supply during receive. There are lots of reasons these old parts are extinct!

I'm finally on the air working people with my old-tech QRP. I'm surprised how many guys are interested in this QRP thing. I call CQ, mention "/QRP" and I get responses from other fanatics. Who else would answer an American "Ø area" RST 449 CQ? Usually we can barely hear each other, but we're having fun. However, you never know! I got a 599 from Albuquerque. Maybe he was just kidding. Anyway, how old-tech can **YOU** go?

✱✱

OLD-TECH SUPER-REGEN

How old fashioned a receiver can you use on the air today?

Once I had my old-tech, 1935-era CW transmitter working, I thought it would be fun to complete my ancient rig with an old-tech receiver. To be successful on the CW bands, I figured I needed a superhetrodyne with a crystal filter. I had once built a pretty good vacuum tube CW receiver so I had little interest in doing the same project again. The 1930 tubes would be bigger than 1960 tubes, but otherwise it would be the same project.

Yardley Beers, WØJF, told me about the regenerative receiver he built in 1930. I doubted it would work well enough for today's bands because I had a previous experience with regenerative receivers. So Yardley didn't inspire me to build another one. Then a few months later I worked Mike, NØMF. He was using a homebrew super-regenerative receiver made from modern FETs as described in QEX magazine. Obviously it was sensitive and selective enough to hear my QRP on 40 meters. Maybe a super-regenerative receiver wasn't so silly.

Ancient tubes

I have never been able to bring myself to throw out vacuum tubes. I have boxes of them in my attic. I've always been especially fascinated by earliest tubes. They have lightbulb-like glass envelopes, bayonet sockets and numbers like 201, 216, 224, 227 and 301A. This was my chance to build a really old-tech receiver.

I started by building an RF amplifier out of a type 201 tube. I had no specs for a 201, but I gently increased the filament voltage until I got a nice warm, orange glow out of the filament. That occurred at 2.5 volts and 0.3 milliamperes. Unfortunately, it didn't amplify the RF noise from the antenna at all. The signal on the plate was smaller than the input on the grid. I tried reversing the grid and plate wires… no luck. No matter how I biased the grid, the tube didn't turn on. I increased the filament current to produce a yellow glow and promptly burned out the filament. Oops! Starting over, I tried to build a regenerative oscillator, but it refused to oscillate or amplify. I suspect that these tubes from the 1920's were extremely high impedance.

Old-tech receiver

Since my oldest tubes seemed inert, I gave up on the triodes before I ruined more of them. From there I retreated to a high-tech type 224. This tube is a tetrode. Iit has two grids and even has a cathode. Pretty modern, huh? 224s are the early version of the types 24 and 24A tubes which were commonly used in the 1930s. The 224s worked immediately in the same circuits I had tried before and soon my super-regen was picking up 40 meter hams and 31 meter commercial broadcasts. The 31 meter stations are mostly sermons, but the sound quality was pretty good. One of my 224 tubes has a test label on it from the Marshing Radio and Electric Company at 246 Main in Longmont, Colorado dated December 19, 1932. The label says the tube is "doubtful." Shows what they knew!
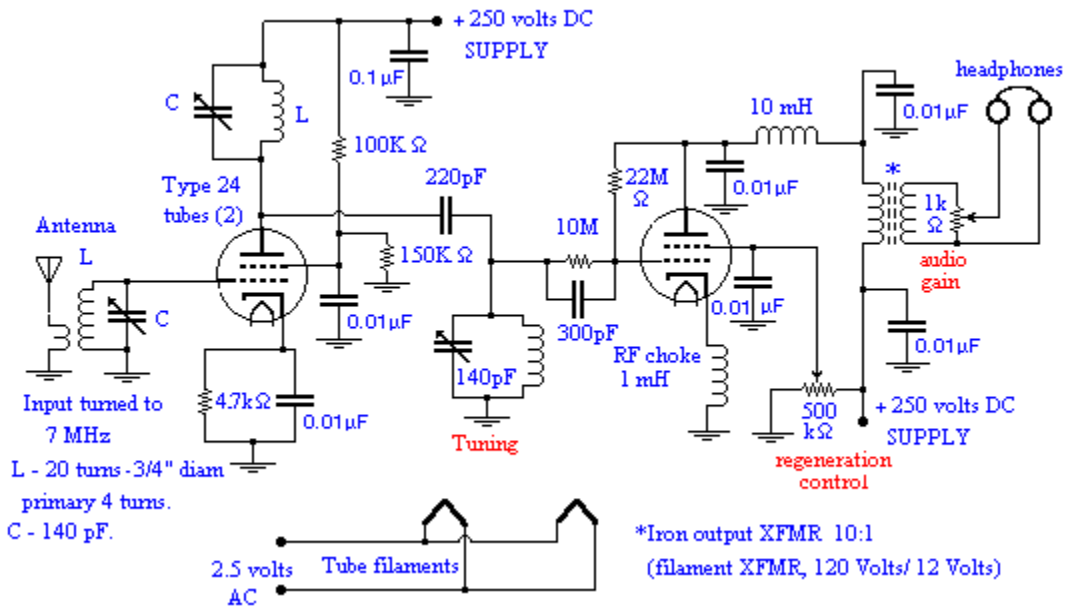
Circuit diagram of the old-tech super-regenerative receiver.

Super-regenerative design

When you think about it, a one-tube super-regenerative receiver is actually quite amazing. One tube is providing RF amplification, detection, audio amplification and a BFO all in one tube. It does this by feeding back to the output, providing far more gain than a simple RF amplifier can achieve. It takes good sensitivity to hear hams on the HF bands. Moreover, the self-amplification greatly increases the circuit Q, making the amplifier much more selective than it would otherwise be. For an audio output transformer I used an iron 12 volt filament transformer, i.e., 120 VAC to 12.6 VAC. It works fine and was easier than trying to find a real old time audio transformer. The secondary side goes to the low impedance headphones. The 120 volt primary side goes to the tube plate circuit.

Motorboating can be a good thing

"Super-regenerative" means that the amplifier is deliberately designed to "motorboat." That is, the power supply is deliberately given a high source impedance with a series inductance (10 mH). This causes the tube to oscillate in short bursts. These typically occur at a rate of 1

KHz. Normally, when RF circuits motorboat it's a darn nuisance and tough to get rid of. It's ironic that motorboating was my big problem with the transmitter and here it is vital to get the receiver sensitivity.

In a super-regen motorboating does two useful jobs: Maximum sensitivity and selectivity are obtained during the feedback, near the peak of each burst. The sidetone caused by this oscillation makes an audio squeal that serves as a BFO. If you are listening to AM modulation, the regeneration can be turned down until just below the point were the squeal begins.

Super-regeneration re-broadcasts what you're hearing

Unfortunately, if you wish to use a super-regenerative receiver today, it must be a two stage device. An RF amplifier (or other device) must isolate the oscillator from the antenna. Otherwise, you'll be rebroadcasting everything you're listening to on your receiving frequency. Even with an RF isolation amplifier, you'll be radiating a few milliwatts of RF signal. To demonstrate this, disconnect the antenna from your modern communications receiver so there are no signals audible on the band. Now tune the modern receiver to the frequency of your super-regenerative receiver. Suddenly, coming out of the modern loudspeaker you'll hear exactly what you're hearing in the headphones of your super-regen. The super-regen really does rebroadcast the signals it picks up!

The power supply

Bob, K6VGA, told me about the homebrew super-regen receiver he built back in 1935. He said its worse fault was AC hum. It was so bad, he replaced the AC power supply with batteries. After that story I figured I would have to filter the heck out of the power supply with a big choke, big capacitors and a voltage regulator from the 1940 era. However, a voltage regulator turned out to be overkill. Unlike my old-tech QRP transmitter, the power supply for the super-regen turned out to be remarkably easy. In other words, simple power supplies like the ones I tried to use for my transmitter worked fine for the receiver. Yes, the receiver hums slightly, but too little to bother me.
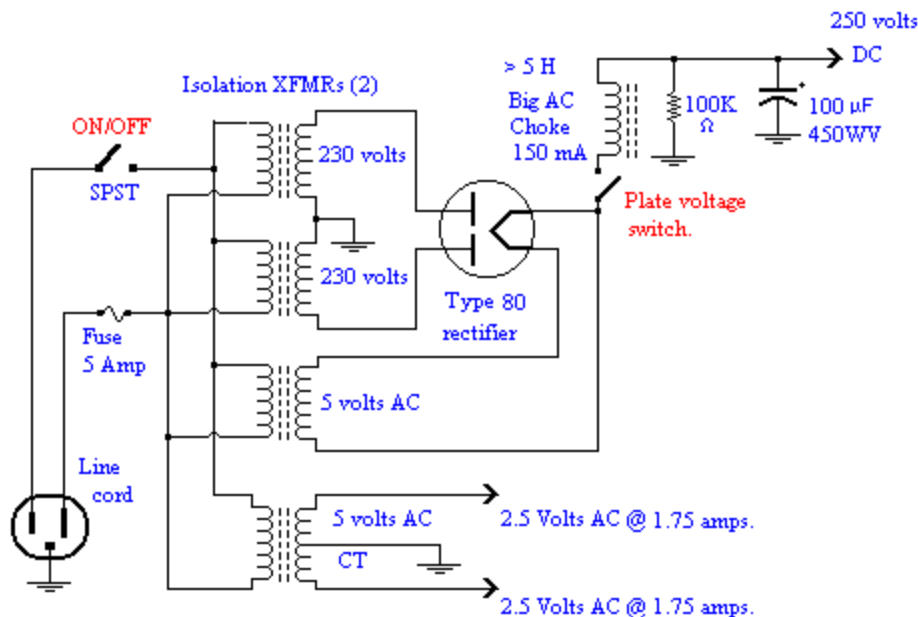
An old-tech power supply for the super-regen.

As explained earlier, you can't buy a new, old-time tube transformer with both high voltage and rectifier filament windings anymore. However, 5 volt filament transformers are still available as separate units. A center-tapped 5 volt, 2 ampere transformer is needed to provide the 2.5 volt filament voltage for the type 24 tubes. Those old tubes draw 1.75 amperes of filament current! My guess is that the old engineers switched from fragile, low current filaments to high current filaments to increase the cathode emission and make the filaments more rugged. The 224 filaments run at a bright yellow color. That's the same intensity that fried the old 201A tube. The tube filament transformer must be separate from the transformer used for the rectifier. Otherwise all the filaments would have +250 volts DC on them.

In my receiver I used an old plate transformer I happened to have. However, you may use two of the same transformers I used for my old-tech QRP transmitter. For a choke I used the primary of yet another filament transformer. Because the current drain is so low, a voltage regulator tube isn't needed.
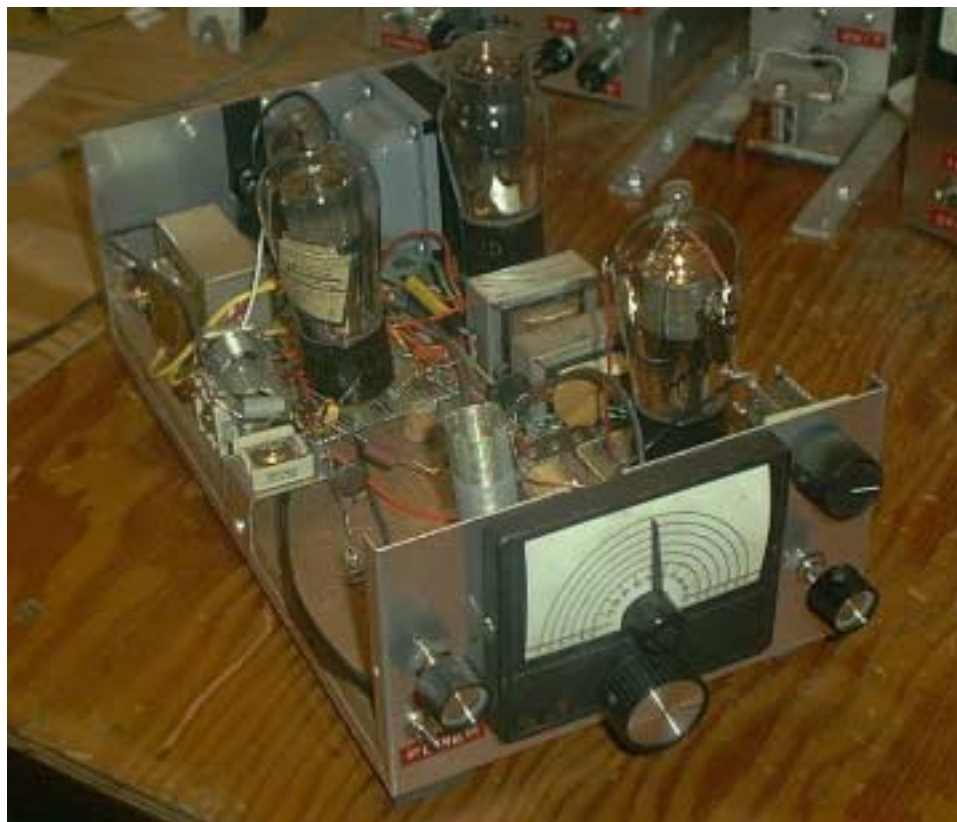
Super-regen on the modern hambands.

In summary my super-regen worked quite well for listening to shortwave broadcast stations on the 31 meter band, around 10 MHz. These are extremely powerful stations like The Deutsche Welle (Radio Germany) and various religious stations. To hear AM stations, the regenerative control is turned down just below where it begins to squeal.

To hear CW stations, the regeneration is turned up just above the squeal. The squeal modulates the Morse code and makes it audible. Unfortunately, as I feared, my super-regen isn't sensitive and selective enough to be used on the air today. Yes, I heard lots of ham CW stations on 40 meters, including guys I had worked before. The stability seemed OK once a signal was tuned in. But that's because I'm hearing at least 20 KHz bandwidth at once. In other words, I was hearing most of the CW stations on 40 meters simultaneously. The worst problem is that the reception is "flaky." If I just touch a control, the pitch of the CW signal jumps to inaudible. Or it leaps from a nice tone to a harsh, static-like sound. When I try to tune it in better, the signal is likely to vanish altogether. Yes, I can work guys with this receiver, but it would be a stunt, rather than practical.

In conclusion, the modern FET super-regenerative designs apparently achieve much higher Q than I got using gigantic, old-time parts with their stray capacitance and leakage inductance. But the project was fun and I learned a great deal. On the other hand, there's no reason I couldn't build a 1930 superhetrodyne using 6 or 7 ancient tubes and 1927 crystals. That would fill a huge chassis and require loads of work. Until I muster the enthusiasm, I guess a practical old-tech receiver will remain one of those unfinished projects in my attic. But wait! I just got a QSL from Biz, WDØHCO. He claims that, when he worked me, he was using a super-

regen made from two type-30 tubes. He found the design in a 1932 ARRL handbook.
Hmmm…… Maybe I'm being too hasty.

