

CRYSTAL SETS TO SIDEBAND

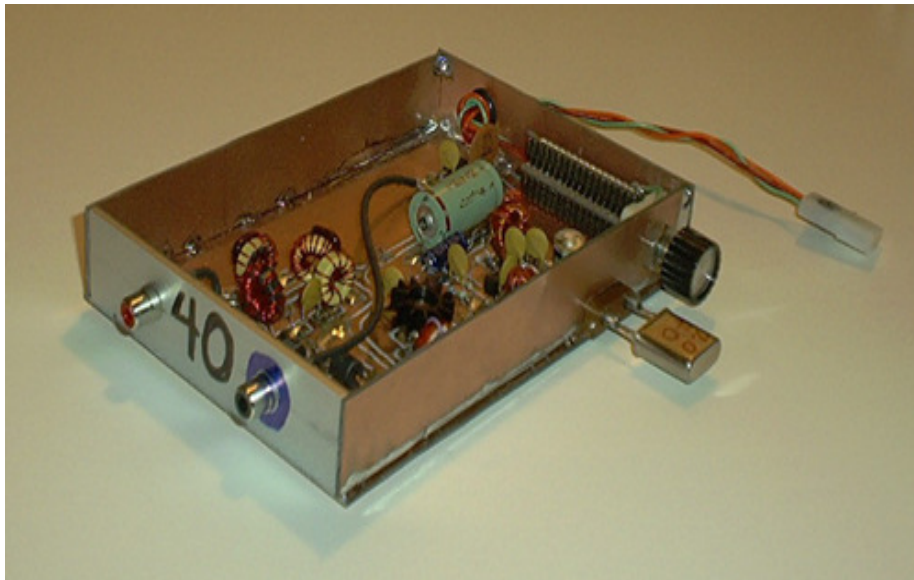
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Chapter 6

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.) On the other hand, chapter 7 describes building a simple, 5-transistor 40 meter receiver that 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.



The QRP transmitter shown on the left is designed exclusively for 40 meters, (7.000 to 7.300 MHz.) The twelve volt power supply comes in through the pig-tail wire 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.

A 40 meter QRP module.

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 over a range of about 3 KHz. As we shall explain in chapter 10, a variable frequency VFO that can cover the entire band is hard to build. I don't recommend starting out with a VFO. You need success, not frustration.

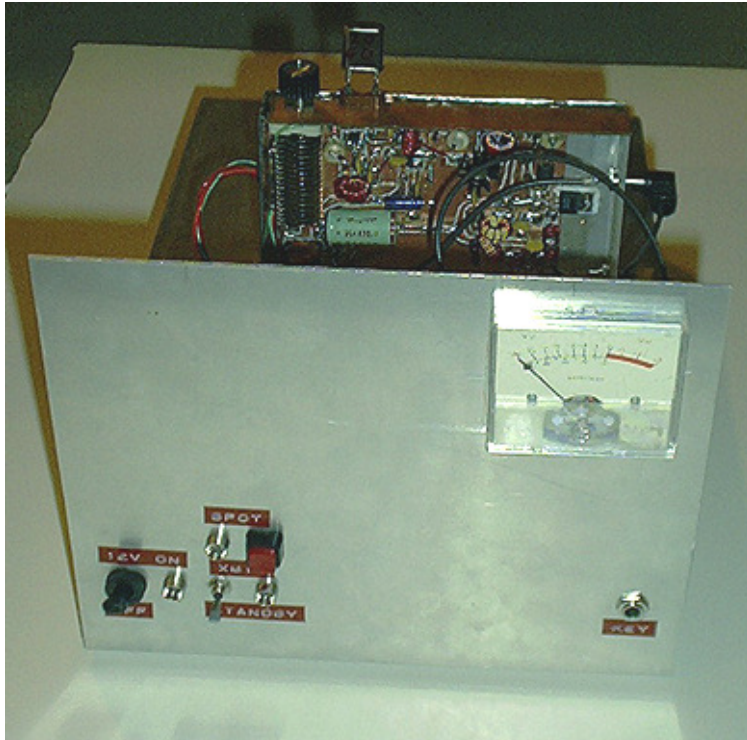
Start simple

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 very 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

Transmitter mainframe

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 skinny 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 printed circuit boards or the transmitter simply won't work.

For example, once I connected an output lead from a 21 MHz (15 meter band) 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 input 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 making 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 layers of thin copper bonded to both sides of a 1/16th inch fiberglass sheet. I only solder components onto the surface of one side. The solid surface of grounded copper on the opposite side provides distributed capacitance over the whole circuit. I believe this gives extra stability and works as a grounded shield to prevent radiating signals to whatever circuits might be adjacent to the bottom of the board.

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 distributed inductance that rings with the distributed capacitance between the center wire and the outside insulation. In other words, a coaxial cable is a distributed LC circuit and does not dissipate voltage and energy as you would otherwise expect. In fact, the energy losses 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 sheet 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-sided 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.

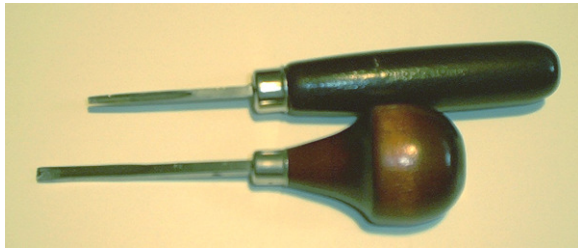
Etched circuit boards

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.

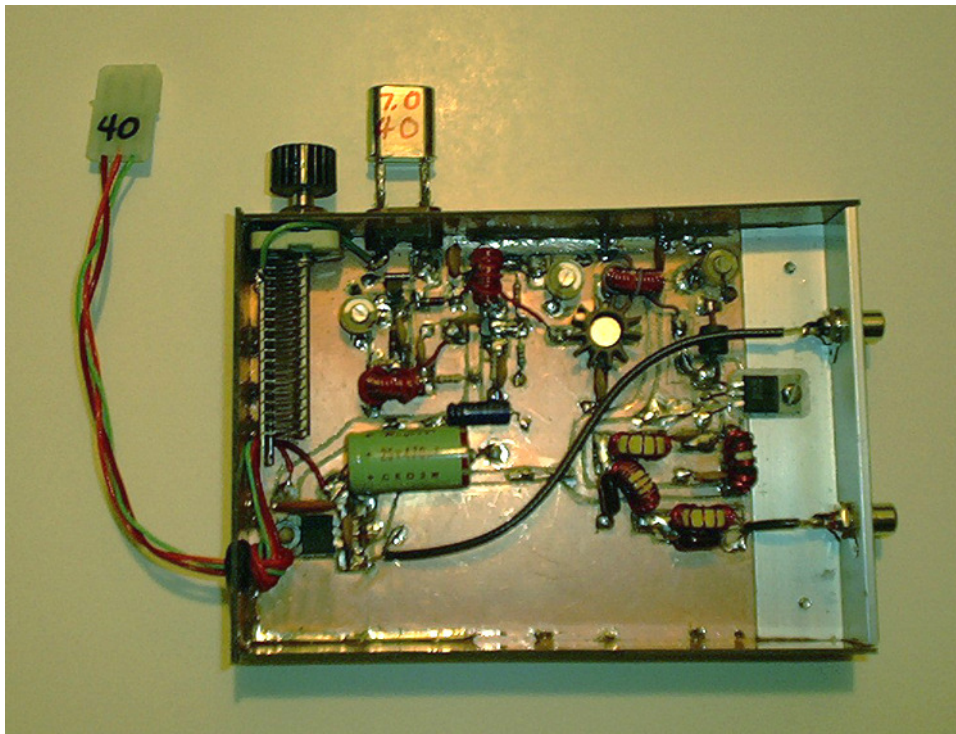
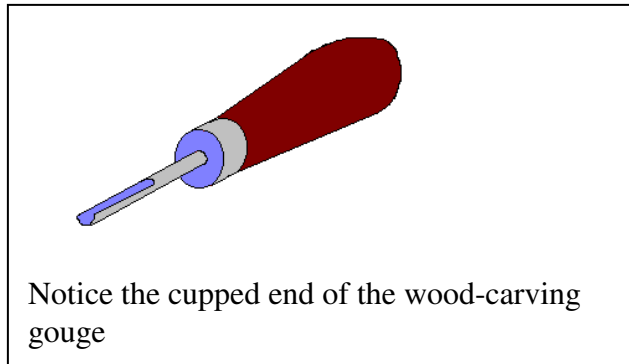
Unfortunately, when you use a circuit layout from an ARRL handbook or QEX magazine, you are making the assumption that you can buy all the exact parts the author used. Good luck! The parts you can actually buy may not fit on the board. I found that the worst limitation of etched PC boards was that I 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 had no room for it. *The key to success in homebuilding is building AND TESTING one small circuit 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, about 0.5 to 3 mm across. I have several, but my favorite is about 1 mm across. I got it from the Traditional Woodworker Co., (www.traditionalwoodworker.com)



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 as 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 your 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.

