CRYSTAL SETS TO SIDEBAND

Chapter 6B

BUILDING A HOMEBREW QRP (continued)

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Using your QRP in the real world

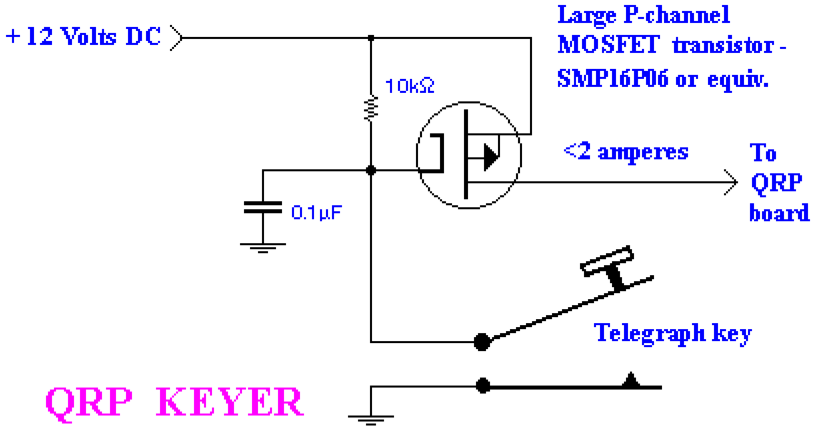
If you compare the picture above with the QRP as it was described in Chapter 6A, you will see that many parts have been added to make it easier to use. These include a receive/transmit switch to transfer the 12 volt power and antenna between the transmitter and the receiver described in Chapter 7. Another addition was a "spot" switch to make it easier to find the transmitter frequency on the receiver dial. A simple audio tone buzzer was added and is located just above the crystal. The buzzer makes it less confusing to monitor your Morse code while sending. Finally, I added another pre-amplifier to boost the power.

Keying CW Transmitters

The QRP described in Chapter 6A is intended for Morse code, but we didn't discuss how to pulse the transmitter on and off with a telegraph key: Very low power QRPs, such as the ones built in sardine cans or Altoid® candy boxes, are usually keyed by keying the power supply directly. Other 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 strong, 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 well as long as the oscillator is completely controlling the later stages. Unfortunately, when you let up the key, the following amplifier stages will often self-oscillate at whatever frequency they please.

If the current is higher than a few hundred milliamperes and, if there is any inductance in the circuits being switched, significant sparking occurs in the key contacts. Over time, sparking blackens and burns the contacts making them intermittent. For keying 10 or more watts of DC power, it's better for the key contacts to switch the main current with a solid-state (transistor) switch. I prefer to key the transmitter by keying the entire power supply on and off. This circuit is not elegant, but it works.



A P-Channel MOSFET Keys the DC Power Supply

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 suggested, 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 capacitor 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. David also suggested keying with an operational amplifier to turn the transistor on and off gradually. He also pointed out that bipolar transistors are much cheaper than MOSFETs (They were then). All those ideas sound good to me, but I haven't tried them.

One of the mysteries of CW transmitters is that producing good quality CW sound with a vacuum tube circuit is much 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.

Even if you have no reason to doubt the quality of your CW signal, you should listen to it in a receiver with the receiver antenna input shorted and the RF gain turned way down. This will simulate how your signal will sound from hundreds of miles away. Chirps, clicks or power supply hum on your signal will be obvious.

Unless you have a spectacular antenna, such as a dipole 100 feet above the ground or a 40 meter rotatable Yagi, your QRP will rarely produce a strong signal 1,000 miles away. A drawback of crystal control is that you will hardly ever be able to zero-in on someone calling CQ. If you are able to precisely match his frequency, the fellow will nearly always make an effort to talk to you. This is true even if your signal is barely above the noise level. When you are unable to reach the frequency of stations calling CQ, you will be forced to call CQ. Hams with commercial transceivers will have no difficulty matching your frequency. Unfortunately the average ham has little interest in answering weak CQs.

You can increase interest in your puny signal by telling them that you are a QRP station; i.e., "CQ CQ de KØIYE/QRP K." Less desirable ways to get their attention are for your signal to chirp or drift! Stations will immediately call you to tell you about your grievous malfunctions. Hey, if you stay in the band, it isn't illegal to drift or chirp! A contact is a contact and at least you will know that your antenna is adequate.