CRYSTAL SETS TO SIDEBAND
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Chapter 15

THE NOBEL PRIZE FOR SIDEBAND

How sideband works

In the beginning of the book I described how Glenn Johnson, WØFQK, recruited junior high school kids into ham radio. We were walking down the street minding our own business when Glenn ran out of his house and grabbed us. "Come on in boys and I'll show you how sideband works!" Glenn's wife served milk and cookies while Glenn worked bunches of guys on 20 meter sideband phone. I sat quietly and watched Glenn effortlessly operate massive equipment that cost enough to buy a car. I was fascinated by ham radio, but I didn't learn much about how sideband worked. I had the impression that sideband was *MODULATION FOR MILLIONAIRES* and too complicated to homebrew. The 1957 handbook's opaque descriptions of "phase shifters" and "balanced modulators" only confirmed my opinion.

Today SSB is affordable, but the technology is still exotic to the average ham. I overheard a conversation at my local ham club meeting that went something like this: "I once knew a guy who built his own sideband rig." "*REALLY*! That's amazing. Are you sure it wasn't a kit!" The implication was that homebrewing sideband was about the same level as a Nobel Prize in physics. So, anyone interested in a Nobel Prize for sideband? If you've already built homebrew QRPs, VFOs and a receiver, sideband is the next logical project. SSB uses all the same basic circuits. Besides, you won't really understand sideband until you've built one.

You begin with the sideband generator
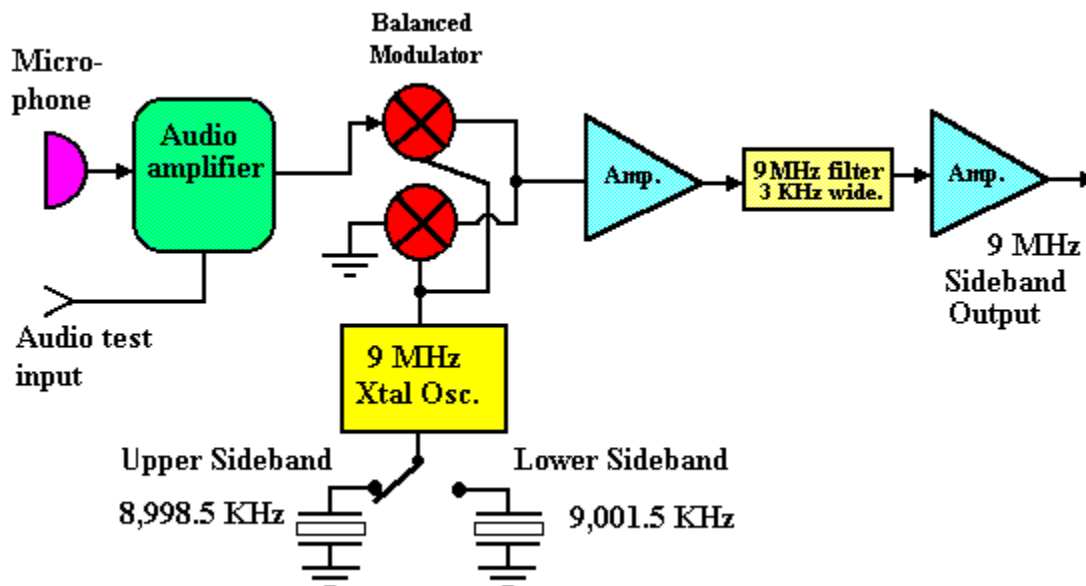
There are different ways of generating an RF sideband phone signal, but the most

straight-forward one I've seen is outlined above. The block diagram shows the five circuit blocks needed to generate a sideband signal on 9.000 MHz. This generator is similar to one found in the 1986 ARRL handbook. After the 9 MHz SSB signal has been generated, it must be moved to the desired ham band using a mixer and a high frequency VFO of the correct frequency range.

The circuits you've used in previous chapters are the audio amplifier, the crystal filter, the RF oscillator/ amplifier and the conversion modules to move the VFO signal to ham bands. The audio amplifier design is similar to the one in the homebrew receiver in chapter 13. The 9 MHz RF oscillator/ amplifier uses the same technology used in the QRP described in chapter 6. In theory, the VFO could be the VFO signal from your receiver. When I started this project, I figured if the sideband generator didn't work, I would at least have a CW signal that was slaved to my receiver so that it would be easier to zero-beat my signal with the guy I was trying to talk to. Unfortunately, that turned out to be harder than it looked.

Don't burn your bridges

If you're thinking about modifying a working CW transmitter to sideband, I don't recommend it. If you already have a working QRP driver based on chapters 6 or 11 from this book, those designs are full of tuned amplifiers and mixers. Tuned amplifiers tend to self-oscillate when used for sideband. To have a good chance of working, every gain stage should be converted to broadband. If you convert your old transmitter, you are likely to have months of struggle in which you aren't on the air at all. Start from scratch! Don't ruin a rig that works!

How sideband works

Ordinary broadcast band AM modulation transmits three separate signals. These are the carrier signal and two sidebands of speech modulation. Single sideband begins with AM, but a cancellation process removes the carrier and one of the two sidebands is filtered out with a crystal filter. Let's begin with the crystal oscillator:
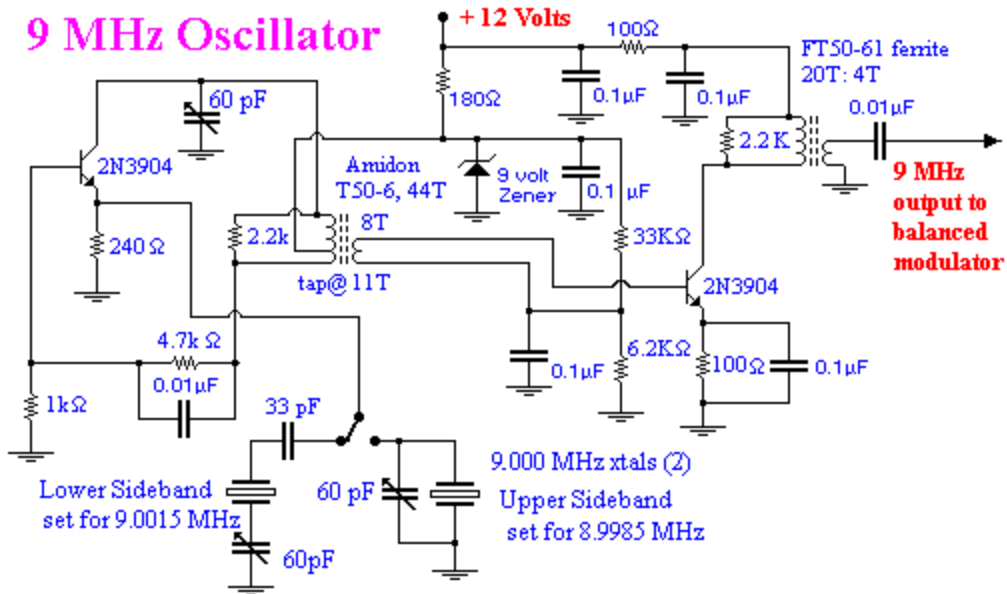
9 MHz sinewave oscillator / amplifier

A stable, fixed frequency RF sinewave signal is generated by a crystal-controlled 9 MHz oscillator and amplifier that resemble the 7 MHz QRP transmitter described in chapter 6. The crystal oscillator has two crystals. Each has tuning capacitors so that the frequency can be pulled about 1 KHz up and down. This allows the two AM sidebands to be lined up properly with the ladder-style crystal sideband filter that follows the balanced modulator. The filter shears off the unwanted upper or lower sideband.

A switch enables the oscillator to select two crystal/ capacitor pairs so that the operator can switch between upper and lower sideband. The crystal filter that removes the unwanted sideband is at 9.000 MHz, almost exactly. Notice that the upper sideband is generated by a sinewave 1.5 KHz <u>below</u> 9.000 MHz. The lower sideband is generated by a sinewave 1.5 KHz <u>above</u> 9.000 MHz. To pull the crystal above 9 MHz, the tuning capacitor is in series with the crystal. To push the crystal below 9 MHz, the tuning capacitor is in parallel with the crystal.

The audio amplifier
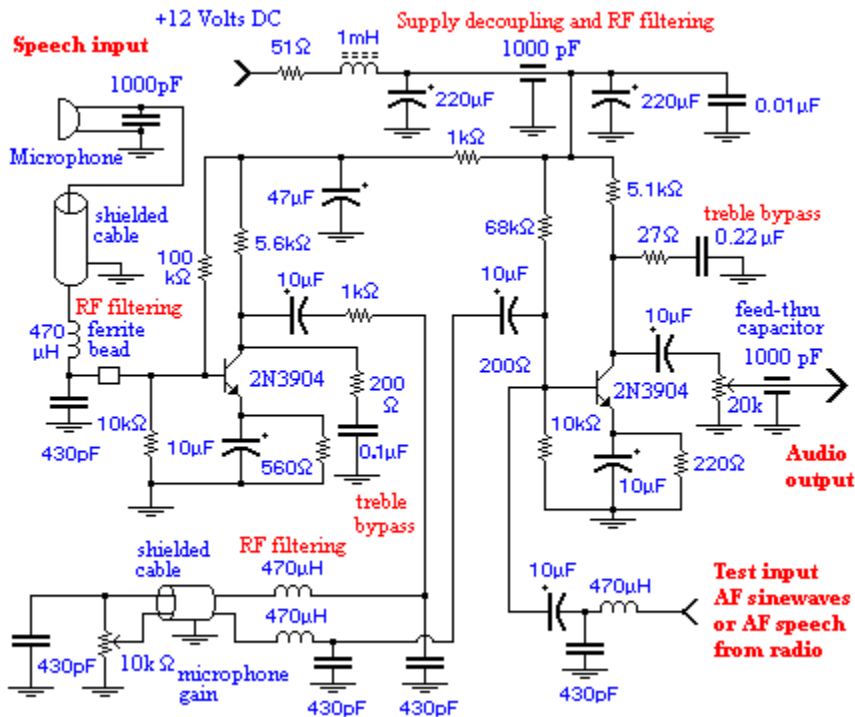
An audio amplifier with test input

The microphone needs a high gain audio frequency (AF) amplifier before it can drive the balanced modulator. The audio amplifier is pretty routine except that heroic effort is needed to shield it from RF. Notice the RF chokes and bypass capacitors on the two audio inputs, the audio gain pot and the 12 volt power input. Because crystal mikes have a puny output, it took me two stages to get the signal up to roughly 5 volts peak. My crystal microphone exaggerated the high frequencies, so I attenuated the high frequencies with series RC **treble filters** on the collectors of both amplifier stages. You may be tempted to add another stage of audio gain. Don't! It's much

better to run the audio gain wide open than to have extra gain and keep the gain turned low. Surplus gain just invites noise and sensitivity to RF feedback. If you like, you can replace most of this circuit with an IC, but as always, building your own amplifier with discrete parts will be more educational.
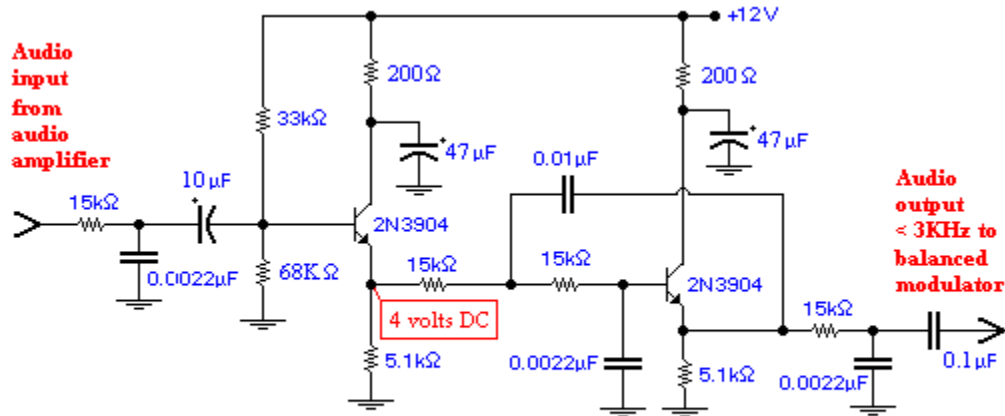
AUDIO LOWPASS FILTER (< 3 KHz)

I added the ***Butterworth*** filter shown above to be sure the bandwidth of my final signal would be less than 3 KHz. Like the treble filters discussed earlier, your generator may not need this. The Butterworth sharply cuts off practically all audio signals higher than 3 KHz. In contrast, the treble filters just help emphasize the lower frequencies. The filter uses two transistor amplifiers wired in the ***emitter follower*** configuration. Notice that the load resistor (5.1K Ω) for each transistor is wired between the emitter and ground, rather than between the collector and the positive supply.

The advantages of emitter followers

Emitter followers have the advantages that the input impedance is extremely high and the output impedance is very low. High input impedance means they will not load down or affect the input signal strength. Low output impedance means they deliver big currents into low resistance loads. Another feature of the emitter follower is that ***the voltage gain is less than unity.*** That is, they don't amplify voltage. This is an advantage here because that insures that the amplifier will not oscillate. Butterworth filters are usually implemented with operational amplifiers. Until this filter, I had never built one with transistors. Yup, simple transistors work too.

No matter what audio amplifier circuit you use, it will be sensitive to RF interference from any strong RF signal in your radio shack. For example, if you are using a simple antenna coupler with no shielding like mine, those RF signals will tend to feedback into your microphone cable. To prevent this I added RF chokes, bypass capacitors and a ferrite bead in series with the microphone input. Since my microphone gain pot is remote from the audio module, the wires to the pot are also filtered with RF chokes and bypass capacitors. Even the output from the amplifier passes through a capacitive feed-through (bypass) capacitor on its way to the balanced modulator.

Decoupling for the power supply lead

The 12 volt power supply lead for the audio amplifier also has a large RF choke (one millihenry) in series with the lead and passes through another feedthrough capacitor bypass. In addition, the power supply lead is isolated or "***decoupled***" by means of the 51 ohm resistor and the large 220 microfarad bypass capacitors. The purpose of these capacitors is to insure that the voltage supplied to the amplifier cannot change as fast as the audio signals. All of the modules in an SSB transmitter, except the final amplifier, need to be decoupled from changes in the 12 volt supply level. Otherwise, as you talk into the microphone, the current drawn by the high power final varies rapidly and the voltage delivered to each module will rise and falls in time with the speech. Because the voltage is rising and falling, the RF output from each module will rise and fall too. This feedback produces surges in the radio signal that sound like noise superimposed on the speech. In fact, it makes nearly the same buzzing roar as RF interference.