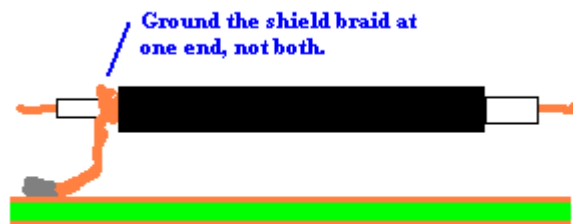
PC boards for integrated circuits

A wood-carving gouge works fine for RF circuits made from discrete transistors, but is impractical for integrated circuits. For through-hole ICs I use 0.1 inch center punch-boards and wire-wrap methods. There is an example of this construction method in chapter 7. Another method of working with integrated circuits is to etch (or buy) tiny boards for mounting 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 especially 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 mainframe 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 must switch the 12 volt power MOSFET transistor on an off, but unfortunately it was located 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.



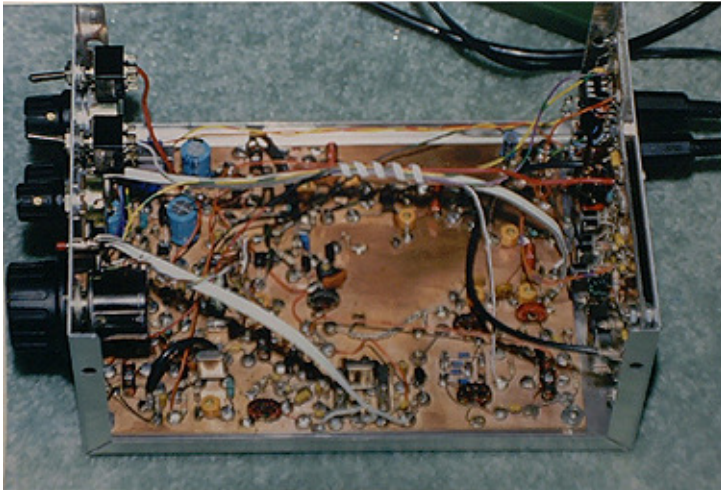
COAX JUMPER CABLE

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 turn of a winding on a transformer. This current loop may 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

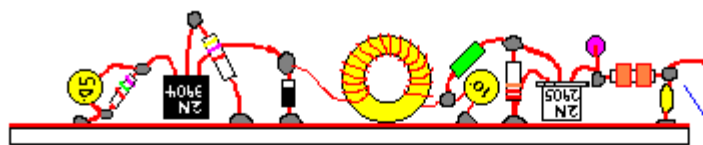
onto the PC board using superglue to form contact nodes and traces. An advantage of this method over gouged board is that the ground sheet is unbroken. That is, when you solder a component lead to ground, you will know that the entire PC board is "ground," and not just areas or strips of "ground." A 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 on the left 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. We communicated easily across 1,400 miles so apparently it works very well.

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 "deceased insects" 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.



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

Channels carved out to make circuit traces.

“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 watts output. Since the stage was a success, I rebuilt it using gouged board construction. Using carved traces, the same circuit and components 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.” The antenna relay shown in chapter 9 uses this technique for the transmit circuit.

Boxes out of PC boards

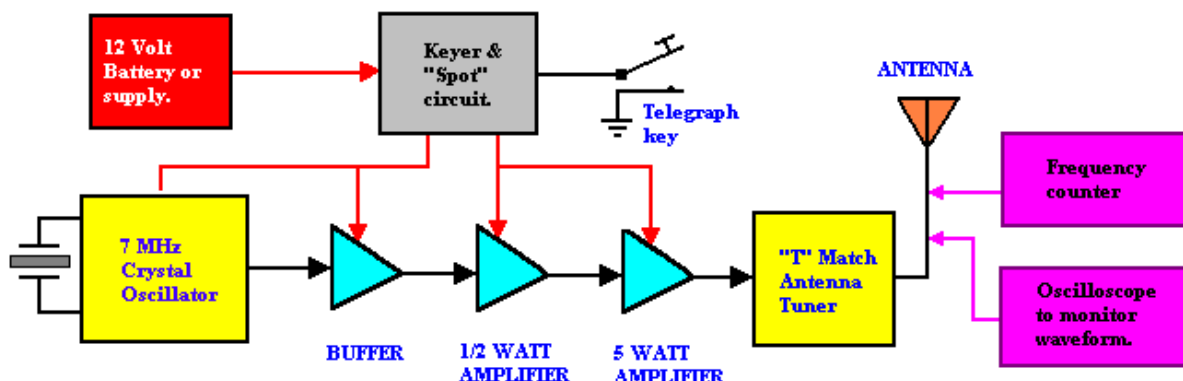
It’s often necessary to shield circuit boards from other circuits. That is, the circuit needs to be completely enclosed in a metal box so that it does not radiate or receive radio signals to or from nearby circuit boards. A gouged board circuit can be shielded by building up the edges into a box. Solder 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 just needs to be snug enough to hold it in place. This technique is essential for receivers and SSB transmitters as illustrated in chapters 13 and 15.

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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 AC plug in power supply for your QRP is fairly easy. But later, when you get into high power amplifiers needing 100 or 200 watts, building high power AC line-powered supplies is much harder and you may want to return to a battery. Power supplies are discussed in chapter 8.

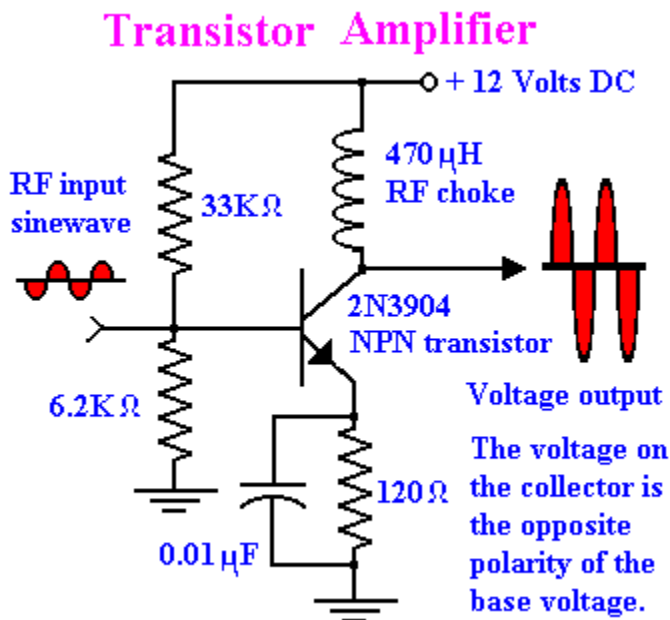
The oscillator, buffer, and amplifiers will be discussed next. The keyer circuit is discussed at the end of this chapter. A receiver is not shown above and is assumed to use a separate antenna. If you hook your antenna to the transmitter and receiver simultaneously, the receiver is likely to be damaged. Suitable antennas are discussed in chapter 5. Accessories like the telegraph key 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.



What is a linear amplifier?

The circuit at the left 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 silicon 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 a silicon 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 *LESS ON*. 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 difference drops, the current flowing into the base decreases, thereby turning the transistor a bit less on. So long as this resistor isn’t too large, it just serves to bias the transistor and make it more stable with temperature changes.