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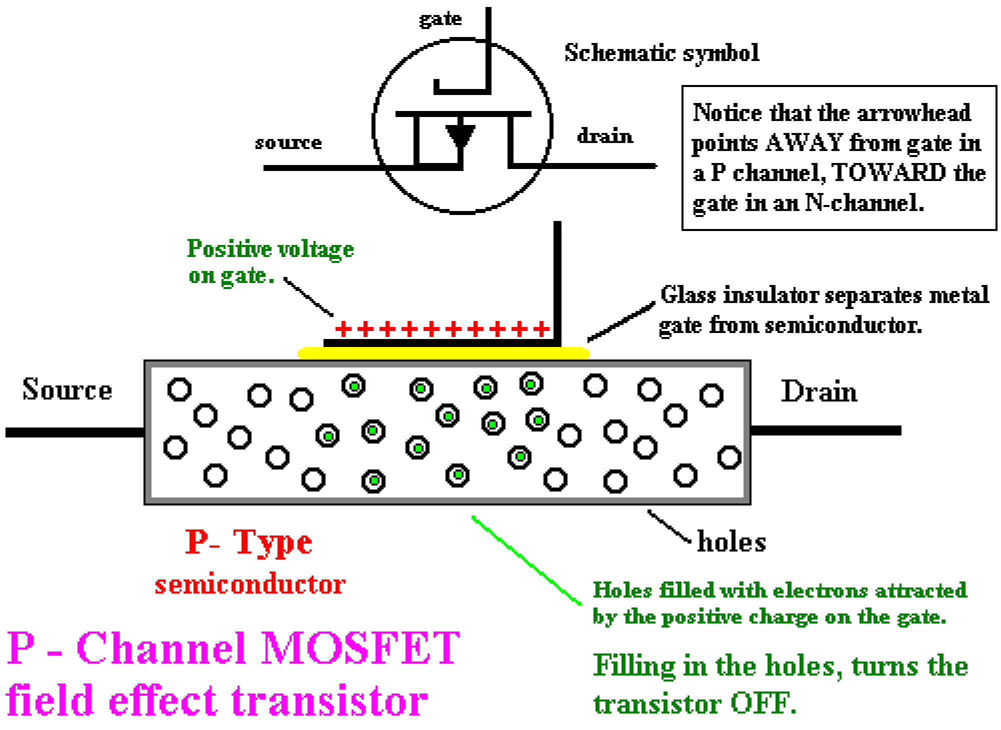
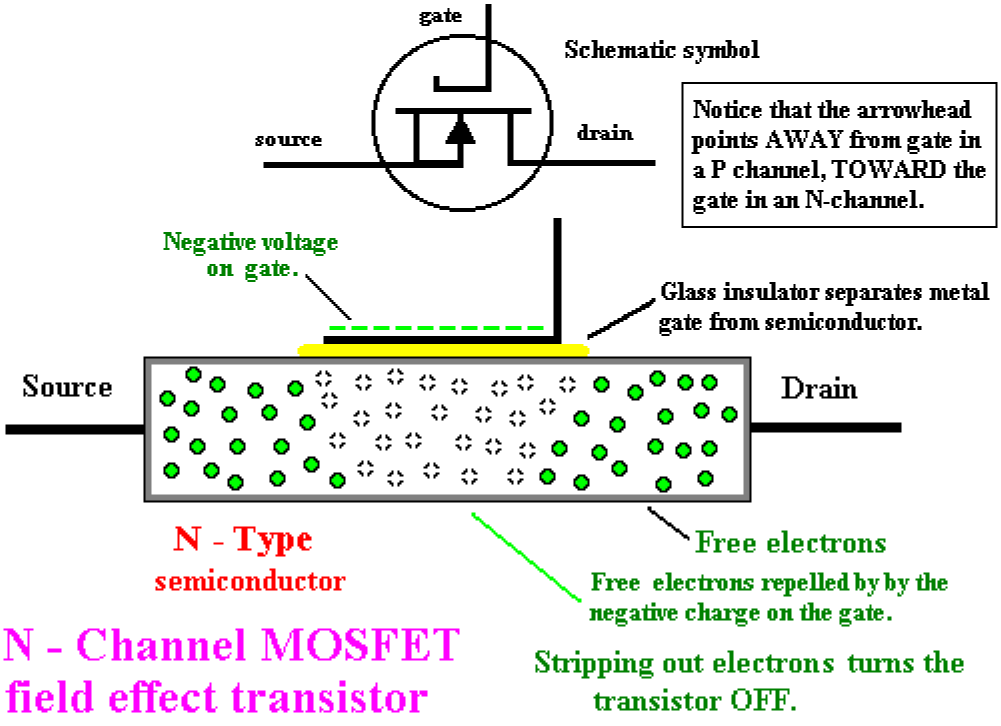
MOSFET field effect transistors

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-type 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 exposed to 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 semiconductor strip in the transistor and protects it from being fried.

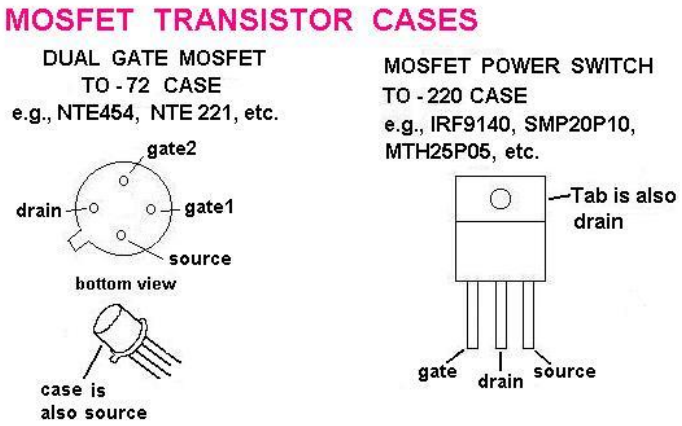
Compared to bipolar transistors, MOSFETs have two major advantages:

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 usually the best choice in high power applications. Small, dual-gate MOSFETs are desirable for receiver amplifiers and mixers because, without PN junctions, they produce less "shot noise." When PN diodes conduct, the charge crosses the junction barrier in random bunches of electrons and holes. This random activity adds to the noise accompanying faint radio signals.

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 high frequency (RF) power amplifiers. 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 would appear to make driving a power MOSFET like the one above impractical for high power radio frequency transmitters.

In the past QST ham magazine had transmitter plans using high power MOSFETs for 20 to 50 watt transmitters. The catch was that they didn’t recommend them for hambands higher than about 20 meters. The capacitance of the little input gate is high enough that, above 20 meters, the required drive power, (or perhaps we should say "drive volt-amps"), begins to approach the output power. The gate is a capacitor. That means that current must be stuffed into and pulled out of the gate millions of times per second. There isn't any heat, (i.e., power), dissipated in the capacitance, but the driving transistor is working just as hard and as if it were driving a resistive load.

Newer RF MOSFETs have been developed that can be used for transmitters running at hundreds of megahertz. They're expensive, the dollar price usually equals half or 2/3 their rating in watts. My main experience with them has been in VHF amplifiers described in Chapters 16A and 16B. ***It turns out that the input capacitance can be resonated with a parallel inductor.*** This makes the input impedance appear infinite and a MOSFET can work even at 144 MHz.



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 are discussed in Chapters 7, 13 and 16C.

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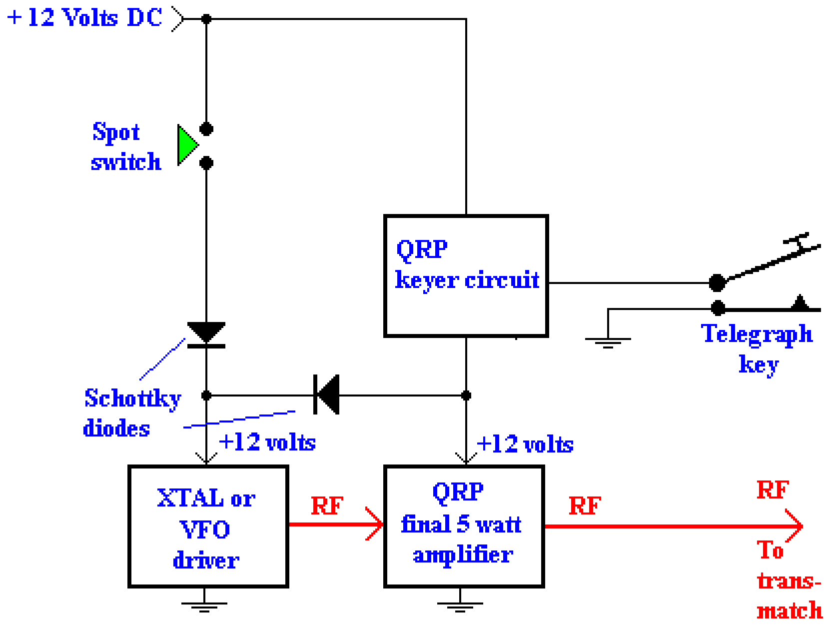
SPOT SWITCHES

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 signal in the receiver. However, your signal will not be broadcast until you are ready to call the station. Using the spot switch, you turn on the oscillator, 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 final amplifiers.