The final amplifier draws too much current for it to be practical to decouple the amplifier supply lead. In fact, it is the huge 10-ampere surges of current drawn by the final that cause the noise in the rest of the transmitter. In general, the <u>less</u> current drawn by a circuit block, the more extreme the decoupling must be. For example, the audio amplifier has a series 51 ohm resistor and 440 microfarads bypass. In contrast the 5 watt RF driver stage has only a one ohm resistor and a 0.1 microfarad capacitor.

Microphones are important

Not all microphones are equal. I tried 3 different crystal microphones. Two small Radio Shack microphone cartridges gave a "tinny" sound. I was able to compensate with RC bypass networks on the collectors of all three transistors to limit the high frequency components (treble) of the speech. For example, notice the 200 ohm resistor and 0.1 μfd capacitor combinations going to ground from the first two transistor collectors. I also tried a 40 year old Hallicrafters crystal microphone designed for mobile radio. It worked fine without the RC bypasses. Next I tried two tiny condensor-type electret microphones. One was too "basey" and made a low frequency hum. The other, a Radio Shack PN # 270-092A, worked perfectly. To bias the electret with about 4 volts, I used a 3.9K resistor in series with a 7.5K resistor to step down the 12 volt supply.

**The balanced modulator**

Balanced Modulator
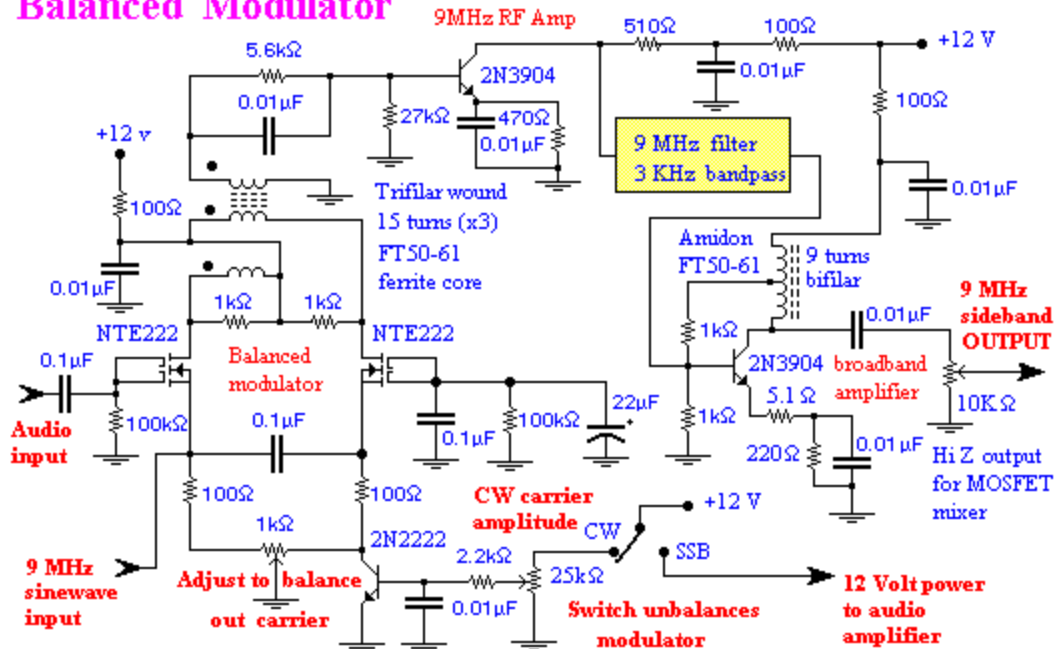
The balanced modulator is the "carrier cancellation circuit." It is a kind of dual mixer in which an audio signal is mixed with the 9 MHz sinewave to produce a AM modulated signal, exactly like AM radio. An AM signal has a carrier signal just like the CW input plus the two RF sidebands caused by the audio modulation. What's different about a balanced modulator is that it consists of two mixers in parallel. The second mixer has no audio input so its output is just another CW signal, just like its RF input. The two mixers share a common output transformer that has three windings - two primaries and one output winding. There is a primary for each mixer. The clever part happens when the primaries generate magnetic signals in the transformer iron. The windings are oriented so that the two primaries work against each other. The CW signals in both windings are "balanced" with an adjustment pot so that they exactly cancel. This means that the only signals that appear in the secondary winding are the two sideband signals. *In summary, a balanced modulator produces a double sideband signal with no carrier.*

The transistors are dual gate MOSFETS with the gates shorted together. The idea is to use transistors without any P-N diode junctions. According to the handbook, P-N junctions act like varactors and distort the speech slightly. Dual gate MOSFETs are used simply because they are the most common small RF MOSFET available. A single gate small RF MOSFET is fine, but you probably won't be able to find one. The above circuit was adapted from the 1986 Handbook.

To use this modulator for CW, there is a switch that unbalances the modulator and allows some carrier to pass through to the filter. This CW mode will be hard to use for actual CW contacts because the crystal filter will tend to remove the carrier again. However, this small 9 MHz sinewave is useful for tuning an antenna with a "test signal" or for "spotting" the VFO on top of the station you wish to call. For CW operation, you may bypass the SSB filter or use a separate 9 MHz oscillator. This sideband generator can also be modified to generate amplitude modulation. This is discussed in chapter 16.

The sideband filter
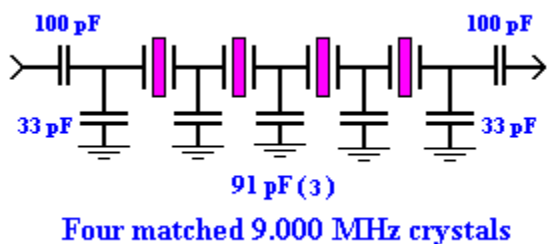
You can buy sideband filters that select a 3 KHz passband, typically 9,000 KHz to 9,003 KHz. Sometimes matched oscillator crystals are also available that will position the RF signal optimally to line up with a particular filter.

In chapter 13 we made a 4-crystal CW receiver crystal ladder filter that was quite similar. The difference is the sizes of the accompanying shunt capacitors. In the receiver the shunt capacitors were 220 pF. However, ***The smaller the shunt capacitors, the wider the pass band of the filter.*** The 91 pF capacitor value in the above filter was scaled from a sideband filter used in a sideband transmitter designed around an 8.000 MHz generator. This filter seems to work, so I haven't had to experiment.

The homebrew way is to buy a bunch of 9.000 MHz microprocessor crystals from Mouser or Digi-Key for 86 cents each. Using the RF oscillator shown earlier and a frequency counter, measure the frequencies of each of your crystals. When used as filters, their natural frequencies may not be the same as in your oscillator, but their *RELATIVE* frequencies will be comparable. Pick four crystals that are as closely matched as you can. Matching within 100 Hz should be adequate. I tried tuning each crystal to the same frequency using trimmer capacitors in parallel with the crystals. This proved to be unnecessary and I later removed the trimmers.

The crystal oscillators are misaligned for CW

The crystal filter is set up to cut off either the upper or lower sideband. When you unbalance the balanced modulator to produce a CW signal, you will indeed get a small sinewave signal through the filter that may be strong enough to tune the antenna coupler or adjust the transmitter. However, because the center of the SSB crystal filter (9.0000 MHz) is lined up 1.5 KHz away from both crystal oscillators (8.9985 MHz & 9.0015 MHz), this CW signal will be far lower than the maximum power you will get on voice peaks.

MECHANICAL CONSTRUCTION

**Sorry! You must shield sideband.**

When building CW transmitters, some of us think it's cool to have the parts out in the open where we can see them. Unfortunately a huge problem with SSB is RF feedback. To prevent that, you must enclose all the modules of your SSB transmitter in metal. All the connections between modules should also be shielded cables. I started out using shielded power cables to my RF modules, but eventually I worked out a way to mount the Molex connectors directly to the shielded boxes. In this way I could plug the module onto the chassis with no exposed wires.

Actually, I still leave the linear amplifier out in the breeze, but all the low power modules and the power supplies are well shielded. All my modules consist of a two-sided PC board with walls of PC board soldered onto the edges to make a box. Then I fold an aluminum cover over the top to provide the lid.

**The completed SSB generator**. An aluminum lid fits over the top of the box.
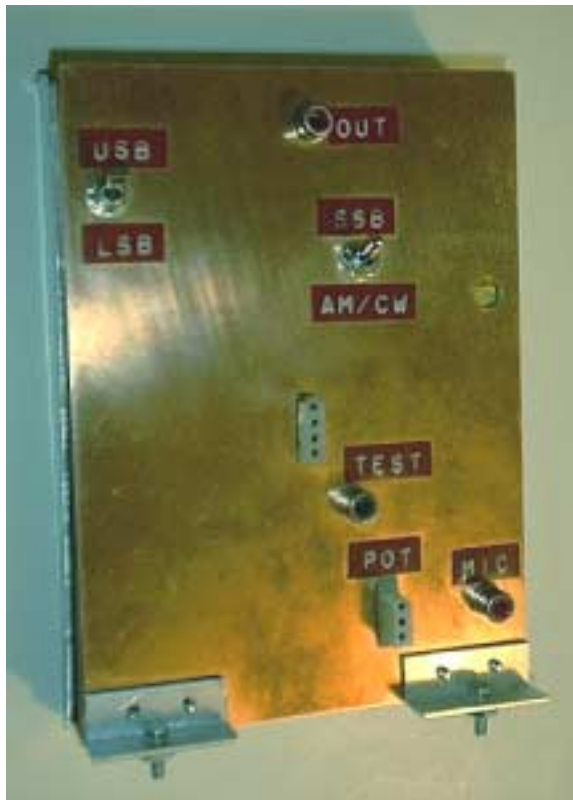
Tuning and testing the sideband generator

The essential tools for tuning up your generator are ***a frequency counter, an oscilloscope***

and a good ham receiver. Ideally, you need one of those same modern receivers that will be listening to your signal. The circuit above generates a sideband signal on 9 MHz. Keep in mind that when you listen to the 9 MHz signal on your ham receiver, unless your generator is well shielded, you'll still hear the carrier signal and the suppressed sideband leaking from your 9 MHz oscillator. That's because those signal components are present on your circuit board and your receiver will have little difficulty in hearing them.

To check out the generator introduce audio from a Walkman radio into the test input allowing you to align the generator. Tune the Walkman to a talk radio station and inject the audio into the test input. Speech should be perfectly understandable in your ham receiver. When you turn off the BFO and set up the receiver for AM modulation, speech should be unintelligible. Music should always sound awful. If music sounds pleasant, your bandwidth is too high.
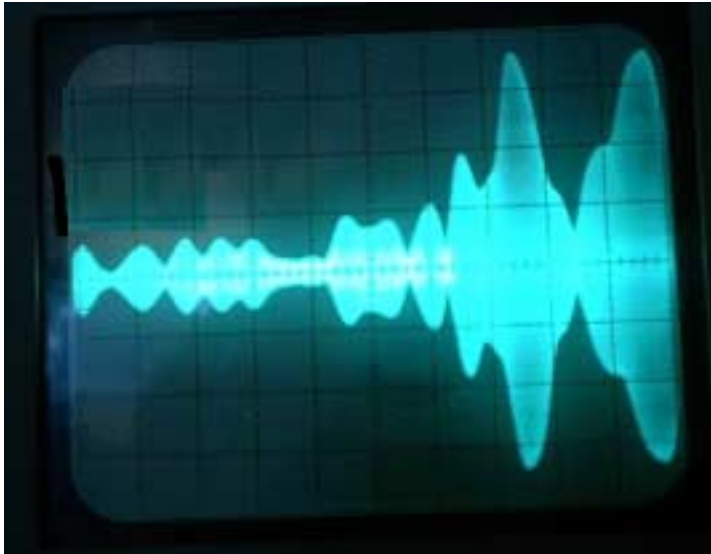
The 9 MHz SSB voice signal seen on an oscilloscope.

An SSB voice signal should appear on your scope as shown above. The audio modulation is symmetrical about the zero axis. In between syllables or words, the signal strength drops to zero. The edges of the sinewave bursts should be reasonably sharp, meaning that the frequency should remain pure with varying levels of speech. When there is no audio input, there should be essentially no RF output.

Checking out the microphone and microphone pre-amplifier can be complicated. It's hard to listen to your own voice critically. Also, the audio from the ham receiver loudspeaker will feedback into your microphone. My solution was to put the microphone up against a high fidelity Walkman headset. Then I wrapped the headset in cloth to muffle the sound. To hear how it sounded on the air, I listened to the sideband generator signal in the ham receiver using headphones. Unfortunately, when used with the 50 watt amplifier, the RF from the dummy load and transmatch interfered with the Walkman so this technique only worked well for 5 watts. I was able to partly test the 50 watt linear by listening to my own voice while wearing headphones with no receiver antenna plugged in. I could at least confirm that there was no RF feedback.

Audio signal generator testing

It is instructive to feed an audio tone from an audio oscillator into audio input jack. As

you sweep the audio spectrum from 20 Hz to 3 KHz, watch the sideband generator RF output on the oscilloscope. Unlike AM modulation, there should be no audio frequency modulation visible on the radio signal. That is, for each audio sinewave frequency you should see a pure, CW-like signal. Another way to think about single sideband is that it is a kind of extremely narrow-band frequency modulation. As the audio frequency changes, the signal frequency shifts up and down in direct proportion. Unlike AM modulation, the amplitude of the transmitted signal shouldn't change when you introduce a constant amplitude audio frequency. That is, with SSB, you shouldn't see ripples on the signal amplitude proportional to the frequency. The amplitude should only change with speech amplitude, not with speech frequency. In contrast, pure FM modulation does not change its amplitude with speech amplitude or with audio frequency.

Suppressing power supply RF feedback and low frequency coupling

My first sideband contact said, "Sorry, old man! I hear some hissing noises, but I can't understand a word you're saying." It turned out that the power supply leads in the generator and other modules in the transmitter needed low frequency decoupling. In the sideband generator this consisted of the 51 ohm resistor and the two 220 microfarad caps on the 12 volt line. Without decoupling, the audio turns into noise as the generator competes with the final amplifier(s) for operating voltage. That is, the 12 volt supply voltage surges up and down with the speech and the amplifiers exaggerate this.

After these improvements my next contact could understand me, but he said my voice was "raspy with popping sounds." I didn't have laryngitis, so I asked Jack Quinn, KØHEH, about the criticism. He instantly diagnosed the problem: "That's RF feedback. Improve the shielding of your microphone and audio amplifier." I placed the 1000 pF capacitor directly across the microphone, the 430 pF bypass capacitors and the 470 microhenry inductors in series with the inputs and power line. Also, the power and audio output pass through feedthrough capacitors to further attenuate the RF. When RF feedback is really bad, the signal turns into a roar of noise that can sounds similar to low frequency power supply decoupling problems.

****

The Hard Part --- Moving the SSB signal to a hamband

Is 9 MHz a hamband?