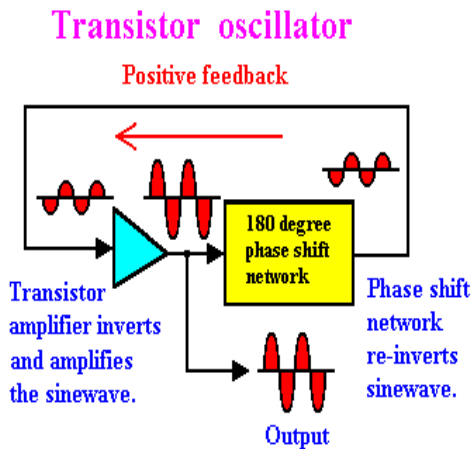
If you replace the 120 ohm resistor with a short circuit, you’ll find that the amplifier still works, but the transistor will run hot to the touch. The **6.2K ohm resistor** makes sure that the charge in the base of the transistor always has a way to leave and turn off the transistor. The 6.2K resistor 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 significantly. For a capacitor this large, the fractions of a microsecond that the RF voltage oscillates up and down are not important. 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

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 an ear-splitting, screaming oscillation. Electronic oscillators work by feeding the output back into the input.

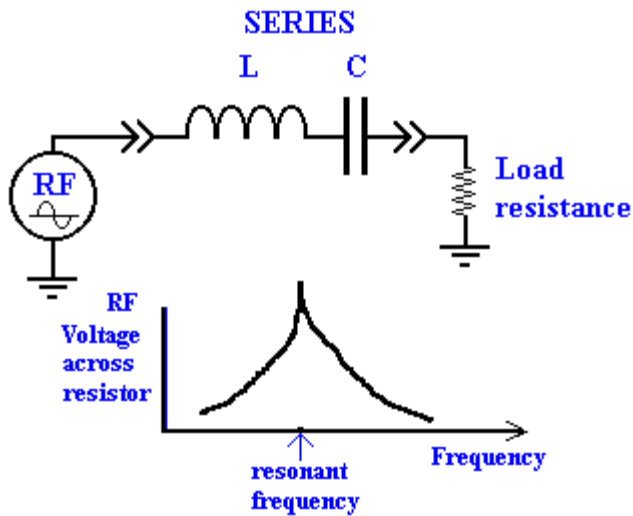


Notice that a one-stage transistor amplifier inverts the polarity of the input waveform. Rising voltage on the base causes the voltage on the collector to fall. In theory at least, if you were to feed the output of this amplifier back to the base circuit, the opposite polarity of the output would cancel out any signal that begins

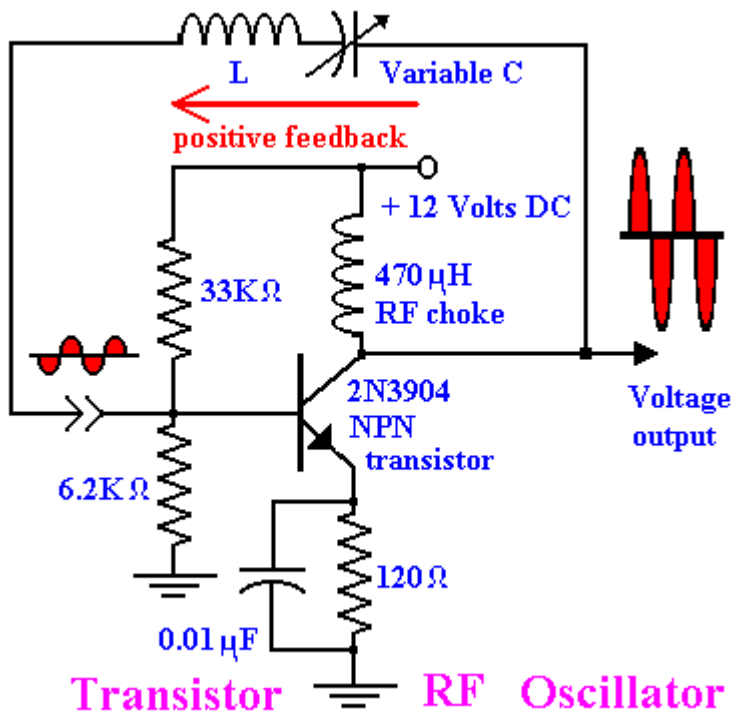
to form on the input. For this reason, if you wish to make an oscillator, the waveform needs to be turned up side down or *phase inverted* before the feedback is introduced to the transistor base.

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 L-C circuit will attenuate every frequency except its resonant frequency. A series L-C 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.



A working transistor oscillator

The circuit on the left 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" its own tiny random noise output and the oscillation never begins. That is, the random noise is way below the 0.6 volt threshold. Restore the 33K and the oscillation will restart immediately.

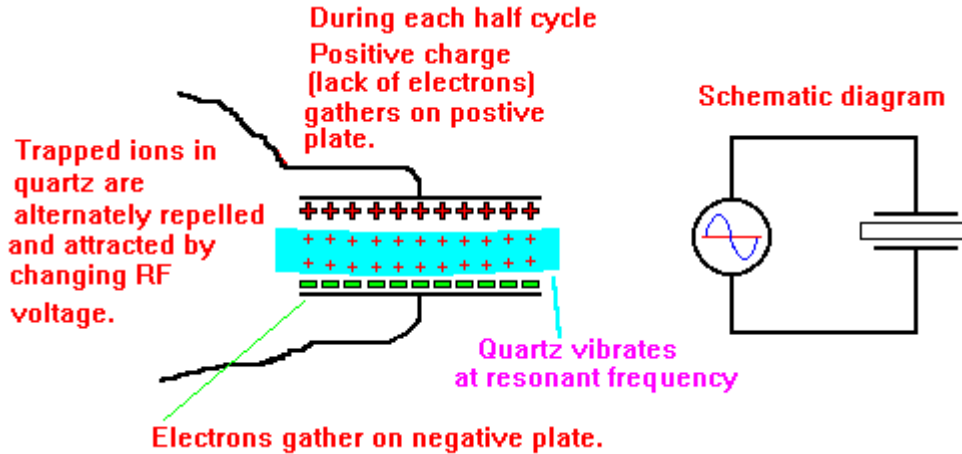
A non-linear amplifier with no forward bias is called a *Class C amplifier*. They are useful for amplifying CW signals that are greater than the forward base drop. That is, the drive for a Class C amplifier must be greater than 0.6 volt, otherwise there will be no output. Class C is not useful for amplifying voice or music signals because the 0.6 volt threshold cuts off much of the waveform and distorts it severely. The good news about class C amplifiers is that they run at higher energy efficiency than a class A. 65% versus 30% is typical.

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.

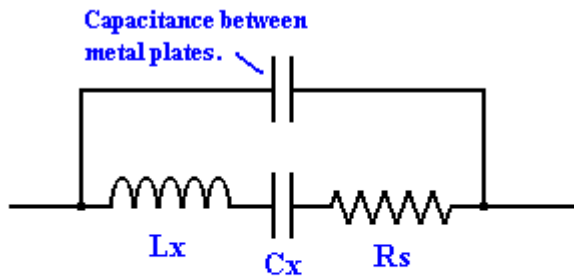
Quartz is a type of natural, crystalline, silicon dioxide glass. It is an extremely good insulator. Household glass is also mostly silicon dioxide, but the atoms are arranged in an amorphous structure, something like a random pile of bricks dumped from a truck. In contrast, quartz has a regular crystalline 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 they were building a simple capacitor with quartz glass as the insulator. Since WWII quartz for crystals is manufactured artificially in ovens.

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 quartz 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.

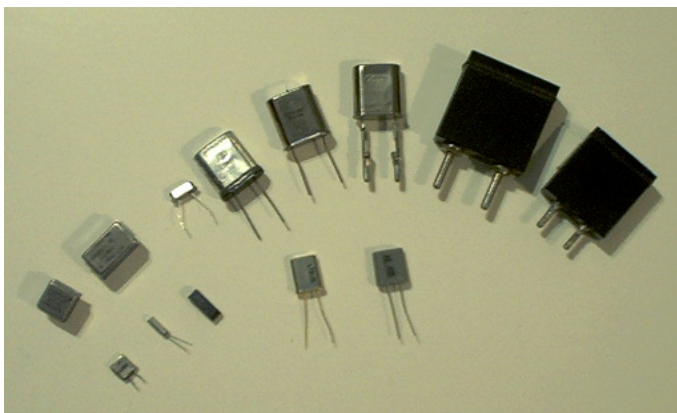
Although the oscillation is mechanical, it also acts as though it were oscillating electrically. Quartz crystals act like a series L-C circuit. They are equivalent to the L-C components we used to tune the crude oscillator above. The equivalent capacitance C_x and L_x



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

Equivalent circuit of a crystal.