The above picture shows the addition of a spot switch and audible tone generator to the crystal controlled QRP. The red handled switch routes the main power from the entire QRP to just the oscillator. A little red LED indicates when the "spot" feature is turned on.

In the circuit below, diodes are used to power the oscillator from either wire under the appropriate circumstances. The back-biased diode between the final amplifier and the oscillator section keeps the spot switch from supplying power to the final. The diode in series with the spot switch isn’t really needed. This is 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 constant if diodes are in both supply lines. Slight changes in voltage to the oscillator can make a subtle change in frequency.

The diodes driving the oscillator and buffer are Schottkys. As explained in Chapter 4, these diodes have only 0.2 volts drop across them instead of the usual 0.6 volts for an ordinary silicon rectifier diode.



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.

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A built-in CW audio tone generator for sending

When I was a boy, I watched our local railroad station master use his electromechanical telegraph to confirm arrivals and departures. He sent and received Morse code with nothing to hear but clicking noises. I presume his keying relay, or "sounder," made a different noise closing the contacts than it did opening. How else could he tell a dash from a dot? Here in the more modern world CW is always modulated so that there is a musical tone to signify the presence and duration of a dot or dash. During receive, the receiver product detector with its BFO provide the tone, but while sending, the operator only hears his key clicking.

Since I'm not an old-time telegraph operator, I want to hear my own code while I am sending. For me, sending clear, clean Morse code is a major challenge. I need all the help I can get with a good key and a consistent, clean tone for me to monitor. The basic QRP has no way to generate a tone, so I added a tone generator.

I could have done this the hard way by building an audio oscillator, loudspeaker and volume control. Since building such a circuit would need lots of space inside the QRP enclosure, I did it the easy way. Radio Shack and a dozen other sources sell little buzzers that are about 1 or 2 centimeters in diameter. (e.g., Radio Shack # 273-074) I added a small switch to turn it on and a trim pot to adjust the volume.

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Troubleshooting your QRP

Eliminating chirp

When you have built several QRPs for different bands, you may notice that each of your creations has a different "personality." They are not all equal and it's often hard to understand why. When you test a QRP design like the one in Chapter 6A and it is keyed with the MOSFET circuit shown above, it should be free of chirp when driving a 50 ohm resistor dummy load. Earlier I described listening to my own transmitter on the air using a receiver which has its antenna input shorted. When I do this, I am sometimes surprised to hear a slight chirp at the end of dashes. Apparently when driving a real antenna, there are reactive (inductive or capacitive) components that produce a chirp on the signal.

I have observed that sometimes when I tune a QRP amplifier stage for maximum power, there is a noticeable jump upward at the exact resonant point. I believe these overly sensitive stages are source of the chirp. The cause seems to be a slight drop in power supply voltage during each dot or dash. The change in voltage causes the sensitive stage to detune slightly. There are 2 cures for this chirp: The easiest is to detune the amplifier stage slightly that shows the little upward jump at the optimum tuning point. This will usually fix the chirp at the expense of a couple percent loss in output power.

A more drastic cure is to improve your power supply. If you're using nearly dead batteries, the voltage will probably slump while you're sending. Charge or replace your batteries. There are two line-powered, ten watt QRP supplies described in Chapter 8. The simpler one uses an LM317K regulator IC. With my crystal controlled QRP this supply dropped its output voltage by a tenth of volt or so when I keyed the transmitter. This small drop was enough to make this particular QRP begin to chirp. I rebuilt my little power supply using the second "precision" supply design. This second design uses a precision voltage reference IC, an LM336, to hold the voltage constant to within 0.01 volts. The better regulated supply eliminated the chirp.

Difficulty getting 5 watts from your QRP?

Suppose you built the QRP described above and it only generates 1 watt. What happened to the other 4 watts? Here are some possible answers:

1. **Measuring the output power.** Perhaps your measurement technique is at fault. Place a 50 ohm dummy load (Chapter 9) on the output and look at the output on an oscilloscope. Measure the peak of the RF voltage sinewave. The peak is the voltage change between the horizontal zero line and the positive (or negative) peaks of the sinewave. Convert peak voltage into RMS voltage by multiplying by 0.707. Square the RMS voltage and divide the result by 50 ohms. (Power = V^2/R) The result is your output power.

Are you sure your oscilloscope is calibrated? Use it to measure the DC voltage across a known voltage source like a fresh 9 volt battery, then compare the result with your DC voltmeter. Is the little calibration knob on the scope vertical amplifier range knob set to "cal" (calibrated)? If not, turn the cal. knob clockwise until it clicks. Check the calibration of your scope with a simple reference voltage. Some scopes have a built-in calibration output - a loop of metal on the front panel you can clip your probe onto. Typically the output will show a 1 volt peak square wave at 1 KHz or other standard waveform.

My new digital scope occasionally goes nuts and calls 1.0 volt "20" or "50" volts. My old analog scope never had troubles like that. I also have a new, first rate, Fluke digital multimeter. It's usually a marvelous instrument - when it isn't making its own digital crazy numbers. Some of us are born to be analog.

Is your oscilloscope rated for the frequency you are measuring? Many ancient oscilloscopes were only rated up to 5 MHz. At say, 7 MHz, the sinewaves will look normal, but will not be as large as they should be. Oscilloscope probes are typically either 10:1 or 1:1 voltage ratio. In other words, at 10:1, 10 volts will look like only 1 volt. Most probes have a switch on the handle to select 1:1 or 10:1.

My newer scope is digital and "rated" for 150 MHz. It produces first-rate, clear sinewaves for 2 meter signals. Unfortunately, at 2 meters the voltage calibration is way off, no matter what probe I use or even with no probe. I had to measure the power by measuring temperature rise on a resistor load and calculating the actual peak voltage. (See Chapter 16A.)

Measure the DC input power

If you doubt your RF power measurement, measure the DC power input to the transmitter. The DC power consumed will always be at least twice as high as the RF power it generates. A class C amplifier runs at about 65% efficiency and class A amplifiers are only about 30% efficient. To measure DC supply power, ***measure the DC input current and multiply it by the DC supply voltage.***

Most battery powered multimeters have a DC current capability. Set yours to 10 amperes DC and make your measurement while operating at full power into a dummy load. The measured current times the DC voltage is your input power. Some multimeters have a separate current meter input lead socket. Be careful measuring current with your multimeter - it's easy to blow the fuse.