To get on the air you need to amplify the 9 MHz sideband signal up to 50 or more watts. Unfortunately, the last I heard, 9 MHz isn't a hamband. The hardest part of this project turns out to be moving the 9 MHz signal to the band(s) of your choice. Or, we could all write to the WARC to ask them to establish a little 6 KHz hamband centered on 9.000 MHz. Maybe not.

Moving the SSB to a hamband is by far the most difficult part of sideband. However, if you don't make the mistakes I did, maybe it won't be so bad. Four principles I learned the hard way were:

* *Move your sideband signal only once.* Double conversion might appear convenient, but it's extremely hard to do without distortion. In other words, don't do the hardest task twice.

* *In the conversion between 9 MHz and your HF band, make sure that the mixer input frequencies are far away from the final frequency.* For example, to get on 20 meters, it is practical to add a 5 MHz VFO to 9 MHz to get 14 MHz. On the other hand I found that it was

impractical to move a 4 MHz sideband signal to 21 MHz using a 25 MHz crystal oscillator. Every time I stopped talking, a significant 25 MHz signal went right out through the transmitter output filters.

Don't use tuned amplifiers and mixers.   When you stop talking, tuned amplifiers tend to oscillate by themselves at frequencies similar to where they were tuned. In fact, getting rid of the noise and oscillations when you're *NOT* talking is the harder than making the speech intelligible. Unlike CW, it is best to use broadband mixers and amplifiers and to put all your hamband filtering into two passive filter networks.   Sideband is different from CW!

*** Beware of having too much gain in your SSB generator and frequency converter.*** I originally had extra broadband amplifiers in the generator output and also right after the converter mixer. These extra amplifiers amplified noise. Every time I wasn't talking, they often began to self-oscillate.

*** It sometimes helps to connect all ground connections to the outside layer of your two-sided PC board.*** The ground connections for all high current RF stages must be extremely low inductance. Otherwise, if your board layout isn't well designed, RF voltages on all the ground traces inside the PC board box will "bounce up and down" with the currents in the power amplifier stages. This feedback introduces noise into the mixer stage and makes the QRP module difficult or impossible to adjust. If you are using 2-sided PC boards, solid grounds can be added by drilling the PC board at each ground connection and soldering a wire through the board to the unbroken sheet of grounded copper outside the PC board.

Getting on 20 and 80 meters

Hetrodyne converter for the SSB generator
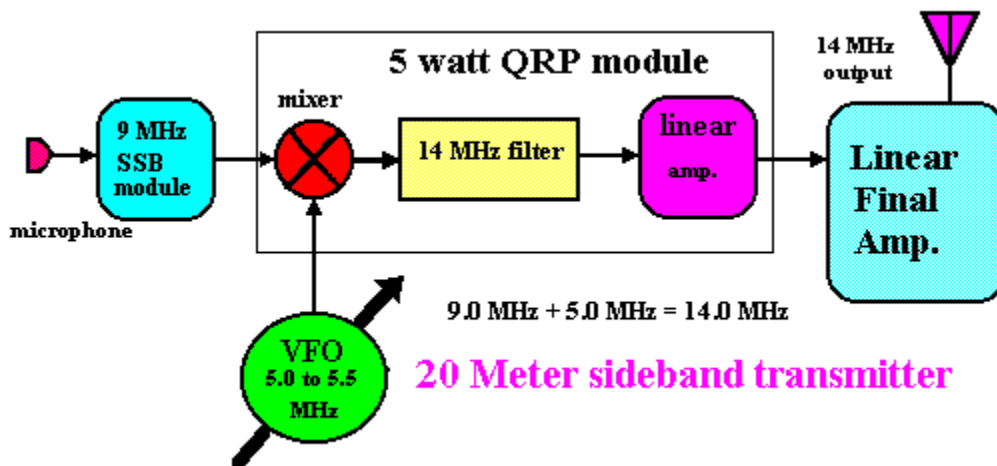
When starting with a 9 MHz sideband signal, 20 meters is the easiest hamband to reach. For 20 meters, a 5.00 to 5.35 MHz VFO signal is mixed with 9 MHz to give 14.0 to 14.35 MHz. 9 MHz is 36% different from 14 MHz. Consequently, building a filter to extract the 20 meter component and suppress the 9 MHz signal is relatively easy.
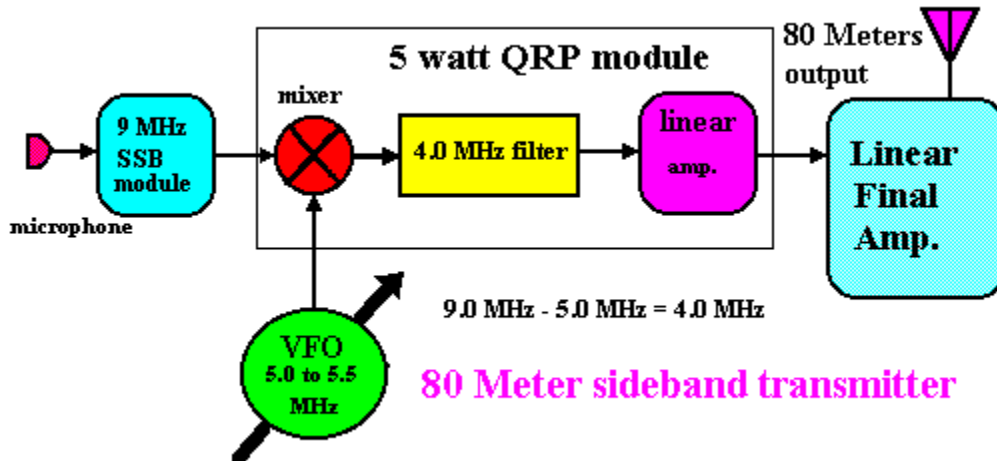
Now suppose that you wish to move the 9 MHz sideband signal down to 80 meters. 9 MHz minus 5 MHz is 4.0 MHz. The phone band extends right up to 4.0 MHz. So the 80 meter (75 meters) output signal can be as little as 20% different from the VFO signal. Filtering the 80 meter signal is almost twice as hard as 20 meters. What happens if your filtering is inadequate? Every time you stop talking, your linear final amplifier will be transmitting a sinewave carrier on your VFO frequency, 5 MHz. As we'll see, when you start with a 9 MHz sideband signal, all the other HF bands are harder than 20 meters.

Self oscillation

When you build a high-Q amplifier/ filter stage, it tends to oscillate on its own whenever there is no signal coming into the input. This means that, in between words, your QRP module may be oscillating on some random frequency on or near the hamband you are using. Sometimes this oscillation can be suppressed by placing a 50 or 100 ohm resistor across the input of the offending stage. Another method is to place a 1K to 2K resistor across the RF transformer primary on the collector or you may add a small resistance (such as 10 or 20 ohms) of un-bypassed resistor in series with the emitter of the transistor. Unfortunately, these tricks are usually not enough. ***The best solution is to use untuned broadband amplifiers!*** Even with broadband amplifiers, you will still have to use some or most of these tricks to keep them from oscillating.

No wonder most rigs are transceivers

There is a great deal of similarity between a sideband receiver and a sideband. Once you've built a receiver, it dawns on you that the transmitter has most of the same modules and that you are building the same circuits twice. On the other hand, using the same circuit modules for both tasks takes finesse. Unfortunately we homebrewers have enough problems without that extra complexity.

Ideally, it would be best to use the 5.0 MHz VFO from your receiver. That way the transmitter frequency and receiver frequency can zero beat exactly. When you answer a CQ, you don't want to take the time to tune the transmitter VFO. When I got on the air with my separate 5 MHz VFO, I found that, by the time I had it precisely zero beat with the guy calling CQ, he was often already talking to somebody else.

Unfortunately, using the receiver VFO isn't simple. If you simply connect it to the transmitter by a long cable, the receiver will suddenly have intermodulation, noise and whistles it didn't have before. To get past this, the VFO signal must be isolated from the receiver by an isolation amplifier. Also, the 9.000 MHz BFO and the sideband generator oscillator must be on the exact same frequencies. Hmmm… Furthermore, the VFO band conversion oscillators in the receiver and transmitter must be aligned to within a Hz or two. Not so simple after all. The transceivers solve the problem by using the same oscillators for both tasks so alignment isn't a problem. As my high school textbooks used to say, these problems are left as exercises for the interested student.

An 80 meter sideband QRP driver

As explained above, an untuned mixer should be followed by a ***totally passive filter***. That is, the filter should be just a network of LC circuits. It should have no transistors. Instead, the gain is provided by two or ***three untuned stages in series***. Three, high-gain broadband amplifiers in series can work without oscillating, provided that their input has very little noise. The basic design shown below has the advantage that, it can be used on any HF band. To change bands, you plug in different filter sections shown in the green boxes below.
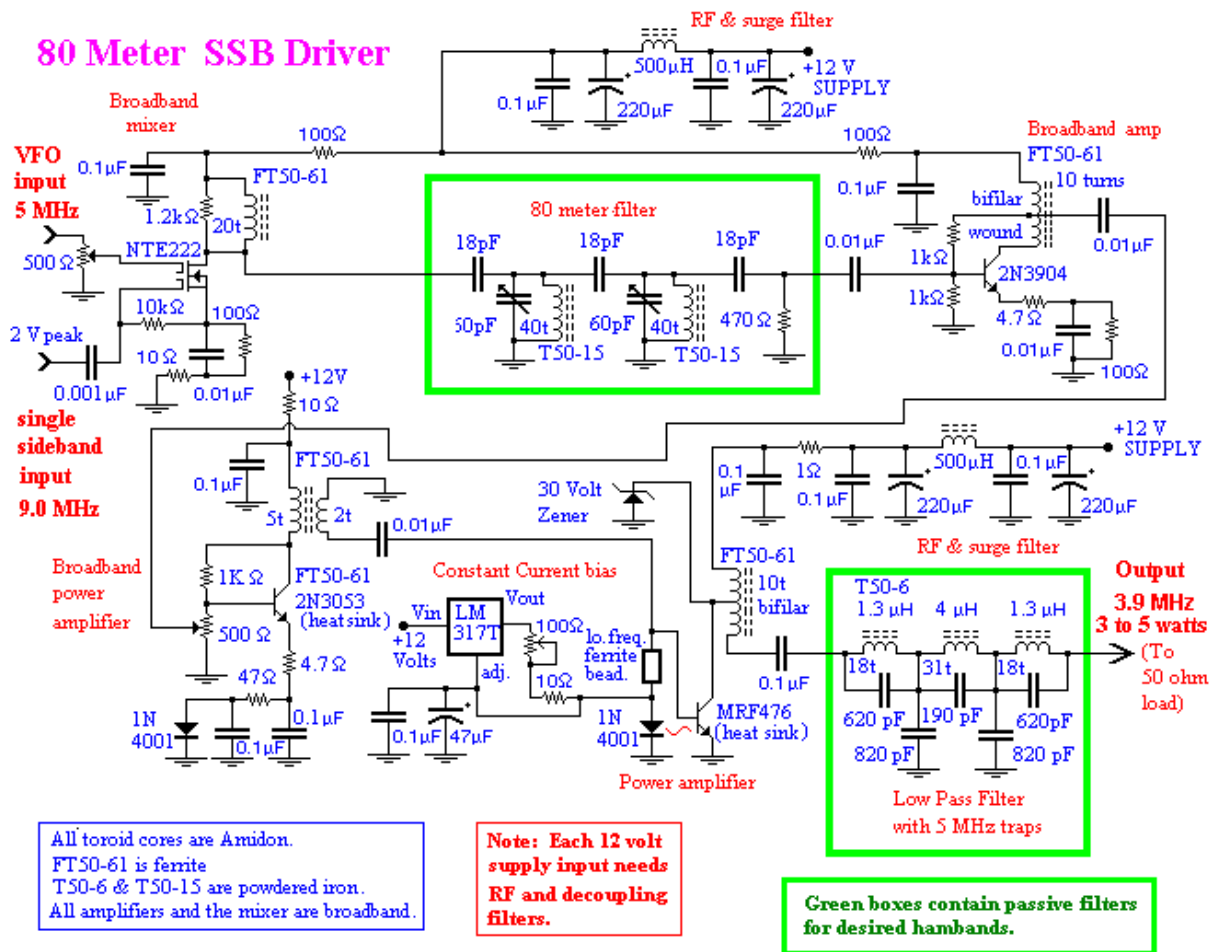
All transistor stages are broadband, including the mixer. Note the 2K resistor across the

primary of the first ferrite core transformer. Without this or other feedback, the broadband amplifiers tend to generate an uncontrolled signal whenever the SSB input drops to zero between spoken words. The un-bypassed 4.7 and 10 ohm emitter resistors in two of the amplifiers also help prevent oscillations. To reduce surging and RF feedback to the driver module I filtered my 12 volt input leads with RF chokes, big capacitors and small ceramic capacitors.

Unlike the CW QRP modules, the SSB module output stage needs forward bias to operate in linear mode. The LM317 circuit current source supplies the needed current. This temperature compensated circuit was used in the 50 watt linear in chapter 12 and is overkill for this 5 watt final, but what the heck! With experimentation I found that just 20 milliamperes of forward bias is plenty to operate linear and give good speech quality. In theory, a 560 ohm 1 watt resistor can provide this bias much more cheaply. However, I haven't tried this.

The passive 80 meter filter is placed between the mixer and the first broadband amplifier. The output filter is the usual Chebyshev low pass except that capacitors have been placed in parallel with the inductors. These make the inductors resonate at 5 MHz and provide extra attenuation to get rid of the 5 MHz VFO signal. Notice that the equivalent of five parallel and series LC circuits were used to clean up the 80 meter signal. In contrast, as you'll see on the next page, a 20 meter QRP (5 MHz + 9 MHz) can be done with just two LC circuits and an output high pass filter.

