Building FM broadcast transmitters from common parts

A problem with a lot of designs for FM broadcast transmitters is reliance on parts that may not be easy to obtain, such as IC's that are specific to generating a wideband FM signal, and specific amplifier transistors that may have been common at the time and in the place the circuit was originally built but may no longer be easy to find.

Assuming the builder does not want to order parts online from domestic warehouses that no doubt keep credit card records available for government surveillance, that leaves local sources and private sellers on Ebay. Online transactions can use prepaid debit cards to avoid leaving computerized records.

In most communities, you will find two main sources of parts: Radio Shack, and tearing down junked electronics for parts. You will rarely get everything you need from these sources, although you might get lucky if you break down enough TV type stuff to find the small ceramic tuning capacitors you need and find a mica trimmer or two in some really old tube stuff. You will absolutely need a tuning capacitor from a small battery powered FM radio, they seem to be the most stable kind for making the tunable oscillator in the “premix” type exciter we've had good luck with at WSQT.

Hamfests are still a good source of all kinds of goodies, ranging from crystals to tuning capacitors to whole old radios that can be broken down for parts. Don't let on your real use for these parts, and remember that the only thing that might be an issue for a seller at a hamfest is a complete, functioning ham transmitter or especially a linear amplifier. Look for trimmer capacitors , 27 MHZ CB crystals, 32 MHZ crystals, and VHF bipolar power transistors. Hamfests are also a good place to get all those computer goodies you might want as well.

In or near most larger cities you should be able to find at least one electronics supply house that sticks transistors, trimmer caps, and fixed ceramic capacitors and resistors in sizes no longer found at Radio Shack.

A related issue to availability of parts is the recent increase in “dirty” signals from pirate transmitters made with low-cost PLL chips meant for “Part 15” usage where spurious outputs can be permitted to equal the signal strength. Spurious outputs within a megahertz or two of the desired signal are nearly impossible to filter out at operating frequency. These little radio sets are tempting to use as exciters, as the digitally-tuned ones are right on frequency, but beware: Unless you get lucky, you will get nearby signals that interfere with neighboring signals and can never be filtered out.

At WSQT, lack of access to PLL chips led to the adoption of the “premix” or “heterodyne” type of FM transmitter instead of a PLL. This layout appears in some kinds of ham gear, as it offers hams the ability to translate a good signal on one amateur band to another band otherwise unchanged. For our purposes that means being able to make a stable low-frequency VFO with varactor diode frequency modulation, then translate that up to a frequency in the FM broadcast band. At frequencies under 10 MHZ it is not difficult to build a VFO that drifts less than the typical tolerance for offset carriers in FM receivers. The FCC standard is plus or minus 3 KHZ, which would be very bad drift for a low frequency VFO. Tuning of this kind of transmitter is very similar to aligning a receiver, and doing exactly that a few time on junk radios will give you the practice you need to tune these circuits and make them work.

TEST EQUIPMENT

You will need an “electronic voltmeter” that reads voltage without taking power from the circuit.

You will need either a “dip meter,” a general coverage receiver covering from the AM broadcast band continuously to the top of the aircraft band, or better yet, both. You will have to be able to detect and measure not only your final frequency, but also the frequency of every intermediate oscillator or multiplier in the circuit. If you will use any frequency multipliers, the dip meter is mandatory. You can make one yourself from plans in some editions of the ARRL “Radio Amateur's Handbook”

You will absolutely need a radio that can tune the entire FM broadcast band and the aircraft bands above it. You must be able to check both the 108-118 air navigation beacon range and the 118-134 MHZ aircraft communications channels to make sure they are free of interference from your transmitter! Look from about 25 feet away while running into a “dummy load” to avoid overloading the receiver and generating the interference. You will also need a digitally-tuned FM receiver like a car stereo so you can check what channel you are tuned to and that your signal is centered in the channel so it is not distorted in this type of receiver.

You also must have a “dummy load” which substitutes for the antenna while testing the transmitter. You will make all kinds of interference in testing and adjustment, these must never go to an antenna. A dummy load is just a bunch of resistors that substitute for the antenna in testing. A dummy load that will take 60-80 watts for about 30 seconds or 15 watts all day can be made from 15 1 Kohm, 1W composition (not wirewound) resistors. Make a tin box jut big enough for an antenna fitting on one end, a copper wire most but not all of the way to the other end, and 7 resistors on one side and 8 on the other almost touching but side by side. Add a trio of mall-signal diodes in series, all cathodes pointing away from the hot side, from the center wire to a capacitor to the box, which is the ground side of the antenna fitting. You can now measure power with an electronic voltmeter by this formula. First, measure the resistance of the load. It will start at about 72 ohms (all WSQT FM rigs use 72 ohm cable TC antenna feed line), but drop with use and repeated heating yo about 69 ohms. To measure power, read the DC voltage at the junction of the diode and the capacitor with the electronic volt meter, multiply by .707 as this is peak and not RMS voltage, then square the result. Divide by the load resistance, and that is your approximate power output. It's not exact because of meter errors and the fact that the load is not a perfect resistance, it has some inductance and capacitance.

You will need and SWR meter to set up your antenna.