If you don't have an oscilloscope, but you do have an antenna tuner, try loading your QRP into an old-fashioned, filament-type, Christmas tree light bulb. These bulbs generally consume about 7 watts. If the light is reasonably bright, you must have about 5 watts.

Now let's assume that your output power really is low:

2. Measure the DC voltage drop across the 1.8 and 10 ohm decoupling resistors in series with the output stages. If these 1/2 watt resistors have been overheated, their resistances will rise and the voltage drop across them will be excessive. You may find that the resistances have become more like 5 or 80 ohms, respectively. The voltage drops across these decoupling resistors should be no more than a volt or so. If it is 5 volts, it means that much of your power is heating the resistor and has already damaged it.

3. **Try increasing the turns on the secondary of the tapped T50-6 coil(s).** This will increase the drive to the following stages. This often works for the drive to the MRF476. Similarly, try increasing the secondary turns on the transformer driving the 2N3053.

4. **Try adding a positive bias resistor to the 2N3053 driver** converting it from class C to class A. Start with about 33K ohms, then try decreasing this resistance to as low as 10 K. With no RF input, the DC collector voltage can be forced as low as 8 volts.

5. **Maybe the 2N3053 driver transistor is oscillating.** Look at the voltage on the collector of the 2N3053 with a scope. There should be a single rounded pulse for each sinewave half. If there are several short pulses for each sinewave pulse, the transistor is oscillating. Very high frequency (fast switching) transistors such as the 2N5109 are more prone to this problem.

6. **Check to be sure that each trim capacitor has TWO best settings.** Look at the output of the entire QRP on the oscilloscope and rotate the trim capacitor 360 degrees. If there is only one best setting, either the capacitor or the inductor is the wrong size and the L-C cannot resonate in the desired band.

7. **Your crystal may be old and feeble**. Old quartz crystals often oscillate reluctantly and can reduce the power from the QRP drastically. That is why I added an additional amplifier to my 40 meter QRP described above. Check this by replacing the crystal with another, preferably new, crystal.

8. **The QRP output is unstable at 5 watts output.** Years after I first built my 20 meter QRP, propagation conditions improved and I tried to get back on the air. Also, my best vertical antenna had been destroyed by a wind storm. The dipole, "fan style" antenna loaded poorly and kept dropping or raising output power. I replaced the high speed 2N5109 driver transistor with a 2N3053 transistor. This fixed the erratic power output and unstable sinewave signal. But because the low speed (low Ft) transistor couldn't keep up with the driver sinewaves, the power output dropped significantly.

9. **If you are desperate, increase the power supply voltage.** If you have the capability, raising the supply voltage above 12 volts will make a huge difference. If the transmitter has 5 amplifier stages, a 10 percent increase in voltage will usually increase each stage output voltage by 10%. It behaves like compound interest - a 10% increase 5 times = 61% increase. Because power is the square of the voltage, this will produce 2.56 times more power. Be sure all your components, especially the electrolytic capacitors, are rated for, say 25%, higher working voltage than your supply.

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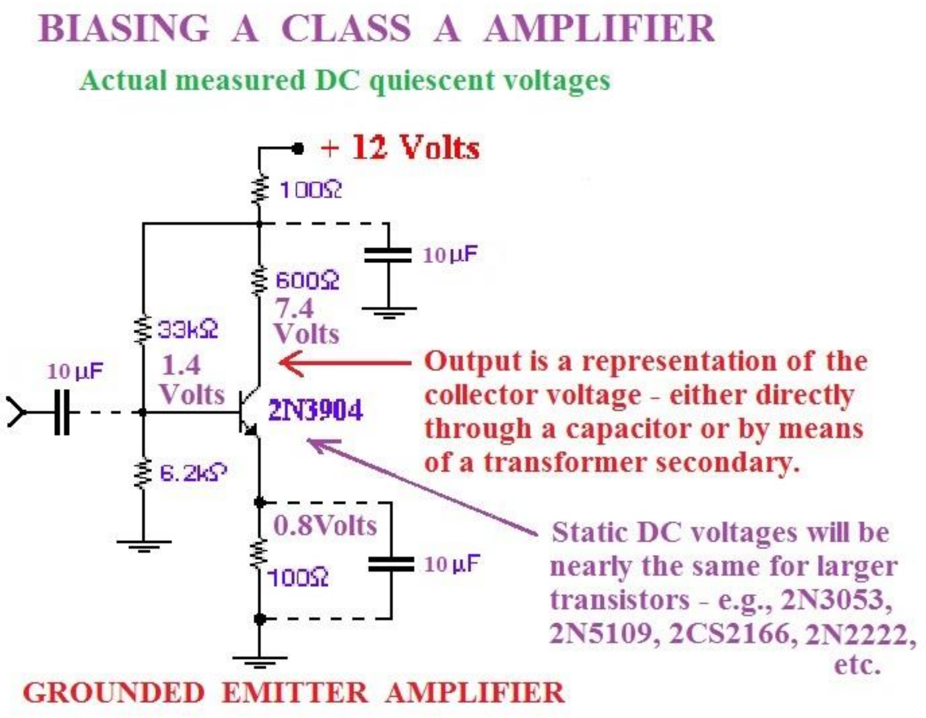
Biasing class A bipolar transistor amplifiers

Are calculations of bias resistances useful?

Don't panic! Unless you feel inspired, you don't need to calculate all the values of the resistors in your circuits. Fortunately, using rules of thumb, copying other people's circuits and cautious trial and error usually work fine. The following sample analyses are slow and painful to creep through. That's why many engineers, including me, do most of their work like technicians instead of math-obsessed professors.

Math is useful if you keep your electronic calculations SIMPLE. For instance, Ohm's law leading directly to an answer works great. Also, manufacturers' data sheets suggest applications for their I.C.s which often need calculations to find the correct supporting inductor, resistors, etc. My experience has been that, if you follow their calculations EXACTLY, the circuit will work the way they promised. But if you go off on your own, you will usually produce pages of reasonable appearing numbers that don't match the real circuit. The difficulty is that the "models" or simplifications that we use to make equations solvable are not identical to the real circuit.

The goal of biasing is to set up the direct current operating voltages that makes it possible for the AC or RF signal to operate within the operating ranges of the transistor base and collector. Biasing establishes the resting, "quiescent" state of the amplifier when there is no AC signal. Another goal of biasing is to make the transistor performance constant during temperature change. Biasing transistors can be confusing, even for those of us who should have mastered it long ago. It is easy to get stuck in mental ruts, ... you know, bad habits.