Beware of residual VFO signal

Once I had the 80 meter driver working well, I fed it into my linear amplifier described in Chapter 12. With the amplifier it produced 60 to 100 watts on voice peaks. However, whenever I stopped talking, the frequency counter shifted to the 5 MHz VFO frequency even though the amplitude of the signal on the scope screen looked negligible. When I turned up the scope amplitude, sure enough, there was a 5 volts peak sinewave on the output. That represented about 0.25 watts of 5 MHz sinewave. To get rid of it, I rebuilt the final amplifier 80 meter low pass output filter using another "elliptical" filter design. Notice that each inductor has a parallel capacitance that resonates at 5 MHz and keeps the 5 MHz out of the antenna. I used the values shown below. After that change, the residual, no-speech, signal was only 1 volt peak and the counter measured it as the correct output frequency, 3.9 MHz.
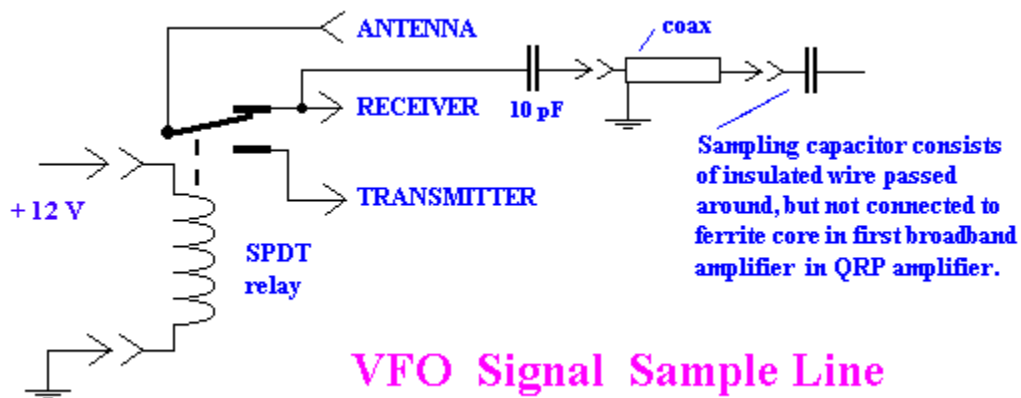

80 Meter lowpass Eliptical Filter for Linear
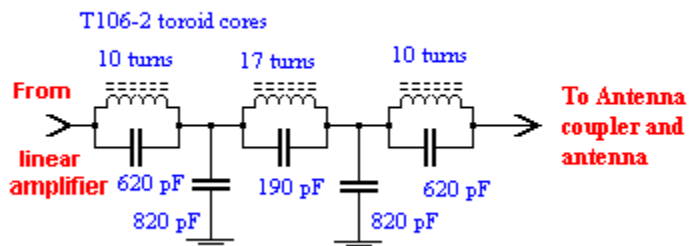
If you are like me, you will have a devil of a time getting your SSB drivers to produce intelligible speech without hissing and noise and problems. All I can tell you is to keep your brain mulling over your difficulties. Shield and filter your prototype until the darn thing works. Persistence will win in the end!
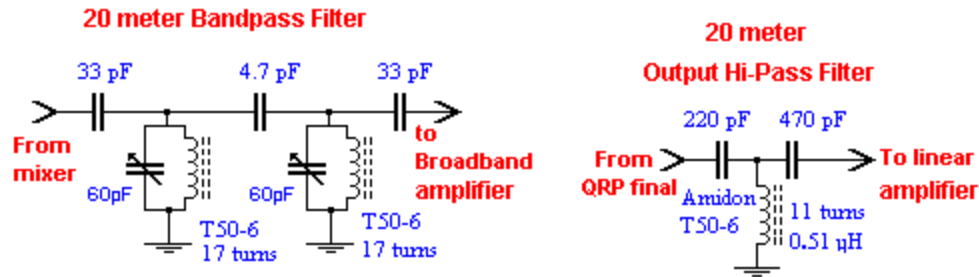
Hearing the transmitter VFO in your receiver

One consequence of shielding and filtering every low power module of my SSB transmitter was that I could not hear my own VFO signal. This made it impossible to tune the VFO to a station I might wish to talk to. Eventually I solved the problem by connecting a tiny capacitor, 10 pF, to the receiver antenna terminal on the antenna relay. This capacitor is connected to a shielded cable that runs over to my QRP module and plugs into a shielded phono connector on the side. Inside the QRP module an open-ended wire runs over to the first of the three broadband amplifiers and passes one turn through the ferrite toroid core. This sampler wire is not a complete winding turn. It is *NOT* connected to ground or anywhere else. The wire just serves as a tiny capacitor to sample a bit of VFO signal for the receiver. During transmit the antenna relay disconnects the sampler wire from the transmitter to prevent it from causing feedback from the antenna into the transmitter.

Sampling capacitor consists of insulated wire passed around, but not connected to ferrite core in first broadband amplifier in QRP amplifier.

VFO Signal Sample Line

When I push the "Spot" button on my transmitter, 12 volts power is connected to all the low power modules of the transmitter. During "spot" mode, the 12 volt power is *NOT* connected to the last two power amplifier stages of the QRP. The 12 volts goes to the 5 MHz VFO, the SSB generator, the VFO frequency converter (if one is used on that particular band), and the mixer and first broadband amplifier of the SSB QRP module. The first amplifier is the first place in the transmitter where the actual broadcast frequency is present for sampling. Because the final frequency depends on the 9 MHz signal from the SSB generator, there will be no signal from the SSB generator unless you are actually talking or the generator is set to "CW." So in summary, to hear the VFO without transmitting, the SSB generator must be set to "CW," the "Spot" button must be pushed, and the receiver antenna needs a tiny capacitive coupling to the first broadband amplifier. In SSB, even simple things are complex.

Adding 20 meter capability to the 80 meter QRP module

In the 80 meter module above there are two filter networks. You can put the QRP module on 20 meters by switching in a 14 MHz filter after the mixer and by replacing the low pass on the output with a high pass filter. On 80 meters the 9 MHz and 5 MHz problem signals are above 4 MHz. Therefore, the 80 meter QRP module has a low pass filter. In contrast, on 20 meters the noise problem is below 14 MHz. Therefore, a high pass is desirable for 14 MHz. The filters to put the module on 20 meters are shown below. My module uses two DPDT switches to switch back and forth between the two bands.

20 meter Bandpass Filter

33 pF   4.7 pF   33 pF

From mixer   60pF   60pF   to Broadband amplifier

T50-6   T50-6
17 turns   17 turns

20 meter Output Hi-Pass Filter

220 pF   470 pF

From QRP final   Amidon   T50-6   11 turns   0.51 µH   To linear amplifier

Feedback and distortion – don't overdrive!

A frequent problem I ran into was using too much drive on a stage. For example, I built my prototype for 20 and 80 meters. And after many changes and fussing I got it to work. Then I reproduced the circuit for use on 17 and 12 meters. However, the second time I knew what I was doing and the circuit was much "cleaner." The result of my compact, pretty wiring was higher efficiency and more power out of each amplifier stage. Instead of 3 watts output, now I had 6 or 8 watts or more and I was overdriving the linear final. Excess drive gave my signal a rough, rasping sound and made the speech hard to understand. To fix this, I had to go back and decrease the output by various methods. I decreased transformer turns driving bases, used more negative feedback (emitter resistance), etc. Finally I put the 500 ohm pot in front of the 2nd broadband amplifier. This enabled me to deliver just what I needed and no more. Finally the voice quality was acceptable. The pot worked so well, I went back and installed one in my 80/ 20 meter driver module.

Moving an SSB signal to the "difficult" hambands

As explained above, the easiest hambands to reach with your SSB generator are 80 and 20 meters. Unfortunately, on weekends 20 meters is the most crowded ham band. It's full of guys running 2000 watts peak into Yagi beam antennas 50 feet in the air. If that weren't bad enough, their sideband transmitters are exquisitely designed to get the most modulation out of every watt. If you do get on 20 meters with your little homebuilt, it will probably average 20 to 40 watts on voice peaks. Combine that with your dipole antenna and it's going to be hard for those big guys to hear you. On the other hand, a band like 15 meters, or possibly 17 meters, is less crowded and you are more likely to make solid, enjoyable contacts there.

Getting on 15 meters

How do we move the 9 MHz to 21 MHz with a 5 MHz VFO? My solution was to move the 5 MHz VFO to 12 MHz. Then I added my 12 MHz VFO to 9 MHz to get 21 MHz. (12 MHz + 9 MHz = 21 MHz) After mixing, the 21 MHz signal was 43% different from the nearest frequency component and filtering was <u>relatively</u> easy. Unfortunately, moving the VFO to 12 MHz sounds really cumbersome… and it is! However, it uses technology you have already mastered. So, in the long run, I believe moving the VFO is the easiest way to go.
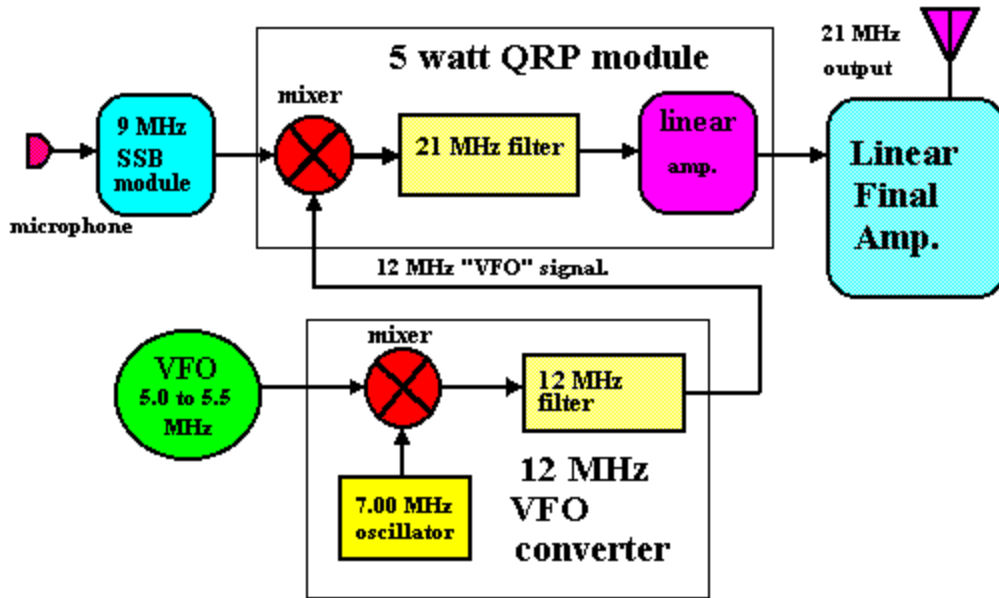
Generating a 12 MHz VFO signal

The VFO signal is just a sinewave so moving it to 12 MHz is relatively easy. There are no frequency or amplitude modulation components present, so the 12 MHz signal is easily filtered and purified. To move the 5 MHz VFO to 12 MHz, mix it with a 7.00 MHz signal from a crystal oscillator. Think of the VFO mover as a primitive frequency synthesizer.
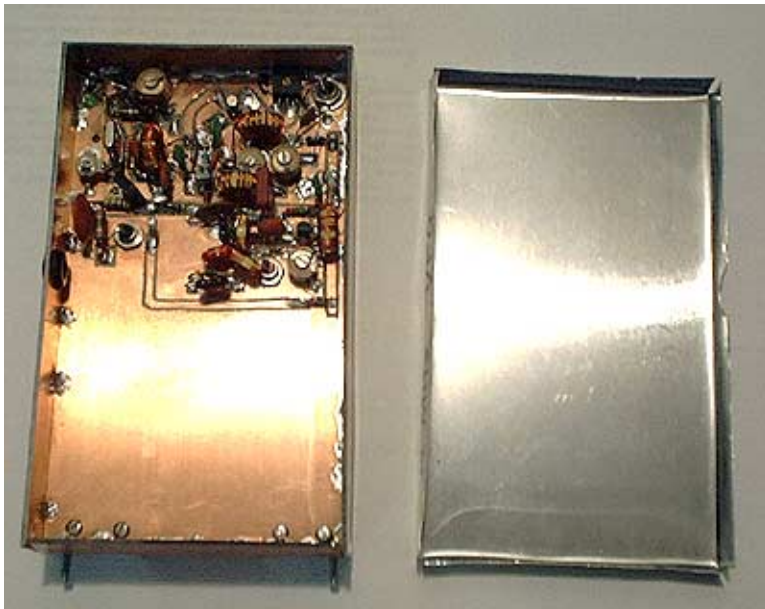
A 5 MHz to 12 MHz VFO converter

The frequency converter contains the same circuits I used in my HF QRP boards in which I used an 80 meter VFO to drive a CW signal on each HF band. I used the dual gate mixer because it was simpler than the bipolar transistor mixers I used in my first QRP boards. If you start with an 80 meter VFO, it can be combined with 8.5 MHz sinewave to give 12 MHz. You get the idea.

12 MHz VFO Converter for 15 Meters
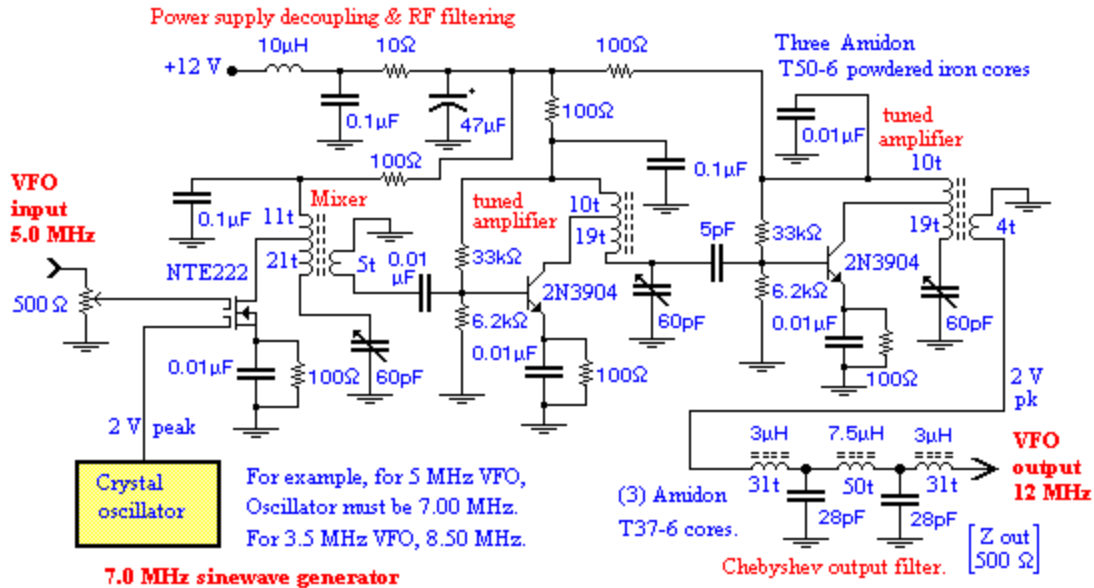
The VFO converter moves the 5 MHz VFO up to 12 MHz.

Before you build this, I suggest you look at the VFO movers for 17 meters and 10 meters shown later. I believe these newer VFO designs are more stable, more versatile and easier to adjust.


The 12 MHz VFO converter. I left room for a second VFO converter for some other band.