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. The resistor R_s represents mechanical heating.



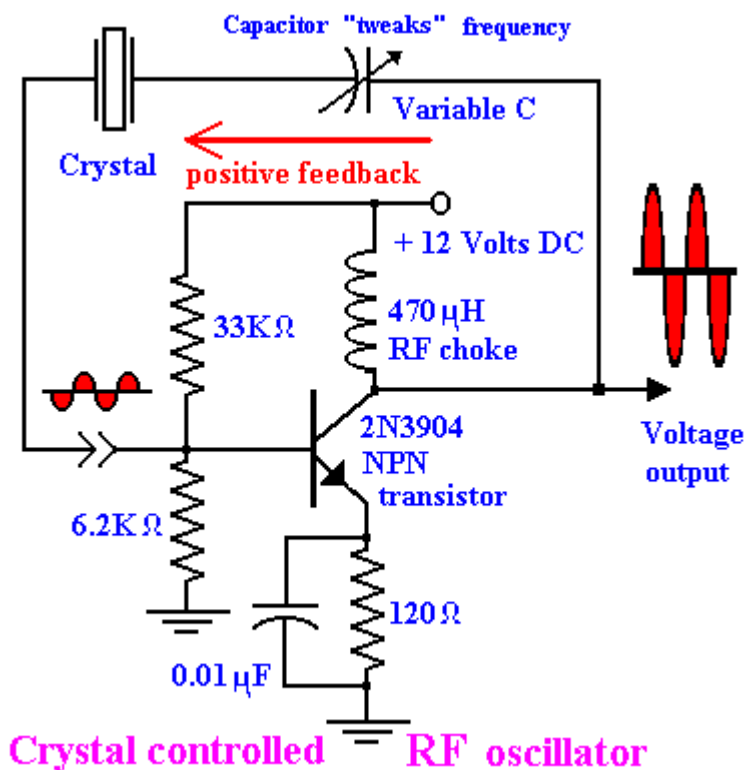
Typical crystals are shown below. Two large ancient, ham crystals are shown at the upper right. These can be good parts, provided they are still working after 50 or more years. Sometimes dead, ancient crystals in FT-243 holders can be taken

apart, cleaned with alcohol, and made to work again. Careful! The bare quartz wafer is quite fragile. But if the crystal was already inert, breaking it isn't a loss.

An assortment of quartz frequency control crystals

The three big silver-colored crystals in center rear are size HC-33 and are modern-manufactured, first-rate parts. The two medium size HC-49 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 HC-49s 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 their frequencies 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 a pistol and drift like crazy. Unless you've checked it out, **don't use an oscillator block!**

Common Crystal Oscillator Circuits



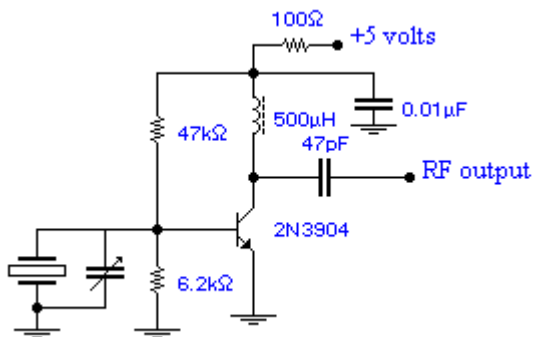
There must be a dozen or more transistor crystal oscillator circuits. The circuit on the left is practically the same as the crude LC oscillator illustrated earlier. The variable capacitor allows you to "tweak" the frequency a kilohertz or more above, on, or below the nominal frequency printed on the 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.

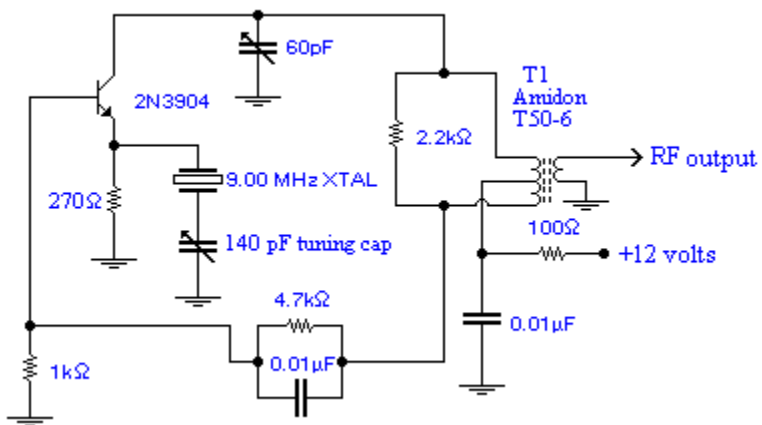
Series-cut and parallel-cut crystals

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 at 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 on the left 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



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 on the left. 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 it is turned on.

A Butler crystal oscillator

Maybe it's because the crystal just shunts the emitter resistor so the crystal voltage is low and it receives little heat energy. 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 that's 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.

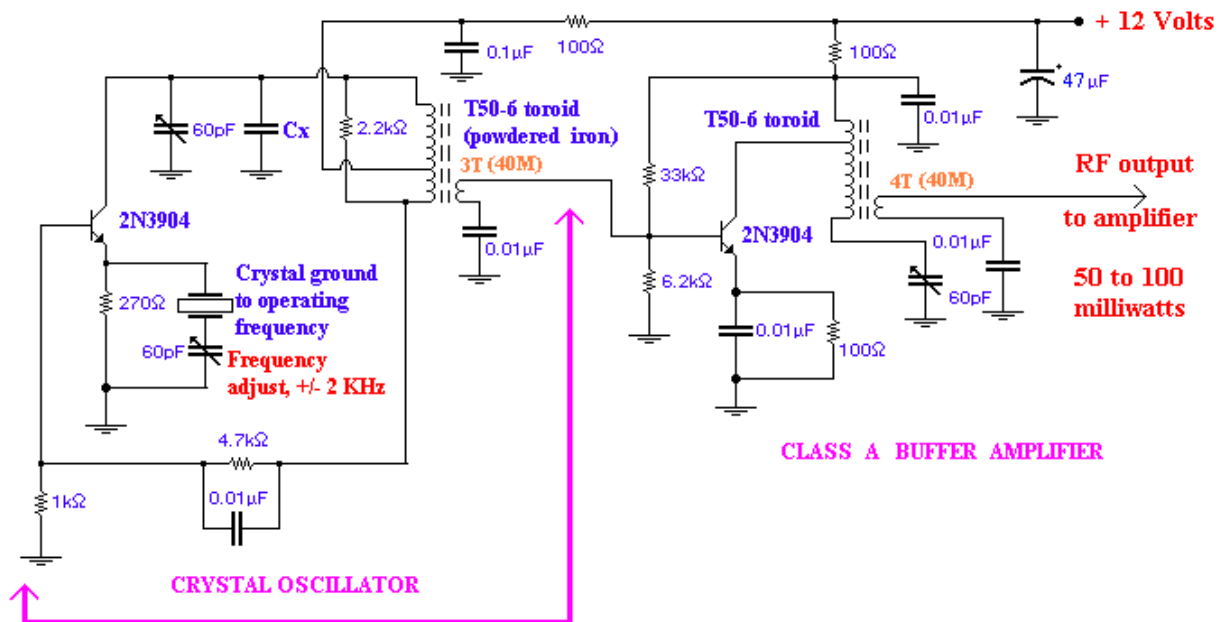
On high frequencies, like 30 MHz, the circuit as shown above may not oscillate right away. If you're sure it's wired right and has 12 volts applied to it, then try increasing the 270 ohm resistor to 470 ohms. If the output is too weak, sometimes it can be increased by lowering the same 270 ohm resistor to say, 150 ohms. Also, big crystals tend to put out much larger signals than small ones.