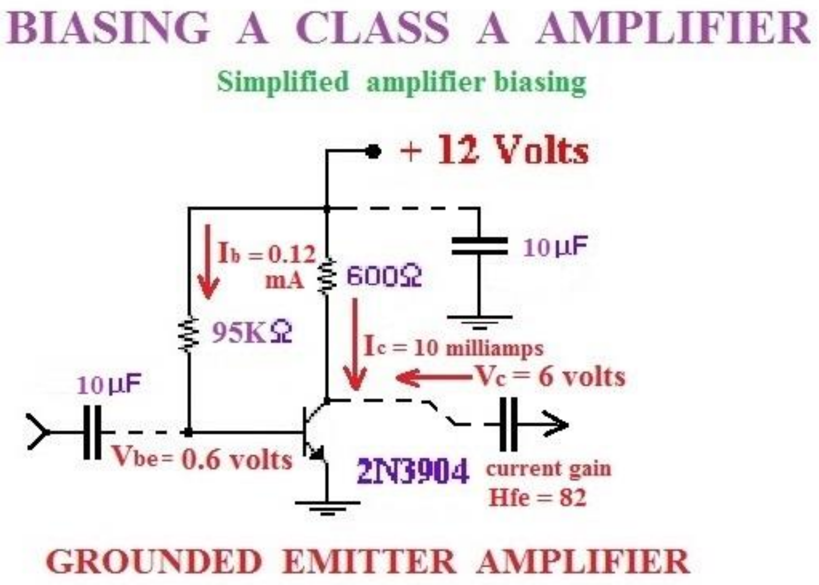


The schematic above is a "standard" 2N3904 transistor audio amplifier that is often used in this book. The purpose of the drawing is to describe the DC, resting-state of the amplifier. Notice that the capacitors have dotted lines connecting them to the circuit. This emphasizes that, from the point of view of the steady-state direct current, capacitors have no effect on the DC currents and voltages. The voltages shown are actual measurements of the circuit.

For years I have been biasing my 2N3904 amplifiers as shown above. Without engaging my brain, I had assumed that bigger transistors needed bigger bias currents. Specifically, I thought they needed lower bias resistances for a class A amplifier. The current gains (H_{fe} or "β") of the physically large transistors in TO-5 and TO-220 cases are often like the 2N3904. It should have been obvious to me that that the same bias resistors would produce about the same static DC voltages.

I recently tuned up two of my QRP 5 watt transmitter modules for different bands. I found that two of them had contracted the "vanishing power disease." Instead of 5 watt transmitters, they had become one watt transmitters. While trying to figure out what changed, I noticed that both class A driver transistors used in the two final amplifiers were drawing excessive power considering that the total output was only one watt. The driver transistors (2N3053 and 2N5109) were running hot, in spite of the small AC signal voltage. The final amplifier transistor, the MRF476, runs class C, so there was no forward bias for that transistor and no significant heating.

I measured the average DC collector voltages on the drivers as about 2 volts DC. In other words, the transistors were nearly fully turned on with the 3.3K and 1K resistors on the bases. I wired up the test circuit shown above and experimented with the bias resistors needed to turn big transistors "half on." The only difference in static voltages was that the bigger transistors have higher forward offset voltages from base to emitter, V_{be}. That is, they had 0.7 or 0.8 volts offset, instead of the usual 0.6 volt for small transistors. I replaced the 3.3K and 1K resistors with the usual 33K and 6.2K. Sure enough. The amplifier stages worked well, they just drew far less DC current.



A minimum bias scheme - educational, but not recommended

Previously I have compared class A amplifiers to turning a water faucet "half-way on." By biasing the amplifier half on, a sinewave voltage signal on the collector has room to rise to the supply voltage, or to fall to the saturation voltage of the fully turned ON transistor. The diagram above illustrates a minimum bias scheme to turn a transistor halfway to 6 volts, assuming a 12 volt supply voltage. To make calculating the base resistor easy, I left out the negative bias, emitter-to-ground resistor. All we need to know is the current gain multiplier of the transistor, the Hfe. The collector current will be Hfe multiplied by the base current. The diagram is labeled so that the supply to collector voltage and the collector to emitter voltage are equal, 6 volts. We only need to calculate the base current needed to turn the transistor half on:

Notice the 600 ohms collector resistor load. This resistance is practical for the collector load of an audio amplifier. The audio output would be taken from a capacitor soldered to the collector where it says "V_c." To turn the transistor "half on" we need to generate 6 volts across a 600 ohm load. We need a collector current of $V = I_cR$. Conveniently, the voltage across the transistor, V_{ce} , is also 6 volts.

$V = I_cR$ or, $I_c = V/R$
Therefore, I_c = 6 volts/ (600 ohms)
I_c = 0.01 amperes or 10 milliamperes

To find the necessary supply-to-base bias resistor, we first need to know the voltage across the supply-to-base resistor. Let's assume the base-to-emitter voltage, V_{be}, is the usual 0.6 volts DC. The voltage across the bias resistor will be 12 volts - V_{be} = 11.4 volts DC. I measured the gain of the actual transistor, Hfe, as 82. To produce 10 milliamperes, we only need 0.12 milliamperes.

Transistor gain varies with the input base current, but it's typically between 60 and 100 for the 2N3904. As a rule, bigger base currents produce less gain. This variable Hfe helps to protect the transistor from being burned out by big input signals. Conversely, it also makes the transistor sensitive to tiny input signals.

The base current, I_b will be the supply-to-base current divided by the bias resistance.

I_b = 11.4 volts / R_b, bias resistor
I_b, 0.12 milliamperes = 11.4 volts / R_b
$R_{b\,=}$ 11.4 volts / 0.12 mA = 95 KΩ

Learn to calculate all the resistances and currents in terms of KΩ and mA. That way the decimal point arithmetic, mA and KΩ, becomes automatic. This avoids constantly converting back and forth between amps, mA, ohms and KΩ.

PREVENTING THERMAL RUNAWAY

Temperature stability using negative feedback

Negative feedback makes a transistor stage design more reliable in several ways. There are the **three characteristics of transistors that change with temperature: I_{cbo}, Hfe, and V_{be}.** Negative feedback makes hot and cold transistors behave the same. This in turns makes your entire transmitter or receiver much more reliable.

Reverse Collector Saturation Current, I_{cbo}

We naturally assume that when the base current reaches zero, that the transistor will turn OFF completely and the collector current will be zero. It turns out that a small leakage current, the **I_{cbo}** still flows. Just like ordinary chemical reactions, **I_{cbo} doubles for every 10° C temperature rise.** This tiny current, usually a fraction of a microampere, can only be shut off completely by applying a reverse, base-to-emitter voltage.