A Linear sideband "QRP" for 15 meters

Once you have generated a stable 12 MHz VFO, it needs to be mixed with the 9 MHz

sideband signal to get on 21 MHz. Using the same design as the 80 meter QRP shown earlier, now all you need are the two passive filters to go into the QRP module. The bandpass filter is the same design as before, but I used a 5 element high pass filter on the output to get rid of the signals below 15 meters that tend to appear when I'm not talking. The two filters are shown below.
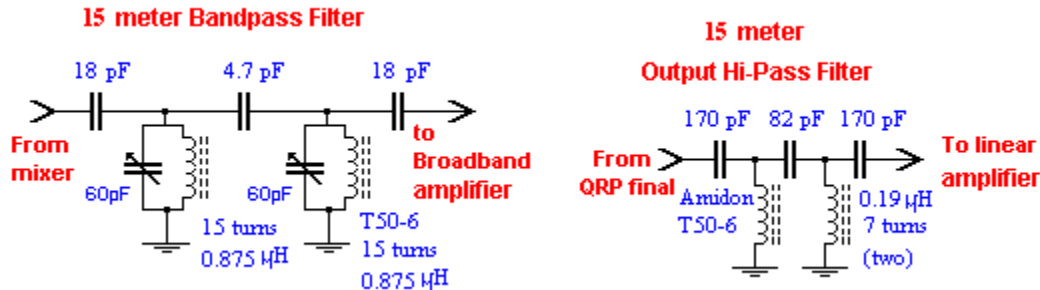
Notice that the output of the QRP driver described above has a *HIGH PASS* filter designed for 50 ohms that works best for driving a final amplifier. If you wish to run the driver "barefoot" and go on the air with just 5 watts peak, you'll also need a low pass filter, just like the ones you built for the CW QRP drivers. The most troublesome unwanted frequencies are the second harmonic of the 12 MHz VFO (24 MHz) and the second harmonic of the SSB generator, 18 MHz.

A 21 MHz Driver module.   The box lid is shown above the board.

Notice the "pigtail" power supply cable in the above driver. This was an invitation to RF interference. This cable acts like an antenna. I later modified the connector so that it is mounted on the bottom wall of the module. Now the module is plugged directly into the metal transmitter chassis with no exposed cable. RF feedback has not been a problem.

17 meters can be really tough

My first problem with 17 meters was that the sweep oscillator in my oscilloscope makes an 18 MHz signal that my receiver picks up right in the middle of the 17 meter band. However, 17 meters is also particularly troublesome when starting with a 9 MHz SSB generator. 18 MHz is the second harmonic of the 9 MHz SSB signal. Therefore the 17 meter frequency converter ill also amplify the second harmonic of the sideband signal. This means that, although there may be

a good signal on 17 meters where it is supposed to be, (for example, 18.120 MHz), there will also be a small sideband-like signal on 18.000 MHz. Of course the frequency deviation of the unwanted signal will have twice the audio frequency modulation. In the old days it was routine to move low frequency VFOs to high frequencies using frequency multiplier amplifiers. It is difficult to avoid building a multiplier/ amplifier here and it will be hard to get rid of unwanted 18 MHz signals with simple filters.

In addition, if you generate a 9.120 MHz VFO signal to add to the 9.000 MHz SSB to get 18.120 MHz, you will also be transmitting at the second harmonic of the 9 MHz VFO sinewave signal. That is, if the desired frequency is 18.120, there will also be another small sinewave transmitted on 18.240.

To be honest, the best way to get on 17 meters is to start over with a different SSB generator frequency, say 6.0 MHz. Then you can combine that with the same 12 meter VFO that you used for 15 meters. In other words, 12.15 MHz + 6 MHz = 18.15 MHz. With this approach you aren't using any 9 MHz frequency components and second-harmonic, out-of-band emissions are highly unlikely. I strongly recommend this approach.

**Pressing on with a 9 MHz SSB generator:**

27 MHz VFO converter for 17 meters
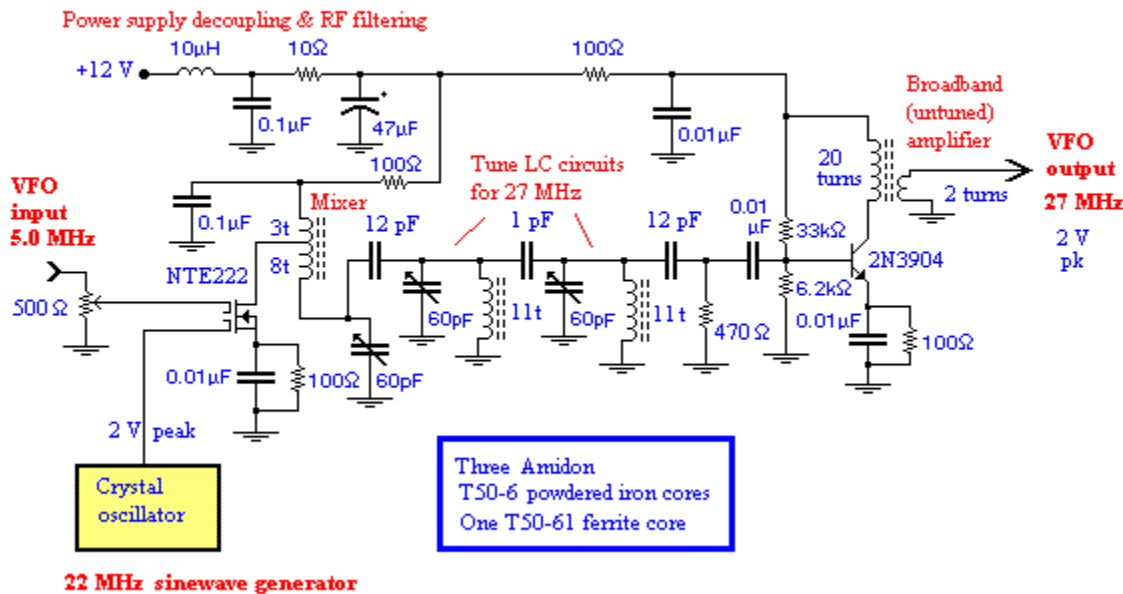
To minimize the 17 meters/ 9 MHz pitfalls described above, I moved my 5 MHz VFO to 27 MHz as shown above. This circuit consists of a 22 MHz crystal oscillator, the 5 MHz VFO and the mixer/ filter. To suppress the second harmonic of the SSB generator, I filtered the output of the 9 MHz SSB generator with a low pass filter before the mixer. This reduces the 2nd harmonic before it goes to the mixer. Finally, I <u>substracted</u> the 9 MHz SSB from 27 MHz to get 18 MHz. Notice that subtraction converts upper sideband to lower sideband and vice-versa. Whew!

The output of the 5 watt driver needs both a low pass to get rid of the 27 MHz artifact and

a high pass filter to avoid the low frequency "bursting" problem. Rather than choosing between high pass or low pass, I used a second 18 MHz bandpass filter that severely attenuates both 9 MHz <u>and</u> 27 MHz. This flat response bandpass filter is designed for 50 ohms. In contrast, the sharply tuned bandpass filter following the mixer is designed for high impedance, 500 ohms input and output. The 500 ohm bandpass filter is easier to build, but it can't handle any power and the impedance is wrong.
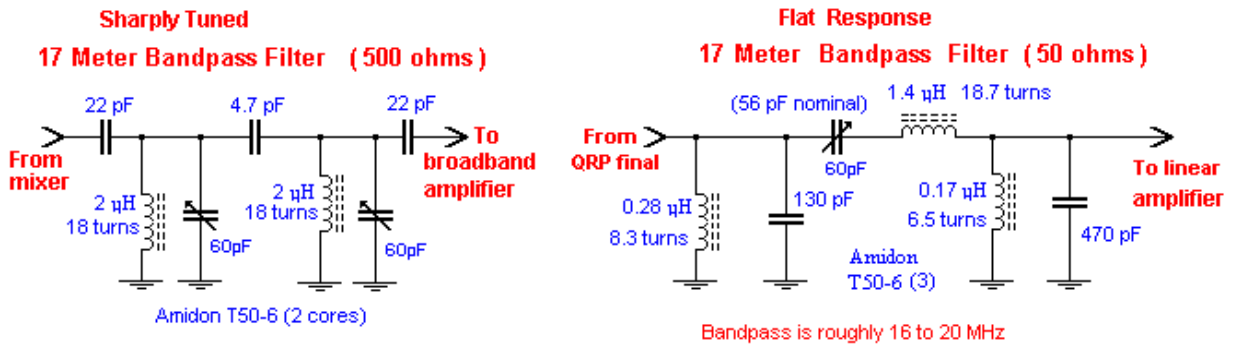
The filter on the right has a flat response from about 16 MHz to 20 MHz. In order to get the flat response, the three LC resonate circuits all have different values. And, of course, the three LCs interact, so a simple calculation wouldn't work anyway. I derived this circuit by trial and error using my Spice program. The component values must be rather precise otherwise the response has sharp peaks. Notice the fractional turns on the cores. These should help you be aware that wrapping the wire a tad more or less might make a difference. I found that making the smallest capacitor(s) variable was useful for final tune up. A few picofarads can make a big difference. Anyway, it was a struggle, but eventually it worked.

The driver for 12 and 17 meters is shown below. Notice how this module has its Molex power plug mounted on the bottom. It plugs directly into the transmitter chassis and avoids exposed wires. This QRP driver also has an aluminum cover to shield the circuitry from RF.
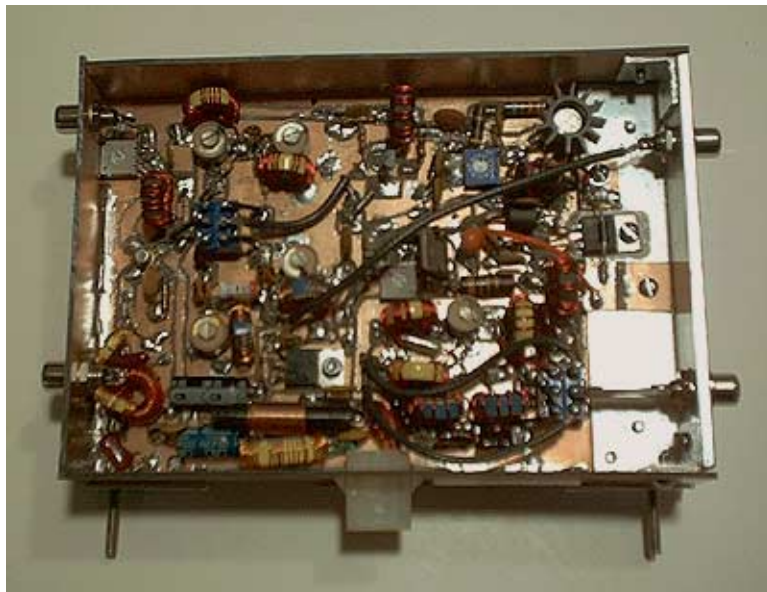
Even now that the 17 meter SSB is working, I still have to be careful. One morning I loaded up the antenna with the SSB generator set to CW. I got a big, fine sinewave and thought it was working perfectly. Then I looked at the counter, which read 18.003 MHz. Oops! How can that be? It turned out that the VFO cable to the driver was broken. With no VFO signal you will get a fine 17 Meter sinewave at twice your SSB generator frequency.

SSB on 10 meters

The tricky part about 10 meters is that it's 1.7 MHz wide, 28.0 MHz to 29.7 MHz. My VFO only tunes a range of 0.5 MHz. Therefore it takes 4 crystal PMOs to cover the whole band. I solved the problem with a quadruple frequency crystal oscillator. A 6 position rotary switch switches in the appropriate crystals for 28, 28.5, 29.0 and 29.5 MHz. My oscillator uses the other two switch positions to cover 12 meters and 40 meters. The crystals aren't switched directly, but rather, they are grounded one at a time by means of diodes that are biased *ON* by means of a 12 volt DC signal passed through the 4.7 K resistors. The advantage of this DC switching method is that the rotary switch can be far away from the oscillator up on the front panel.

Be sure to minimize the capacitances between the oscillator emitter and ground. All those crystals connected to the emitter will be affected by the extra capacitance. This will tend to pull each crystal frequency away from its nominal value. Too much capacitance and it may not oscillate at all.
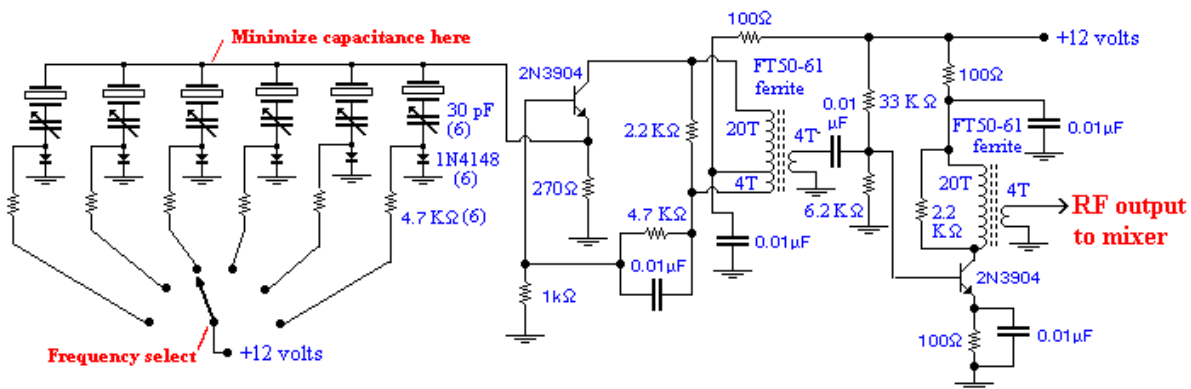
MULTI - CRYSTAL OSCILLATOR

The oscillator covers a wide range so the oscillator could not be tuned and had to be broadband. Therefore the oscillator frequency is entirely controlled by the crystal frequency. Obviously the particular crystal must spontaneously oscillate on that frequency and not a lower, primary frequency. And, because the oscillator stage isn't tuned, its signal output is tiny, tenths of a volt. Consequently, I had to pass the oscillator signal through a broadband amplifier to make it large enough, about 2 volts p-p, to be sent to the mixer to be mixed with the 5 MHz VFO.

After the mixer, each VFO signal must be filtered to select the desired frequency component. My 6 position rotary switch has a second section that allowed me to switch in a filter for each frequency. I found that just two tuned filters could cover the whole 10 meter band. I didn't need 4 separate filters after all.