Depending on your application, the Butler also has the advantage that the auxiliary tuning capacitor can pull the frequency lower than the base-connected oscillator shown earlier. 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 have 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 HC-33 that worked so well, that instead of 5 watts, my QRP (including the final amplifiers described below) put out 15 watts with 12 volts on the power supply. Oops! When I run it on 6 fresh 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 many 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

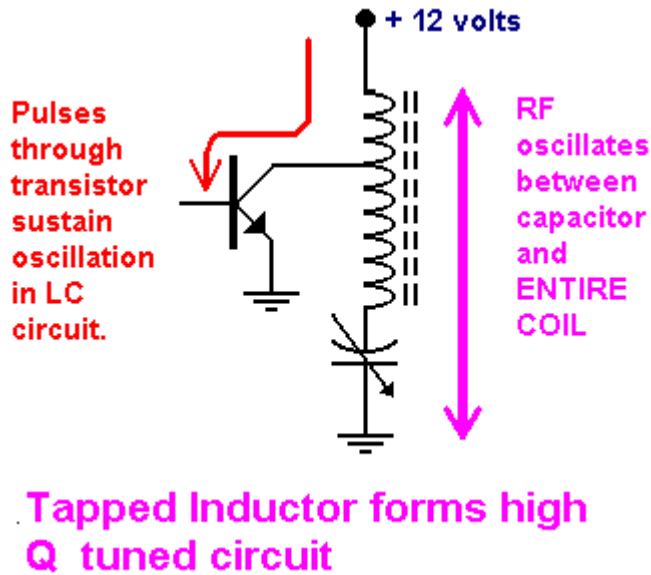
Band	Toroid type	Primary turns	Secondary turns
80 Meters	T50- 15	41 turns, tapped 1/3	4 turns & 5 turns
40 Meters	T50- 15	30 turns, tapped 1/3	3 turns & 4 turns as shown.
	Or, T50- 2	51 turns, tapped 1/3	5 turns & 7 turns
30 Meters	T50- 6	36 turns, tapped 1/3	7 turns & 9 turns
20 Meters	T50- 6	28 turns,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

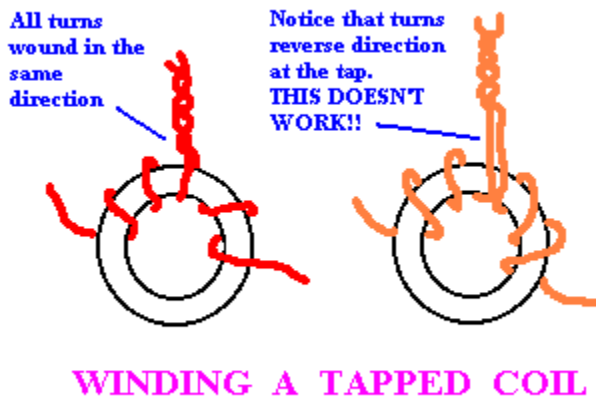
The crystal oscillator and following tuned amplifier stages of this QRP transmitter use tapped coils for the primary windings of the output transformers. The tap is 1/3 of the way from the power supply end of the coil. The DC current from the 12 volt source flows into the primary

winding, then after 1/3 of coils, it leaves through the tap and enters the transistor which turns on every half cycle and shunts the current to ground. The opposite end of the 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.



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



The drawing on the left 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 cancel 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 resistance of the copper metal, the resistance of inductors wound with fine wire and many turns can be significant, even without the reactance component. Therefore, inductors are sometimes “low Q.” In contrast, the resistance of the short 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. Frequency multipliers can be explained by the adult-pushing-the-kid-on-the-swing analogy. Instead of the adult giving the swing a push with every cycle, suppose the adult only pushes every other cycle or every 3rd or 4th cycle. In this way the frequency of the pushes can be some fraction of the natural frequency of the swing. Notice that the frequency of the kid's motion on the swing depends on the length of the swinging pendulum and has little to do with the frequency of the adult pushing. In other words, the length of the pendulum must be "tuned" to the frequency of the pushes. Or, the push frequency can be tuned to the swing frequency or an even fraction of the swing frequency.

For example, let's apply a 7 MHz sinewave to the input. 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 2 pF, between the coil and the trimmer capacitor. A bigger capacitor will tend to 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 winding wrapped around the primary 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.

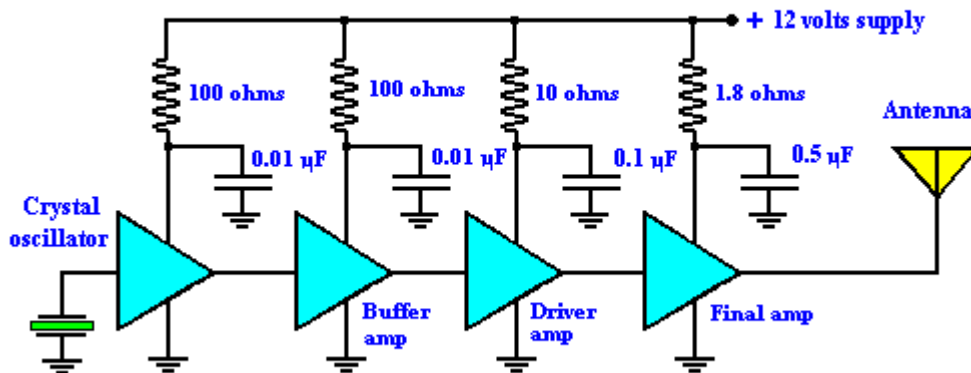
The buffer stage and power supply decoupling

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 by soldering feed-through ground points through the PC board to the unbroken grounded copper sheet on the far side.

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 some of its supply voltage, just when it needs 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. That is, the R-C time constant of each network should be much longer than the variations in the power supply voltage.

R-C time constant is just **resistance times capacitance = time constant in seconds**

e.g., 1.8 ohms X 0.5×10^{-6} farads = 0.9 microseconds

This limits the voltage change to the output stage much slower than an RF cycle. That is, $1/0.9 \mu \text{ sec} = 1.1 \text{ MHz}$

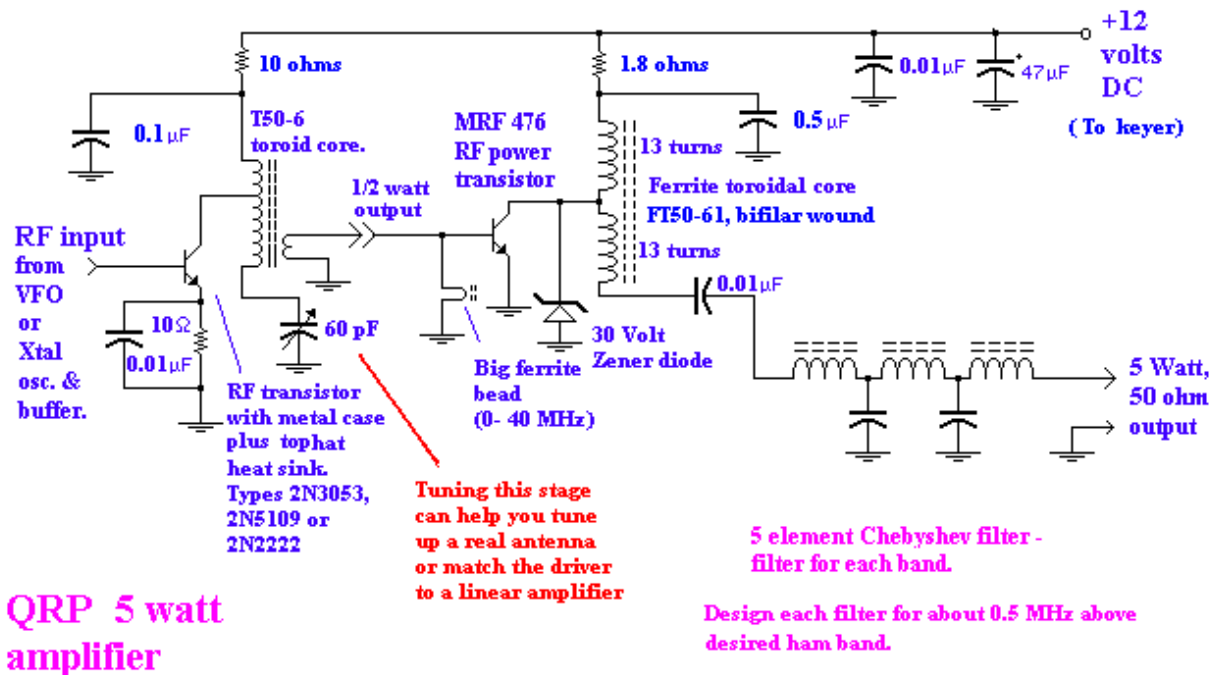
These RC decouplers prevent the voltage changes from feeding back to earlier stages. For the stages that draw the most current you need smaller resistance so that the DC voltage loss across the resistors will be as low as you can tolerate. Also, ***The more current each stage draws, the more capacitance it needs.*** The capacitors should be low loss types designed for RF bypass applications such as disk ceramic or mica. 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.