Amplification gain, Hfe

Warm transistors have higher current gain than cold ones. In other words Hfe increases with temperature. For example, a 2N708 silicon NPN transistor, a base current of 0.4 mA produces a collector current of 20 mA at 25° C. This is a gain of 50 times. When the temperature rises to the boiling temperature of water, 100° C, the same base current will produce over 30 mA, an Hfe of 75. Also, the transistor might no longer be turned half-on. Instead, it will be approaching saturation, perhaps 80% turned on. If you touch a transistor with a wet finger and the moisture hisses into steam, you may expect that the transistor is about to fail, if it hasn't already.

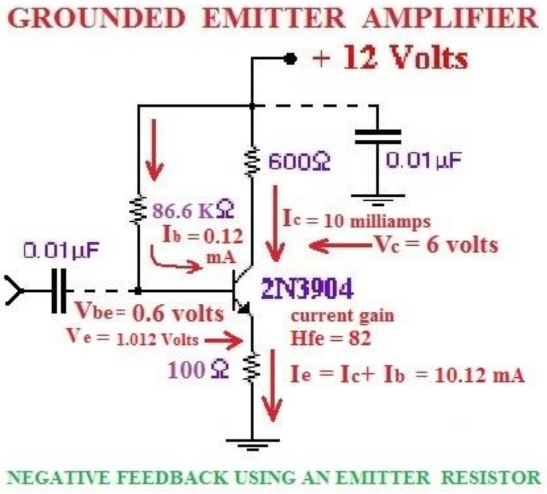
Base-to-emitter voltage, V_{be}

As temperature rises, the forward voltage offset will fall, e.g. 0.6 volts will decrease. This will increase base current and therefore collector current will rise as well. As you can see, all three of these variables tend to increase collector current and transistor heating. Temperature rise produces *POSITIVE* feedback. The more it rises, the more heating occurs. This in turn increases collector current and increases heating leading to transistor failure. This is ***thermal runaway*** and results in clouds of stinky smoke and loud cursing.

Emitter resistor negative feedback

Now we'll repeat the calculation adding an emitter resistor, R_e. When collector current rises due to temperature and the input AC or RF base current, the emitter current is almost the same as the collector current, so the emitter to ground voltage will rise. This in turn pushes the base voltage upward as well. The input bias and signal voltage will now have to overcome this additional voltage barrier. Typically, 0.6 volts base-to-ground will become something like 1.4 or 2 volts to ground. Consequently, the voltage on the base will have to rise considerably to maintain the same base current. This turns the transistor more OFF and lowers the transistor temperature. During actual operation the input capacitor will charge up to the elevated offset voltage, e.g., 2 volts. When AC signals appear on the input capacitor, the base voltage will still rise and fall above and below the resting voltage. The base will receive the same AC voltage as before, even though the DC resting voltage is higher.

In the circuit below, the 100 ohm resistor R_e has been added to the previous circuit.



The total resistance between supply and ground is now 700 ohms. Therefore,

12 volts = $I_c(600\Omega) + V_{ce} + V_e$

$Ve = (I_c + I_b)\ 100\Omega$
For Vc = 6 volts, I_c must still be 10 mA.
The base current needed to produce I_c = 10 mA is
10 mA / Hfe = 0.12 mA
Therefore, Ve to ground = (10.12 mA)100Ω = 1.012 volts
Let's assume that V_{be} is still 0.6 volts,
so V_b = 0.6 + 1.012 = 1.6012 volts.

The voltage across the base resistor will be:

12 volts - 1.601 volts = 10.3988 volts, about 10.4 volts.
Therefore, R_b must be 10.4 volts / 0.12 ma = 87K ohms

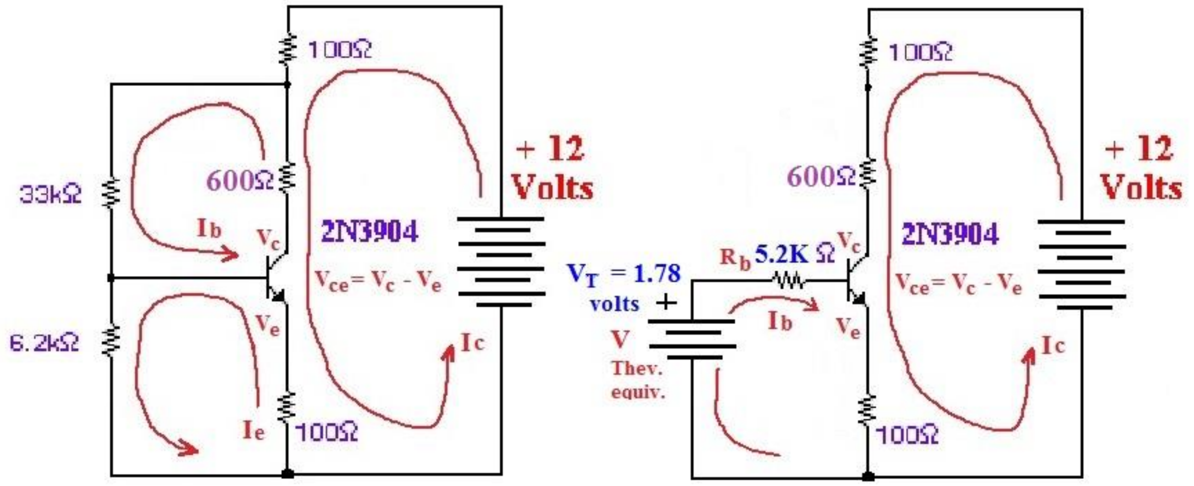
Three and four digits after the decimal point aren't needed because real parts aren't that accurate. Standard resistor values like 82K or 91K will work just fine. Three total digits, such as 10.4 volts, are plenty for most engineering purposes. Old time sliderules (like I used to use) produced 3 digit precision and that's enough for nearly all calculations in engineering. What is *REALLY* important is that we place the decimal point correctly.