MULTIPLE FREQUENCY MIXER
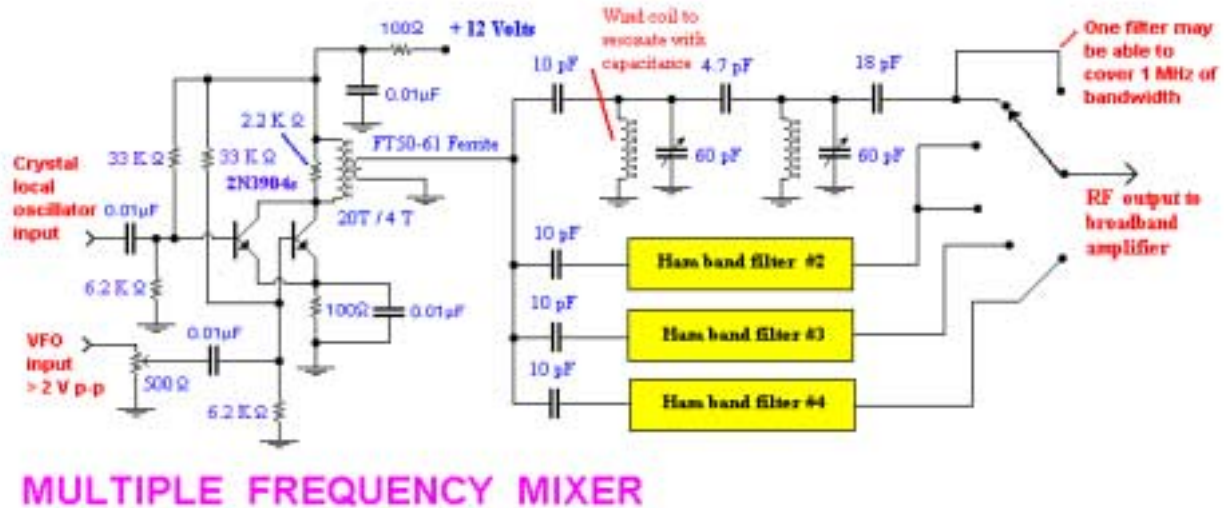
The tuned filters are high impedance and connected to the mixer with 10 pF capacitors. Because all the filters are connected to a low impedance transformer winding, the mixer can drive all of them at once. As shown the total load is only 40 pF. The rotary switch on the right then picks out the desired filter output. Another broadband amplifier amplifies the filter output before it goes to the SSB QRP driver where it is combined with the 9 MHz SSB signal. By the way, I tried to use the switching-by-grounded-diode trick to switch filters but that idea worked poorly.

Checking out the QRP module

You will have to experiment with how to listen to your sideband signal at a signal level that simulates what it would sound like if you were receiving it off the air. I run my QRP into a 50 ohm dummy load.   Then I disconnect my receiver from the antenna and leave the antenna coax from the receiver lying on the bench a few feet from the sideband generator. If that's not strong enough, I clip a test lead to the transmitter ground, then clip the other end to the center conductor of the receiver antenna coax connector.

I start by feeding a 9 MHz sinewave (CW) signal into my QRP board and then tune the filters to produce the largest, stable sinewave output into the dummy load. I monitor the frequency with a counter to be sure the VFO is controlling the frequency properly over the entire ham band. I adjust the VFO input level to produce the maximum output signal. However I just use the minimum 5 MHz VFO level that achieves this. When you are *NOT* talking, excess VFO will tend to induce signals on unwanted frequencies. I increase the DC bias to the output transistor until the transistor draws about 20 milliamperes DC more than it does with the bias set to minimum.

After the CW mode is working properly, I switch to SSB and use an audio signal injected into the "test input" of the generator. I use speech from a talk radio station as supplied by a little Walkman radio. If you're lucky, the speech should sound pretty good in your ham receiver. If it doesn't, decrease the drive to the last two stages of the QRP using the 500 ohm pot. You may also need to reduce the number of secondary turns on the transformer feeding the output transistor. For example, instead of 3 turns, 2 turns or even one turn may be optimum for your particular QRP board.

Driving a linear amplifier

A QRP sideband transmitter is just fine for communication around town. One or two watts are plenty for talking a few miles. But unless you have a great antenna and good conditions, you won't talk to many stations with just a few watts. For distant stations a linear amplifier will be a big improvement. Building a 50 watt linear is explained in chapter 12. If you are going to have trouble with RF feedback and insufficient power supply decoupling, a big linear amplifier will bring out these troubles. RF from my antenna coupler feeds back to my Walkman radio and (usually) makes that speech source impractical for testing. I usually listen to the receiver with headphones with the receiver turned way, way down. Don't deafen yourself! When I speak into the microphone, my voice should sound clear, as though I were talking on a public address system. It should not sound rough and gravelly.

Watch the output waveform across the dummy load with your scope. The waveform should look just like it did coming out of the 9MHz generator. You will probably find that speech sounds terrible at first. It may just be bursting, sputtering sounds.

Adjusting DC bias to the final

You'll have to adjust the DC bias to the final amplifier for optimum speech quality. As you increase the bias current, watch the DC current drawn by the entire transmitter. It should not be more than about 2 amperes when you are not talking. As you talk, the current should jump up to 6 to 12 amperes, depending on the drive levels, the band you're on, etc. As always, the higher the frequency, the more difficult it will be to obtain clear speech. ***DC bias that is adequate for one band, may not be enough for another.*** That little pearl of wisdom cost me days of frustration.

If the speech still sounds bad, RF chokes and RC decoupling filters for power leads to each module can help the problem. Also, filter the DC power line entering the transmitter chassis and the remote "mute" line going to the receiver. If troubles persist, filter all the wires entering your transmitter.

Finally, SSB works best with a good antenna

A high gain, beam antenna is highly desirable. As you listen to the other SSB stations, you'll find that most strong signals come from a beam antenna. Directional antennas improve the signal by focusing most of the RF energy toward the guy you are talking to. Think of beam antennas as being comparable to the mirror reflector in a flashlight. The mirror concentrates the energy in one direction only.

In conclusion

My first real sideband contact was with W9WFE, a fellow about a thousand miles away. When I explained to him that my rig was homebrew, he said, "Well, it certainly sounds like sideband to me. It seems to work!" Sweet success.

My sideband transmitters are still in the experimental category. You will find that it takes a great deal of tweaking and fussing to get SSB tuned so it sounds good and doesn't radiate on unplanned frequencies. You won't believe how many diseases your SSB transmitter will invent for you to conquer! Sideband is not a project for impatient people.

Shortly after I got my sideband working, I tried to arrange a schedule with Doug,

KD6DCO in California. We failed to make contact. In that weak moment I thought I should stop messing around with homemade junk and buy a modern transmitter. No, wait. If I want to communicate with Doug, all I have to do is write him an e-mail or call him on the phone. I'm already on-line and long distance calls are cheap. If I wanted to use radio, I could even talk with him by cellphone. No, it was back to the drawing board for me.

And after some major redesign, my next schedule with Doug was successful, but my signal was pretty weak out in California. That's OK. I have to keep reminding myself that, so long as my station falls short of what is technically possible, my hobby continues. Woe to me if I ever finish. Long live homebrew!!

CRYSTAL SETS TO SIDEBAND
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Chapter 16
ANCIENT MODULATION
And other topics

When I got back into ham radio 5 years ago, my ham friends told me that AM was extinct. I had the impression that SSB was the only mode of HF phone permitted. Later I learned that AM isn't actually illegal and there are a few diehards using AM on the 75 and 10 meter phone bands. I've also heard AM stations on 15 and 160 meters. In short, you might find a use for it. Besides, it's an interesting challenge to AM-modulate a transistorized transmitter.

Homebuilt AM

Back in the vacuum tube days many of us built our own AM transmitters. My first AM transmitter was a Heathkit DX-20. That was a 50 watt, CW, kit-built, vacuum tube transmitter to which I added a homebuilt AM modulator. Unlike SSB, AM could be added onto an existing CW transmitter. Rather than generate a low power AM signal and then amplify it with a linear amplifier, in the old days the usual method was to AM-modulate the final amplifier of the CW transmitter.
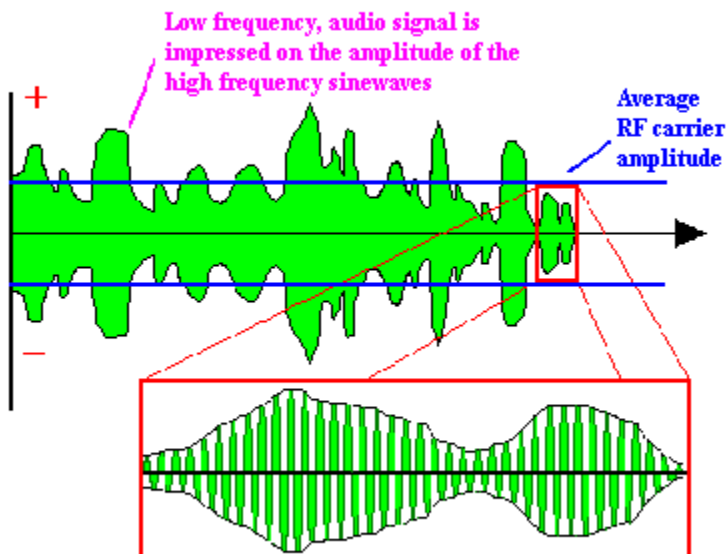

On an oscilloscope, the hallmark of AM is that, when you are **not** speaking, the RF carrier wave runs continuously at an average power. That is, in AM the highest peak power and zero power only occur at the very highest voice peaks. Although I could see these transient peaks on the scope, when I tried to catch one with a storage scope, they are statistically rare and I

couldn't catch a zero power level. The waveform below was typical of what I saw.
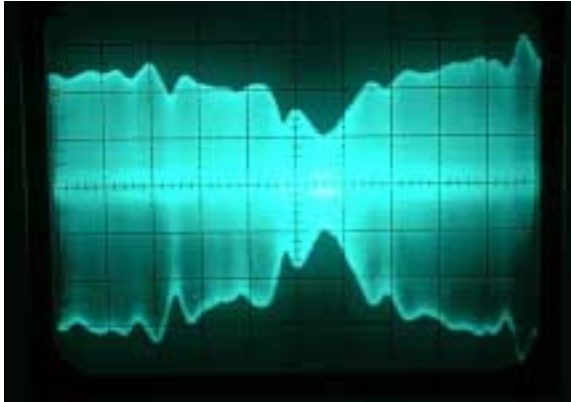
In contrast to AM, the RF output amplitude in SSB is always **zero** whenever you aren't talking. Notice in the SSB oscilloscope picture below that each RF blip representing the audio starts from zero. It doen't start from a halfway, continuous carrier level.

Plate, screen and cathode modulators

Formerly, there were three common methods of AM modulation. The "Cadillac" method was to use a "plate modulator transformer." The transformer impressed the audio signal onto the DC supply current. That is, as you talked, the DC input current rose and fell around the level of what it would be for a CW sinewave. For a 100 watt transmitter, this transformer was about the size of a softball, weighed a ton and cost like crazy. The transformer was driven with a big audio amplifier that put out at least 50% of the CW carrier power. In other words, the plate modulator was nearly as large and expensive as the rest of the transmitter.

"PLATE" OR "COLLECTOR" MODULATOR
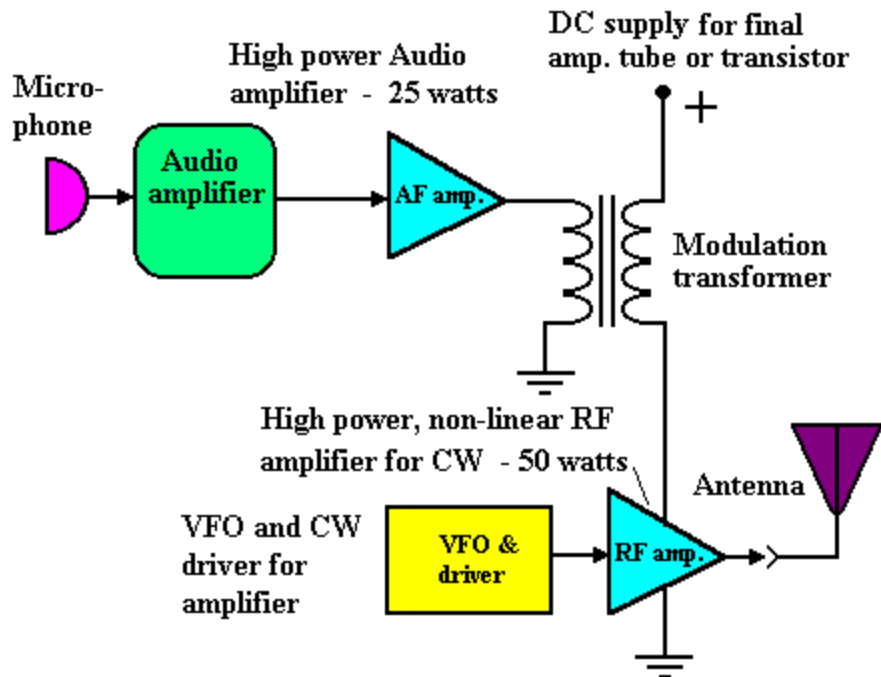
The "Ford" and "Yugo" approaches to AM modulation were to modulate the gain of the final amplifier tube by impressing the audio on the screen or cathode, respectively. Screen modulators usually sounded pretty good. Cathode modulation, sometimes called Heizing modulation, tended to produce "down modulation" which meant that power decreased whenever you talked. It sounded OK, but was inefficient use of RF power output. These methods required less audio power than plate modulation and were easy for a high school kid to afford and build.

Modern AM construction

Now forward to 2003. Most modern SSB transceivers have the capability to generate AM modulation. To get into this mode, you read your manual for 20 minutes, bring up menu #26, push button numbers 14, 7 and 12 and you're done. That wasn't hard, I guess. But did you learn anything?

Let's suppose that you're a homebrew fanatic and wish to scratchbuild your own AM rig using transistors. Is that hard? Hmmmmm. Well, for one thing, transistors don't have cathodes and screen grids. Emitters are analogous to cathodes but, as explained above, cathode modulation wasn't all that great. Another difference between tubes and transistors is that, for the same power levels, *the final amplifier transistor has DC currents about 50 times larger.* So for DC supply modulation, you must impress 10 or 15 ampere audio signals onto the 12 volt DC power supply line. The modulation transformer will have to be just as large but it will need a super low impedance output winding.