LC decouplers

The first QRP I built was from a design in the 1979 handbook. This design used inductors instead of resistors in the decoupler circuits. Since there is no appreciable DC voltage drop across an inductor, inductors look like a good idea. Unfortunately my circuit was extremely unstable until I took out the LC decouplers completely. It was only later when I tried to run the QRP on flashlight batteries that I discovered that RC decouplers were useful.

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. QRP is defined as less than 5 watts. As explained earlier, you shouldn't have any trouble getting enough power from this little transmitter.



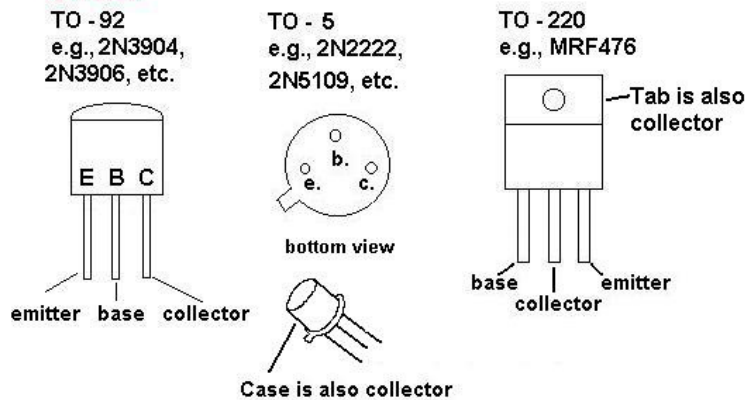
A QRP Two Stage Power Amplifier

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,

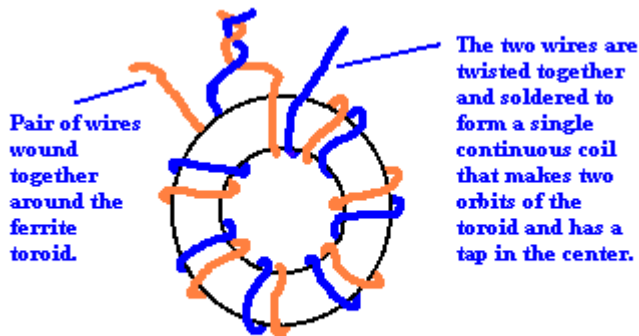
with 27 turns on the primary, you can (barely) cover 20 to 10 meters. Make the tap about 1/3 of the total number of turns, or about 9 turns in this case. The secondary would be about 6 turns. The input of a transistor amplifier is usually a low impedance. Therefore the transformer lowers the voltage 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 metal 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.

COMMON BIPOLAR TRANSISTOR CASES



Bifilar wound transformers



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

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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. This is really easy to screw up! *If you connect one of the wires to itself, that wire becomes a shorted turn that will dissipate most of your RF energy.* Before you solder your bifilar into a circuit, use an ohmmeter to confirm that all three terminals have zero ohms between them. If you find that the "centertap" is an open circuit with respect to the other two wires, you have connected it wrong. I have made this error twice and wasted considerable time finding it.

Tuned amplifiers versus broadband amplifiers

The QRP described 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 QSO. 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.

Noise mode

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.

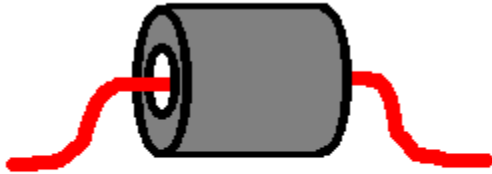
The output stage in the QRP is a broadband amplifier that uses a five-element Chebyshev filter to suppress high frequency harmonics in the output. Chebyshevs are described in detail below. The filter component values can be found in tables and formulas in an ARRL Handbook, e.g., 1986 or later. This broadband 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 2 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 MRF-476 transistor. They are pricey, \$13 or more.

According to the RF Parts Co. 2006 catalog, the type 2CS2166 is direct replacement for the MRF-476 and costs only \$1.95. I haven't tried any, so I can't vouch for this. There must be hundreds of cheap transistors that can put out 5 or 10 watts at HF frequencies. Unfortunately, the cheap transistors I have actually tried needed 24 to 80 volts collector supply voltage to deliver the same power. The virtue of Motorola "MRFs" for HF seems to be that they deliver big power with a 12 volt supply. To me it was worth the cost.

Ferrite bead RF chokes



FERRITE BEAD RF CHOKE

Notice the bead RF choke on the MRF-476 base. It's just a short piece of 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 a low frequency like 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.

**

CAPACITORS

Capacitors are rarely a problem

In contrast to inductors, capacitors are rarely a problem. If the label on the capacitor says 330 picofards, that's probably what it is. Small mica capacitors are often labeled with 3 numbers. The last number is the number of zeros following the first two digits. For example, a 330 picofarad capacitor would be labeled "331." 33 picofarads has no zeros so it would be "330" which is confusing. If the label is puzzling, a capacitance meter usually tells you everything you need to know about the unlabeled capacitor in your junk box.

Electrolytic capacitors can be a little tricky. Those are the caps with the plus and minus labels on the leads. You have to orient them with the correct polarity. The positive end must be aligned with the positive voltage in your circuit. Also, there are a few rules about what kind to use where. Aluminum electrolytics have large capacitances and are often used to stabilize power supplies. They are packaged in little plastic-coated aluminum cans and have + marked on the positive lead. They do not conduct RF particularly well so it may sometimes be advisable to shunt an aluminum electrolytic cap with a ceramic or mica RF bypass.

Tantalum electrolytics have the largest capacitances relative to their small physical size. They are usually packaged in tiny plastic rectangular blocks or blobs of colored epoxy. Again, they have plus and minus lines on them to indicate polarity. Sometimes the positive is just marked with a dot of colored paint. They conduct RF well. That is, they make good RF bypass capacitors as well as low frequency ripple stabilizers. On the other hand, tantalums have low

voltage ratings and you should not place them directly across a battery. Sudden rises in voltage across a tantalum can cause it to break down and burst into flames. For example, I once designed a battery-powered circuit with a 10 volt rated tantalum wired across a 9 volt battery. It wasn't long before I had a charred capacitor and circuit board.

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. 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 a vital skill.

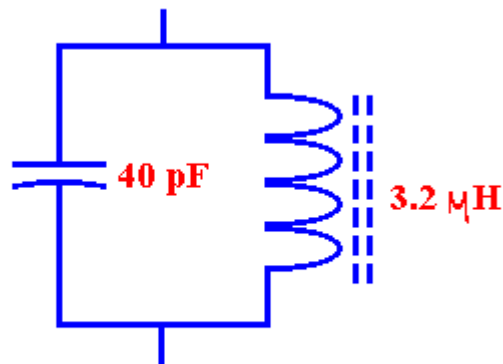
LC circuits. What size inductor do I need?

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?

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

L = inductance in Henries.

C = capacitance in Farads.