The full calculation

Thevenin current loops & simultaneous equations

In the 1880s a French engineer, Northon Thevenin, showed that circuits could be simplified by defining a voltage source and a resistor to replace more complex resistive voltage divider circuits. When we put in the complexities of the full circuit shown at the beginning, the math difficulties increase significantly. Resistor collector loads of 600 ohms are practical in a low frequency, audio amplifier, so this calculation should be useful. The following is an example of how we engineers were taught to analyze a circuit like this:

Using a Thevenin equivalent circuit to reduce complexity



DC Thevinen current loops

Using an equivalent Thevinen voltage source

The first step is calculating the equivalent base resistor and Thevenin voltage "battery." The 33K and 6.2K bias resistors on the left can be thought of as two resistors in parallel. The parallel combination becomes a single base resistor. Yes, I know that isn't obvious. However:

$R_b = (33K)(6.2K) / (33K + 6.2K) = 5.2K\ \Omega$

The equivalent battery voltage V_{Thev} will be

Equation I $V_{Thev} = (\text{Volts at the top of the divider})(6.2K) / (33K + 6.2K)$

Unfortunately, thanks to the annoying upper 100 ohm resistor, we don't know the voltage at the top of the divider resistors. To find that voltage, we need to know I_c. Also, we write 100 Ω as 0.1K to make the decimal points consistent. We also know that $V_{(\text{top of divider})}$ will be slightly less than 12 volts:

Equation II (Volts at the top of the divider) = $[12 \text{ volts} - I_c(0.1K\ \Omega)]$

This can be substituted into equation I, thereby eliminating the $V_{(\text{top of divider})}$ unknown.

$V_{Thev.} = [12 \text{ volts} - I_c(0.1K\ \Omega)]\ (6.2K) / (33K + 6.2K) = 12\ (0.158) - I_c\ (0.1K)\ (0.158)$

$V_{Thev.} = 1.90 - I_c\ (0.0158)$

Equation III The voltages around the I_b loop are:

$V_{Thev.} = 1.90 - I_c\ (0.0158) = I_b\ (5.2K) + V_{be} + (\ I_{c+} I_b\ )(0.1K\ \Omega)$

Transistor gain, Hfe = 82, therefore

Equation IV $I_c = 82\ I_b$ or, $I_b = (I_c / 82)$

I_b is small but important in the I_b loop, but is only (1/82th) of I_c. Therefore let's ignore the tiny voltage contribution of the base current in the I_c loop in equation III,

$V_{Thev.} = 1.90 - I_c (0.0158) = I_b (5.2K) + V_{be} + I_c(.1K\ \Omega)$

$V_{Thev.} = 1.90 - I_c (0.0158) = (I_c / 82) (5.2K) + V_{be} + I_c(.1K\ \Omega)$

V_{be} = 0.6 volts base offset. Also, we now have two expresions for $V_{Thev.}$ We set the two expression equal and $V_{Thev.}$ disappears.

$V_{Thev.} = 1.90 - I_c (0.0158) = I_c (5.2K) / 82 + 0.6 + I_c(.1K\ \Omega)$

Solve for I_c

$1.90 - 0.6 = 1.30 = I_c [0.0158 + (5.2/82) + 0.1] = I_c (0.1158 + 0.0634) = 0.179 I_c$

I_c = 7.26 mA

We don't really need a number for $V_{Thev.}$ but just to be thorough,

$V_{Thev.} = 1.90 - I_c (0.0158) = 1.90 - 7.2 (0.0158) = 1.90 - .114 = 1.78$

$V_{Thev.}$ = 1.78 volts

The voltages around the I_c loop are:

Equation V 12 volts = $I_c(.1K\ \Omega) + I_c(.6K\ \Omega) + V_{ce} + (I_{c+} I_b)(.1K\ \Omega)$

Ignoring the tiny contribution of the base current,

12 volts $\approx I_c(0.1K\ \Omega) + I_c(.6K\ \Omega) + V_{ce} + I_c(0.1K\ \Omega) \approx V_{ce} + I_c (0.8K) = V_{ce} + 7.2 (0.8K)$

12 volts $\approx V_{ce} + 5.76$

Solving for V_{ce} , V_{ce} = (12 volts - 5.76)

V_{ce} = 6.24 volts

$V_e = (0.1K) I_c(.1K\ \Omega) = 7.26(.1) = 0.726$ volts

V_e = 0.726 volts

The voltage on the collector to ground will be 6.24 + 0.726 = 6.97 volts

V_c = 6.97 volts

In the very beginning, when I measured the actual circuit, **V_e was 0.8 volts** and **Vc = 7.4 volts.** This is close and not wildly wrong, but it is not accurate. That was a lot of work for an answer that wasn't quite correct.

The difficulty is that the "constants" I relied on, like Hfe and V_{be}, aren't really constant. Perhaps a better approach is to begin with an actual graph of 2N3904 transistor collector current versus collector voltage characteristics. This plot is repeated for many different base currents resulting in a family of curves plotted on top of each other. A "DC load line" is drawn across the family of curves. The end point of the load line on the horizontal abscissa is V_{cc} , which is +12 volts in our circuit. The end point on vertical ordinate is V_{cc} / R_L , or 12 volts/ 600 ohms in our circuit. With these plots we can see where the load line intersects the various curves for different levels of base current. The goal is to locate the exact I_b needed to reach the center of the load line. This turns the transistor half way on. The manufacturer's specs don't usually include such a plot and personally I don't care to spend the time to make my own.

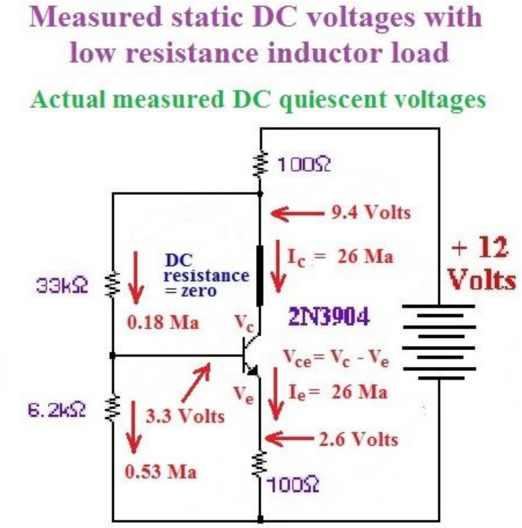
Complete bias calculation for a real RF amplifier

Our RF amplifiers are different from the above 3 circuits in three ways:

(1) Our collector loads in the RF amplifiers are just a few turns of wire so the collector resistance is essentially zero.

(2) We protect the amplifier stage from power supply voltage surges by means of a 100 Ω resistor and a capacitor. These help shield the amplifier stage from feedback from later stages.

(3) Instead of a single bias base resistor, the base is biased by a voltage divider, such as the 33K Ω and 6.2K Ω resistors.