Modulating a transistorized 50 watt CW transmitter

I have a 25-watt, "plate modulator" transformer from the 1960's designed for use with a transistorized modulator. Since it had low impedance primary windings, I thought I could "run it

backward" and supply enough audio current drive to build an AM "collector modulator." I used an old 10 watt tube hi-fi amplifier and kludged it together. Sure enough, even with music it sounded great when I broadcast into a dummy load. However, it only modulated about 30% of the carrier amplitude. That is, I was wasting most of my RF power. I could have built a 25 watt audio amplifier, but I had a more modern idea. Why not use my MOSFET CW keyer as an audio modulator?
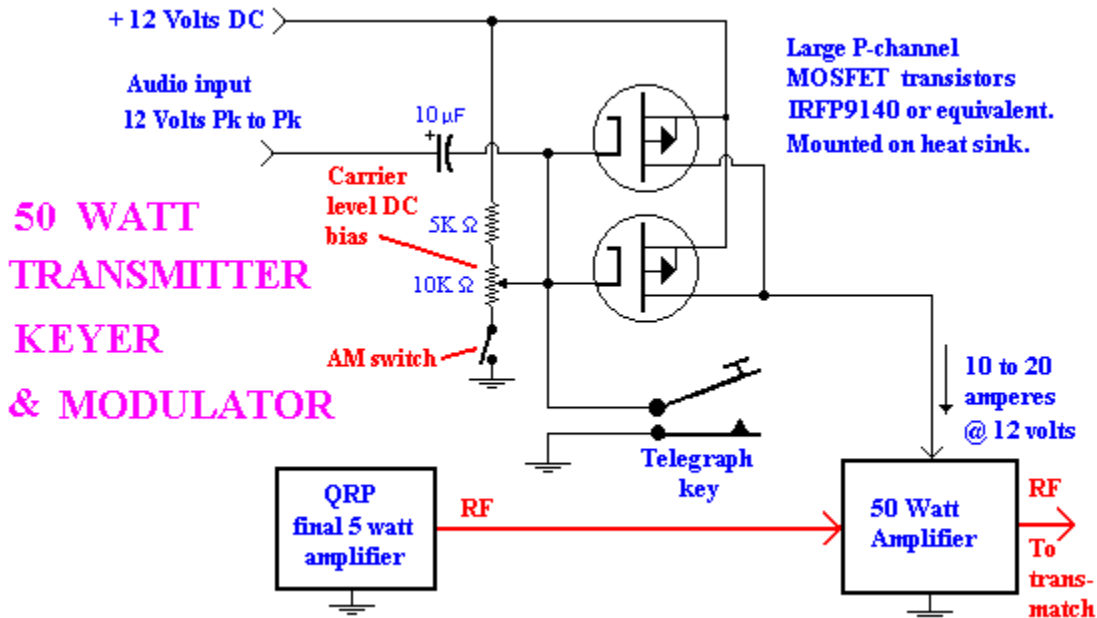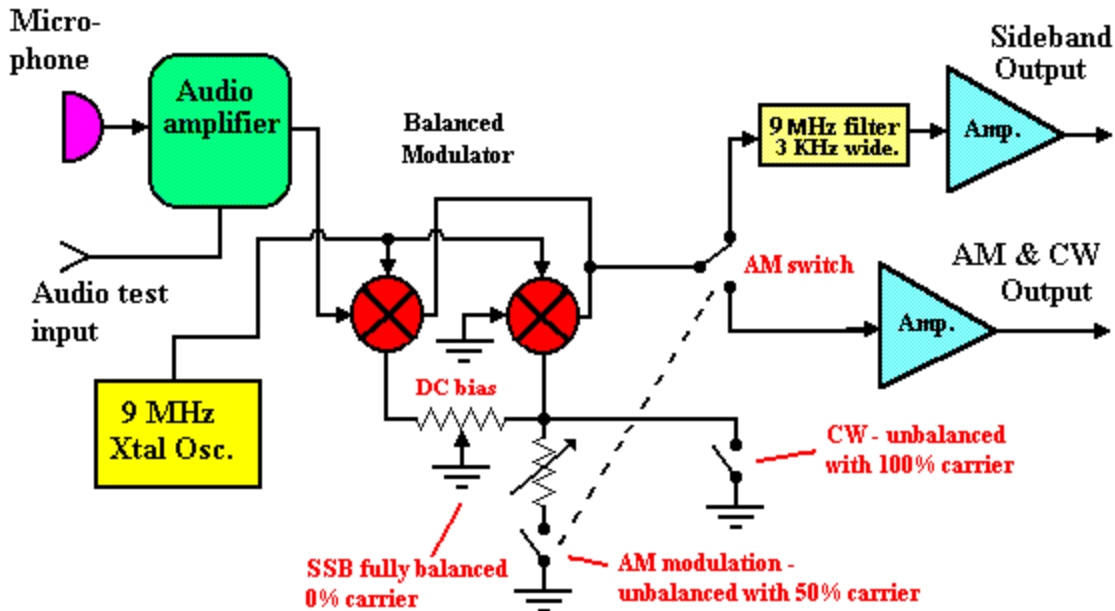

The above keyer was originally designed to turn the DC power to my final on and off with a telegraph key. My AM modulation scheme was to turn the MOSFETs half-on with a simple DC potentiometer, then modulate the gates with a 12 volt P-P audio signal. This simple scheme worked pretty well, but it was extremely tweaky. It was easy to have too much bias or too little and too much modulation or too little. The problem is that the gate voltage versus drain current transfer characteristic is rather non-linear. With feedback and a more sophisticated drive circuit, I believe this method can be made to work well.

The SSB approach to AM

At this point in my R&D, I had not yet succeeded in building a practical SSB transmitter. So rather than invest more time on "obsolete modulation," I went back to work on SSB. I figured that, if I ever got the SSB working, it would be easy to downgrade my SSB generator to AM. This turned out to be true. I tried out several variations. However, *the method that was simplest and worked the best was bypassing the SSB crystal filter with a switch and unbalancing the balanced modulator circuit using a circuit that resembles the CW switch.*

BALANCED MODULATOR

Micro-phone

Audio amplifier

Balanced Modulator

Audio test input

9 MHz Xtal Osc.

DC bias

9 MHz filter 3 KHz wide.

Sideband Output

Amp.

AM switch

AM & CW Output

Amp.

CW - unbalanced with 100% carrier

SSB fully balanced 0% carrier

AM modulation - unbalanced with 50% carrier

AM resembles CW in that a sinewave carrier is generated continuously. However, the same "unbalance" switch used as a SSB/ CW mode switch can't be used for AM. When modulation is applied, the instantaneous power must rise above and below the no-speech carrier level. Ideal AM modulation drives the carrier alternately between zero and 200% of the carrier level. Because there is only so much signal amplitude to work with, *the carrier must be set to 50% of the level used for CW.* This gives the range available to modulate +/- 100%. A separate AM mode, double-pole switch bypasses the SSB filter and unbalances the modulator 50%. The AM switch is in series with an adjustable 5K ohm resistor that unbalances the modulator just enough to produce the 50% carrier.

The audio gain pot and your voice level should be adjusted to produce voice peaks twice the carrier level. Compared to SSB, you'll find that AM modulation is quite HI-FI. While testing the generator and transmitter on an 80 meter dummy load, music retransmitted from a walkman was quite acceptable. In contrast, when using SSB, speech sounds OK, but music is really terrible. The principle difference is that the sideband filter greatly attenuates frequencies below 300 Hz whereas AM preserves the low frequencies. In contrast, speech transmitted on SSB can sound like the person's normal voice, but music on SSB is truly terrible. It's just as well. The last I heard, ham music is still illegal.

COMPRESSION BY ACCIDENT
Or, sometimes we get lucky

A modern single sideband generator processes the amplified audio from the microphone before the audio is fed into the balanced modulator. This "*compression*" process attempts to equalize the voice peaks so that as many voice elements as possible are transmitted with full Peak-Envelope-Power. Without this process, most of what you have to say will be transmitted

with far less than the nominal peak power. When most of your sentences are reduced to QRP muttering, your intelligibility suffers.
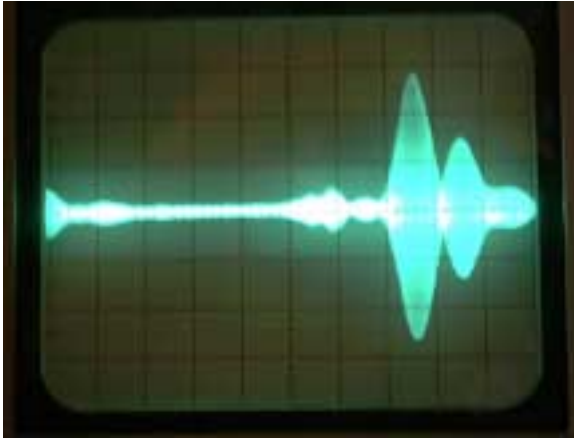
In other words, without compression, the single sideband RF envelope of a spoken word is close to zero most of the time. It would look something like the waveform shown above. A compressor circuit attempts to leave the peaks alone while proportionally amplifying the subtle, low voltage waveform wiggles near the horizontal axis. I guess the latest transceivers use digital processing to accomplish this feat. However, 15 years ago a compressor circuit usually performed the following tasks:

1. It amplified the whole audio waveform.

2. It clipped off the highest audio peaks.

3. And finally, it filtered the clipped audio with a 300 Hz to 3KHz bandpass filter.

After compression, the same RF sideband waveform might look something like the above picture. The idea is that all the tiny stuff near zero has been expanded. (These waveforms aren't actual before-and-after pix, but they illustrate the principle.) After transmission some modern receivers "re- expand" the waveform to try to restore the original waveform. This entire process is called "***companding.''*** However, for me, building a homebrew SSB that worked at all seemed plenty difficult. Therefore I didn't worry about secondary issues like "companding."

A crystal filter does more than clip the unwanted sideband

On the other hand, I was afraid my RF signal might be too wide. So, because it was relatively easy, I built a 3 KHz audio low pass filter. It turned out that I didn't need it. Once I had passed the 9.000 MHz RF double sideband signal through the crystal filter to cleave off the unwanted sideband, I found that the filter had also removed virtually everything above 3 KHz anyway. Also, when I adjusted the original sinewave frequency to get rid of every trace of the carrier, I found the filter had also clipped off the lower 300 Hz of the audio. It's remarkable how normal a voice can sound without the lower 300 Hz. Music sounds awful, but voices are quite lifelike. In any case the crystal filter accomplished the same filtering that the ARRL Handbook specified for the audio compressor. Interesting!
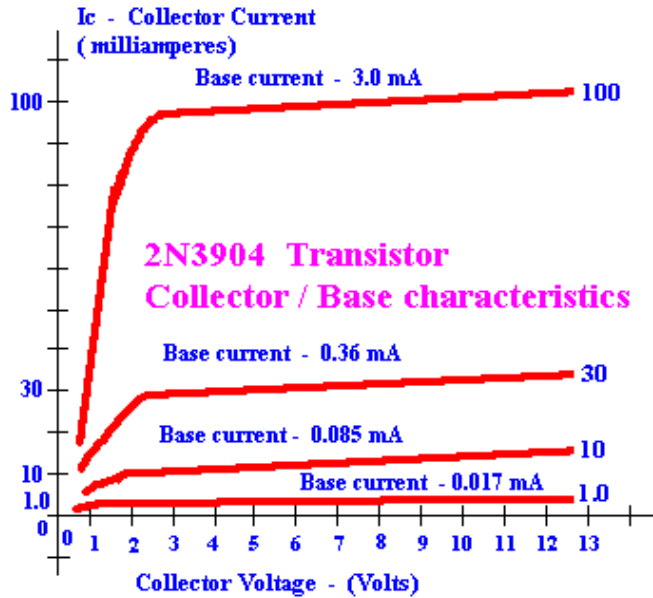
An SSB transmitter has several linear amps in series

After the SSB RF signal has been generated at a milliwatt level, the signal must be amplified and converted to the desired hamband. Including the mixer, this meant that my SSB signal had to pass through 5 stages of amplification to get to 100 watts peak. Each linear stage is forward biased so that even tiny signals will be amplified. Without this bias, all you hear are the voice peaks. In other words, an unbiased amplifier cuts off all the little audio signals a compressor tries to accentuate. I knew that the linearity of all these stages in series couldn't possibly be "perfectly linear." But since it sounded good, I didn't worry about linearity.

**Where has all the AM modulation gone?**

I didn't realize that my RF amplifiers were significantly non-linear until I added an Amplitude Modulator mode to my SSB generator. I listened to my little 9 MHz AM generator in the receiver and it sounded fine and looked like 100% modulation on the scope. Next I fed the signal from the 9 MHz AM generator into my 80 meter "linear" QRP module which put out about 3 watts on 80 meters. Yes, it worked, but the signal was nearly all carrier. Instead of 100% modulation, on 80 meters I only had about 5% modulation. Where did that huge carrier signal come from? What happened to my modulation?

Transistors aren't linear

Ic - Collector Current
(milliamperes)

**2N3904 Transistor
Collector / Base characteristics**

Collector Voltage - (Volts)

"Linear" implies that big signals will be amplified just as much as the small ones. However, if the raw output of the transistor covers most of the collector operating range, then small signals will be amplified more than big ones. I have two 2N3904 transistors in my chain of amplifiers, so the Base/ Collector current characteristics for this transistor are shown above. Notice that one milliampere of collector current requires 0.017 milliamperes base current. But to get 10 milliamperes of collector current takes 0.085 milliamperes. That's 5 times more base current to get 10 times more collector current.   But if you want 100 milliamperes of collector current, you need 3.0 milliamperes of base current. That's an additional 35 times more base current. Sure looks non-linear to me. ***BEHOLD, A NON-LINEAR COMPRESSOR!***

Transistor Amplifier
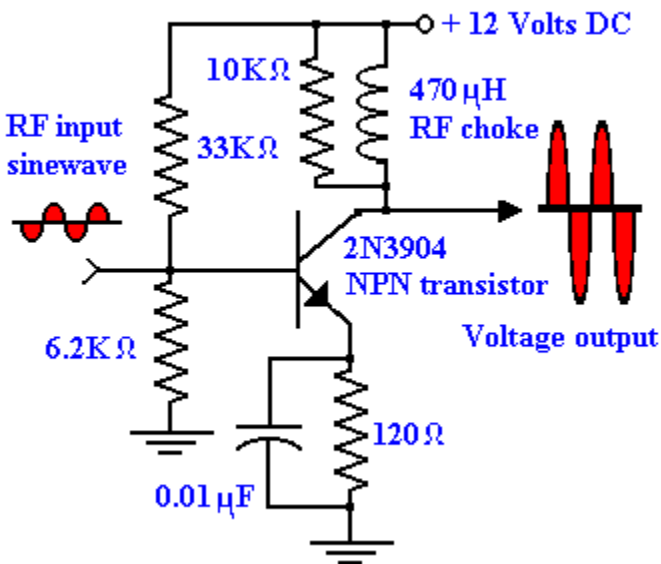
The "linear" amplifier above illustrates an accidental compressor circuit. The 33K resistor biases the transistor ON so that even tiny RF signals will be amplified. (By the way, the 10K resistor across the inductor keeps the amplifier from oscillating when there is no input signal.) The main reason for the 120 ohm resistor is to provide negative DC feedback to make the amplifier thermally stable. Without the emitter resistor, the amplifier works, but the transistor runs extremely hot. The emitter resistor also makes the amplifier more linear than the transistor characteristic would suggest because the feedback restricts the transistor to a narrower range of operation. However, 120 ohms feedback makes it a long way from linear. 470 ohms is much better, but still far from perfect.

Oh, well, why fight it? To fix my AM mode, I reduced the imbalance of the balanced modulator to just a few percent of voice peaks. This gives me roughly 50% carrier by the time it arrives at the final amplifier. And as for the SSB, it already works well. Apparently I had a pretty darn good compression system all along and I didn't even know it. Imagine! A happy accident!   They sure don't happen often.

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