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:

$$[2 \times 3.1416 \times 14.1 \times 10^6 \text{ MHz}]^2 = 1/ (40 \times 10^{-12} \text{ Farads})(L)$$

Solving for L, $L = 3.18 \times 10^{-6}$ 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) simply because I know where to buy them. Go to www.bytemark.com or www.coilws.com. The important issue is that *the cores must have a known inductance factor, A_L* . A_L allows 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, tuned 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 and size 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 the upper 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}

Suppose we are using a T-50 type 6 powdered iron core to 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."

$$\text{Number of turns} = 100 (3.18 / 40)^{1/2} = 28 \text{ turns.}$$

Note: a bracketed number to the power 1/2 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.

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Calibrating the trimmer capacitors

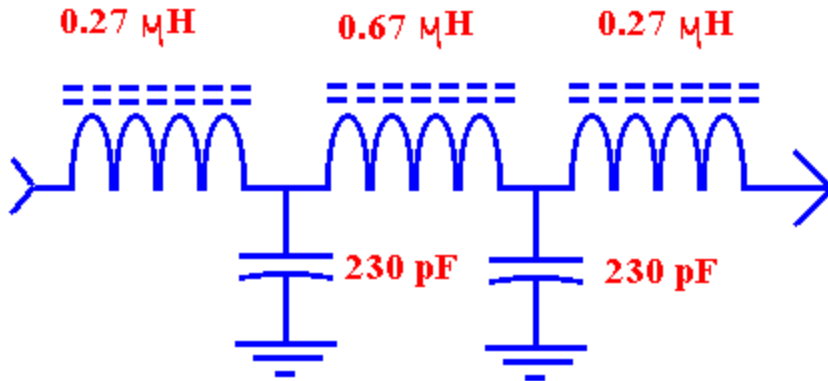
I used small, cylindrical variable "trimmer" capacitors to tune the first three stages of my QRP module. They are about the size of a grape and are adjusted with a small screwdriver. A problem with these devices is that you can't tell what capacitance they are set to by just looking at them. Since the 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 capacitor 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



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 above the transmitting frequency. The output stage of nearly every transistorized linear transmitter final has a 5-element filter to

prevent harmonics above the operating ham band. Your ARRL handbook has long, long, detailed explanations about designing different kinds of Chebyshevs. Most guys look at all 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 design 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:

$$C_s = 1 / 2 \pi (Z) f$$

where $\pi = \text{pi}$, 3.1416, $Z = \text{impedance in ohms}$ and $f = \text{frequency}$

$$\text{Capacitance, } C_s = 1 / 2 \pi (50 \text{ ohms}) (14.35 \text{ MHz}) = 222 \text{ pF}$$

The normalized inductance is defined as:

$$L_s = Z / 2 \pi f$$

$$\text{Inductance, } L_s = 50 \text{ ohms} / 2 \pi (14.35 \text{ MHz}) = 0.55 \text{ microhenries } (\mu\text{H})$$

Fourth: Multiply the normalized C and L by the *design factors* for each of the five elements.

The values of the five elements are:

$$L1 = \mathbf{0.4869} L_s = (.4869) (0.55 \mu\text{H}) = 0.27 \mu\text{H}$$

$$C2 = \mathbf{1.05} C_s = 1.05 (222 \text{ pF}) = 230 \text{ pF}$$

$$L3 = \mathbf{1.226} \quad L_s = 1.226 (0.55 \mu\text{H}) = 0.67 \mu\text{H}$$

$$C4 = \mathbf{1.05} \quad C_s = 1.05 (222 \text{ pF}) = 230 \text{ pF}$$

$$L5 = \mathbf{0.4869} \quad L_s = (.4869) (0.55 \mu\text{H}) = 0.27 \mu\text{H}$$

For the capacitors, 220 pF (a standard value) will work just fine.

Heat sink for the output transistor

Use a big metal heat sink on your MRF-476 and keep it cool. I haven't damaged any, even with as much as 15 watts RF CW output. Notice that a bare MRF-476 is only rated at 3 watts dissipation. I use large aluminum heat-sinks made from 1" aluminum angle from the hardware store. The metal tab on the MRF-476 is the transistor collector and must be kept insulated from the grounded heat sink. I insulate the transistors from the aluminum with mica insulators. I use a film of silicon grease on the mica to improve heat conduction. Look for "transistor mounting kits" in your parts catalog index. The mounting hole for the MRF-476 is tapped into the aluminum with 4-40 thread so that no nut is needed.

Zener over-voltage protection for the output transistor

The 30 volt Zener helps protect your MRF-476 from open circuit operation. The Zener doesn't seem to be vital, but it doesn't hurt performance either. With these precautions I have found these transistors extremely hard to damage. However, the book does say 3 watts only, so try not to run them so hard or so continuously that they become too hot to touch.

Connectors for your QRP module

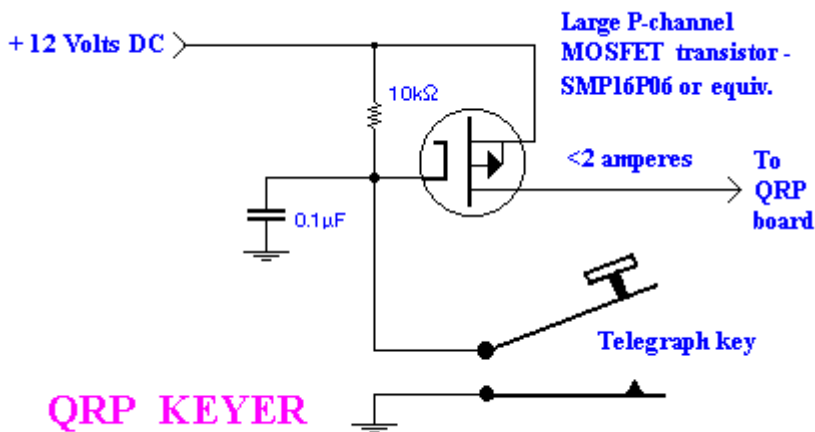
I use "RCA" audio phono plugs and coax for RF connections between HF modules. Yes, I should be using BNC or other connectors designed specifically for RF. However, phono plugs are cheap, easier to wire, and there seems to be no difference in performance, so long as the power level (current level) is under roughly 10 watts and frequency is below 30 MHz. After all, phono 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 produce 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 the 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 completely controlling 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 QRPs, like homebrew transmitters in Altoids boxes and sardine cans, I notice they just put the key in series with the supply. Keying the battery directly works, but for keying 5 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 power MOSFET as shown above. The resistor and capacitor in the gate circuit soften (extend) the turn-off time to prevent key click.

David, VK6DI, pointed out to me that my circuit shorts out the charge in the capacitor thereby turning the 12 volt signal on abruptly. I agree with him when he says this *should* cause key clicks. As he points out, I could slow the turn-on by putting a small resistor in series with the key. It must be small, like less than 1K so the gate turn on voltage will charge to be nearly 12 volts. Or better yet, we could put another cap across the 10 K resistor. These steps may be "gilding the lily." The above circuit has worked well for me. Perhaps it is the relatively slowly charging capacitors in the rest of the transmitter circuitry that soften the turn-on time and prevent key clicks. He also suggested keying with an operational amplifier to turn the transistor on and off gradually. He also suggest saving money by using bipolar transistors instead of MOSFET. Those ideas all sound good to me, but I haven't tried them.

One of the mysteries of CW transmitters is that producing good-sounding CW with a vacuum tube circuit is harder than with transistors. I had lots complaints about my vacuum tube key clicks and chirp. (See chapter 14.) But in my experience, avoiding clicks and chirps with transistors has been much easier.