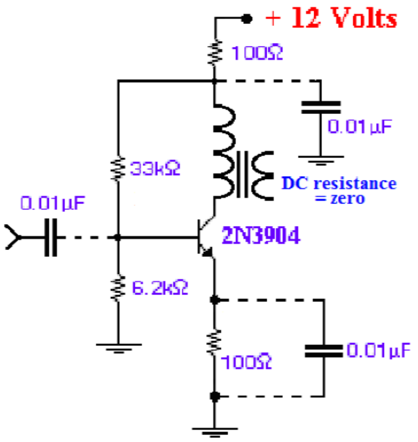


Measured static DC voltages with low resistance inductor load

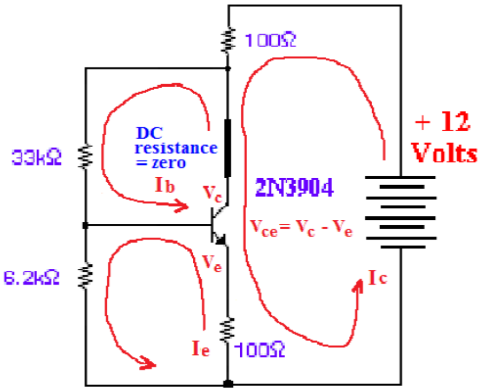
Actual measured DC quiescent voltages

Here are actual DC static measurements of the circuit described above. These measurements surprised me and made me remember why I abandoned the analysis methods I was taught in school. To begin, notice that the V_{be} base-to-emitter voltage rose from 0.6 to 0.7 volts. That wasn't shocking, but then I realized that the current through the 6.2K resistor is much greater than the current from the 33K resistor. The 0.53 mA must be coming from somewhere, so most of the current must be flowing out of the base from right to left. I didn't know that was even possible! Just like "simple" crystal sets, when you look closely, electronics always has more mysteries for you to solve.

BIASING A CLASS A RF AMPLIFIER



Original circuit



DC Thevinen current loops

I used the same math as before to find **I_c** and **V_{ce}** . My results for the RF amplifier were:

I_c = 7.2 mA and **V_{ce} = 10.56 volts**

The actual currents and voltages were:

I_c = 26 mA and **V_{ce} = 6.8 volts**

This is radically different from the real circuit. Clearly this second calculation wasn't worth doing. The backward flowing base current should have been my first clue. And now you know why many engineers resort to rules of thumb and trial and error. Computer circuit simulation programs like Spice work much better than these tedious calculations. Unfortunately, Spice is only useful if the program has a full, detailed description of the transistor or integrated circuit it is simulating. From now on I'm going to use Spice when I can. Otherwise, I'll make trial circuits on a punch board prototype. That way, I can figure out the bias before I hard wire it into my project.

How the professionals do it

Free "student" circuit analysis programs like "5Spice" work really well for designing L-C or R-C filters. Alas, they will probably work poorly for circuits with transistor or integrated circuits because they don't contain precise models of the parts we're using. Professional Spice programs used by electronic firms work well but cost thousands of dollars. When my employer bought one, we had to enter our custom activation code - a half page of solid gibberish - a 30 minute job.

In the company where I worked our chief electronics engineer, Al Owens, was actually a technician, trained by the U.S. Navy. Unlike me, he had the patience to dive deep into math solutions and make them work. The super Spice program described above was his project. It took a year of spare time work, but he managed to simulate all the circuit boards used in our product line. Using Spice, he analyzed the component tolerances for every part. He adjusted component values and tolerances so that production boards worked every time, regardless of how random probability combined the individual parts. This largely eliminated board failures and trouble shooting by the production technicians. Since the circuits were always electrically correct, the repair guys only had to fix mechanical faults, such as cold solder, misaligned parts and so on.

Math and physics

The community of physics professors has recently had a wake up call. Their beloved "string theories," multiple dimensions and parallel universe theories are proving useless. They must swallow the inconvenience of having mother nature disagree with their calculations. Many physicists have assumed that, if their math is logically correct, nature must follow the math. Unfortunately, mother nature doesn't always use the same logical pathways followed by ignorant human physicists or dumb electronics engineers. Conjecture, guesses and math is often useful for *BEGINNING* a search for knowledge in physics. But very quickly, if the "theory" fails actual measurement or can't even be tested, the theory is useless and should be discarded. Let's all remain practical and we'll make the most progress.

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Retuning a crystal controlled QRP for other bands

It is awkward to build a new QRP for every band. On the other hand, the upper bands above 20 meters are not always open and, if you have a 15 meter or 10 meter QRP, you may not have much chance to use it. It should be possible to plug in an appropriate crystal for bands other than the original design. Then, if your trimmer capacitors have enough range, it is often possible to tune up the QRP for several different bands. Notice that the broadband output stages will work on any HF band, so only the stages with trimmer capacitors need to be retuned. The other limitation is the Chebyshev output filter. This could be solved by having plug-in output filters. This isn't easy bandswitching, but it's not impractical if you are anxious to get on 20 or 30 meters and all you have is a 40 meter QRP.

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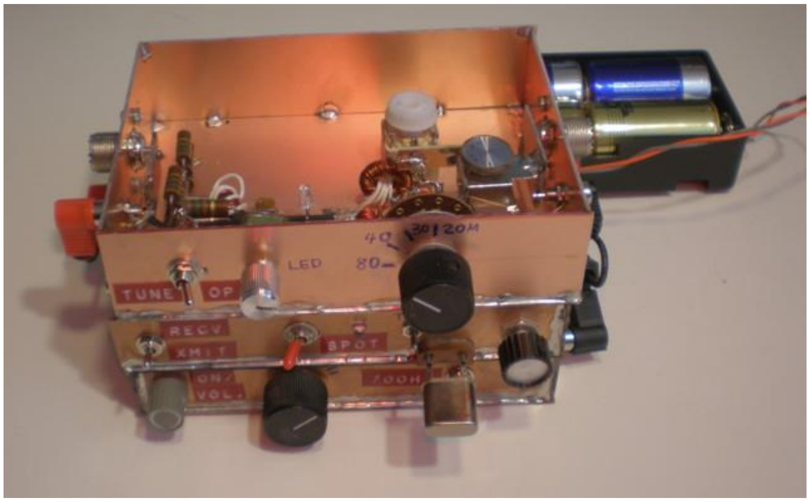
Necessary accessories for your QRP and matching it to an antenna

Power supplies for your QRP module are explained in Chapter 8. Other necessary accessories, such as a telegraph code key and an antenna tuner are discussed in Chapter 9. The QRP, the antenna tuner and the direct coupled receiver described in Chapter 7A are shown below. The transmitter and receiver are powered by a battery pack consisting of eight ordinary alkaline D-cells. The battery holder came from Radio shack. How to tune your QRP to an antenna is also covered in Chapter 9.



A complete 40 meter receiver, transmitter, antenna tuner and battery pack