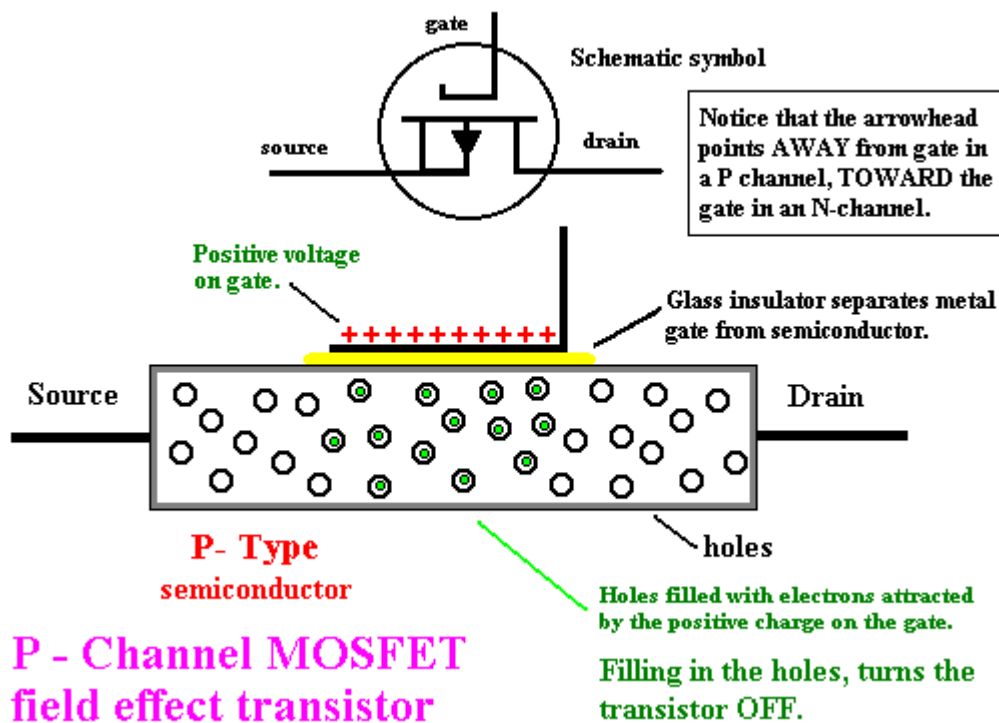
If you have any doubts about the sound of your signal, listen to it in a quality receiver

with the receiver antenna input shorted and the RF gain turned way down. This will simulate how your signal will sound from hundreds or thousands of miles away. Chirps, clicks or power supply noise on your signal will be obvious.

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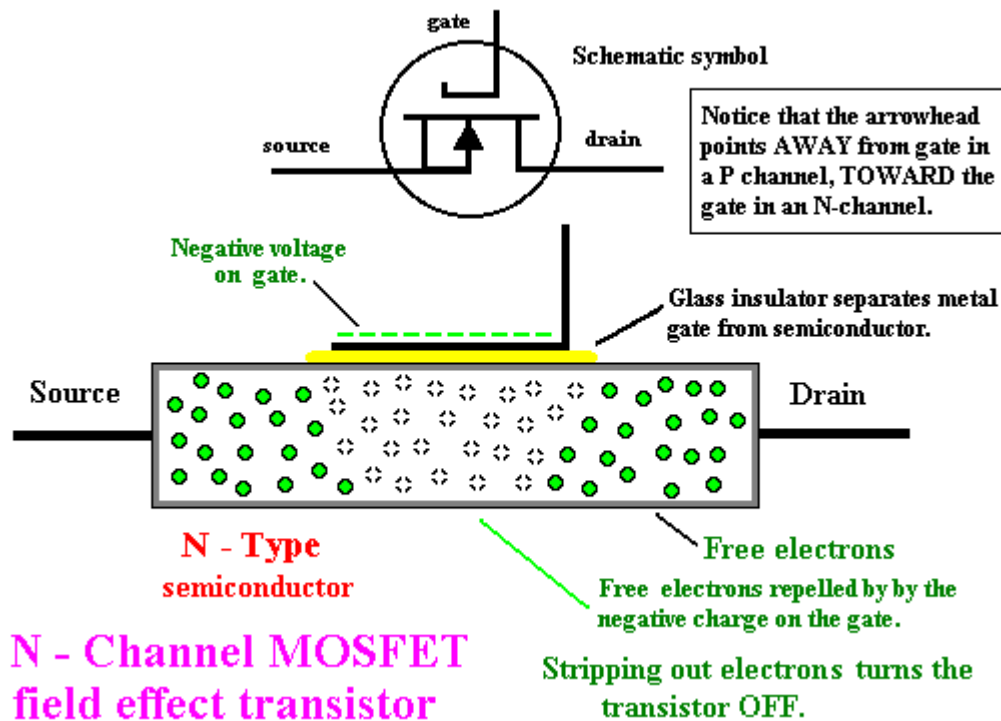
MOSFET field effect transistors

What is that weird transistor called “MOSFET,” you ask? Metal Oxide Semiconductor Field Effect Transistors work differently than the bipolar transistor you met in chapter 4. Fortunately, they 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 the middle so that the center is very narrow. The narrow region also serves as one of the two conductive plates that make up the capacitor. The other plate of the capacitor is the metal control gate. The gate is insulated from the transistor by a thin film of glass. 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.



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.



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, such as when it is exposed to a ringing inductor, 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

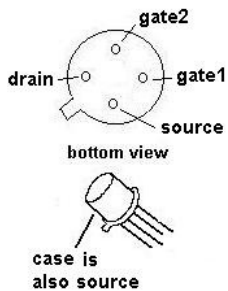
transistors are hard to break, they are often the best choice in high power applications.

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 can be used for high powered audio amplifiers. Power MOSFETs, like the P-channel used to key the QRP transmitter, aren't so well suited for use as a high frequency (RF) 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 times per second. This makes driving a power MOSFET like the one above impractical for high power radio frequency transmitters.

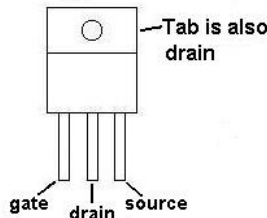
For example, from time to time QST ham magazine has had transmitter plans using high power MOSFETs for 20 to 50 watt transmitters. The catch was, they didn't recommend them for hambands higher than about 40 meters. Above that frequency, the power needed to develop the drive current had to be so high, 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.

MOSFET TRANSISTOR CASES

DUAL GATE MOSFET
TO - 72 CASE
e.g., NTE454, NTE 221, etc.



MOSFET POWER SWITCH
TO - 220 CASE
e.g., IRF9140, SMP20P10,
MTH25P05, etc.



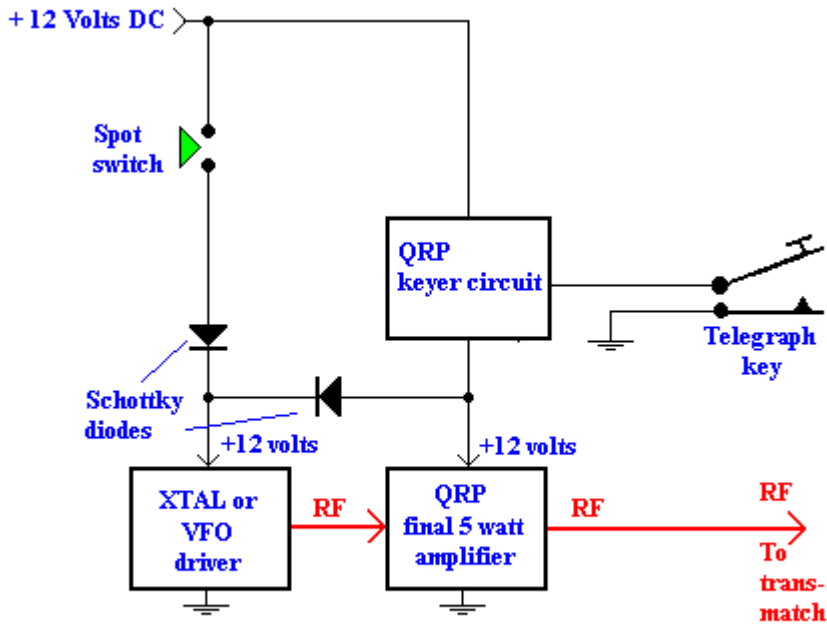
Power enhancement MOSFETs made by different companies have various designs that make them more rugged, handle larger currents, work at high frequencies, and dissipate more waste heat. Names like HEXFETs and V-MOS are examples of sophisticated power MOSFET designs. Dual gate MOSFETs are used to make mixers, product-detectors and RF amplifiers in receivers. As the name implies, they have two control gates instead of one. They will be discussed in chapters 7 and 13.

*

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 to 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.

Building 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 covered in chapter 9.