You will need the usual soldering equipment, and a battery big enough to run your transmitter in testing. If it will be AC powered, build the power supply first and use it while building the rest.

Selection and Acquision of Parts

A lot of the stuff you buy at Radio Shack is cheap as individuals parts, but adds up fast and becomes shockingly expensive. It's really easy to blow $100 on parts if you use mostly new ones bought as individual parts. Get assortments whenever you can, you will save a lot of money. Be sure to get the resistor, capacitor, and inductor assortments offered at Radio Shack. The capacitor assortment is not as good as it used to be, no longer containing values intermediate between 1 and 10 PF, between 10 and 68pf, or between 68 and 100pf. You will have to supplement it with capacitors removed from old TV and FM radio circuit boards, or bought at a real electronics warehouse.

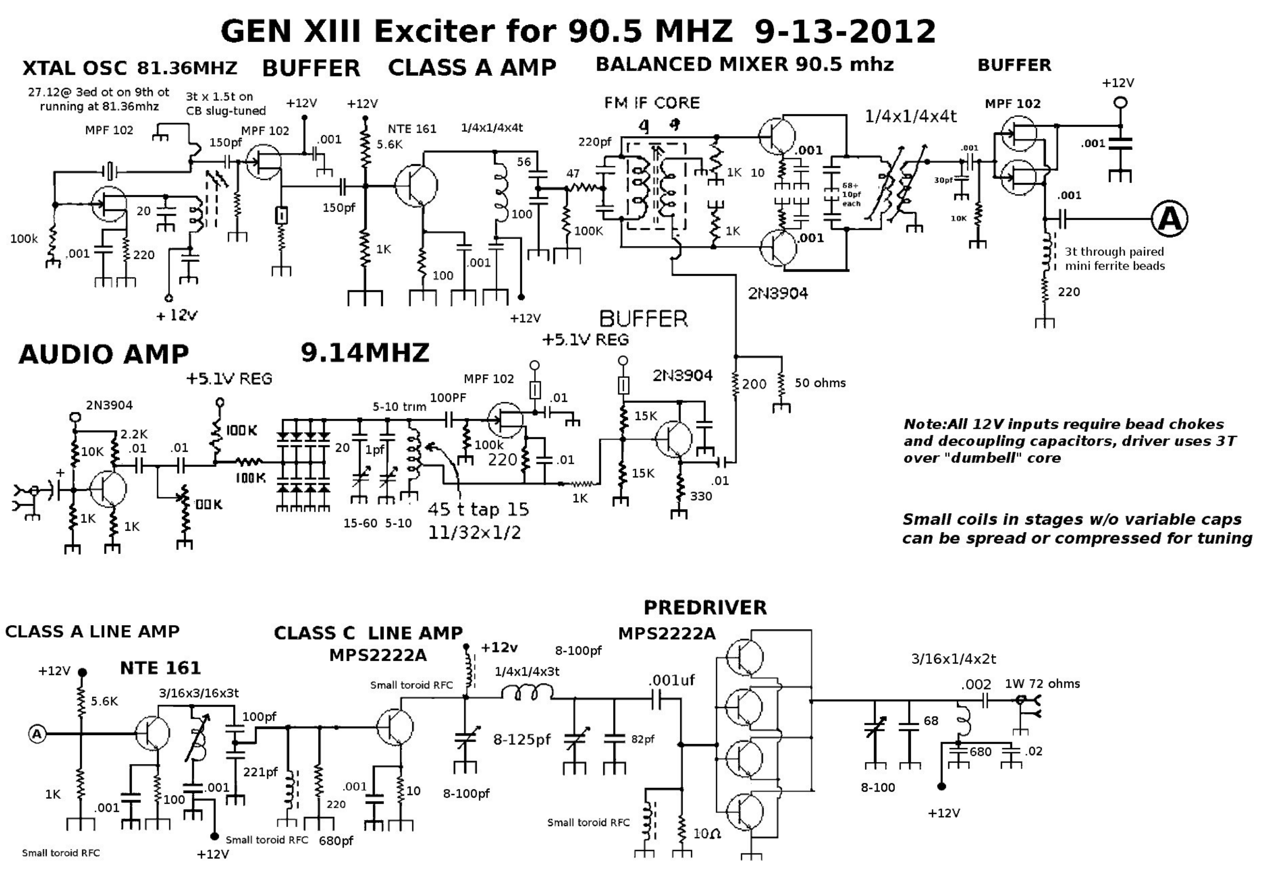
Note: a lot of times no inductor assortment is offered. You will find molded chokes and can-shaped chokes with “dumbell” ferrite cores within on old circuit boards, as well as boatloads of resistors and capacitors. Hit the dumpsters, collect old transistor radios, TV, especially things like VCR's and tuners.

We will discuss the big PA amplifier transistors in the power amp section, but these will be something you will have to get at hamfests or on Ebay. Some newer ones can be bought new from electronic warehouses if there is one in your town, but will cost big bucks. I've seen new prices over $100 for a transistor that on Ebay will be reliably available for $30-$40 and can bought by bidding as low as $10-$20 or so!

Evolution of the WSQT heterodyne transmitter design

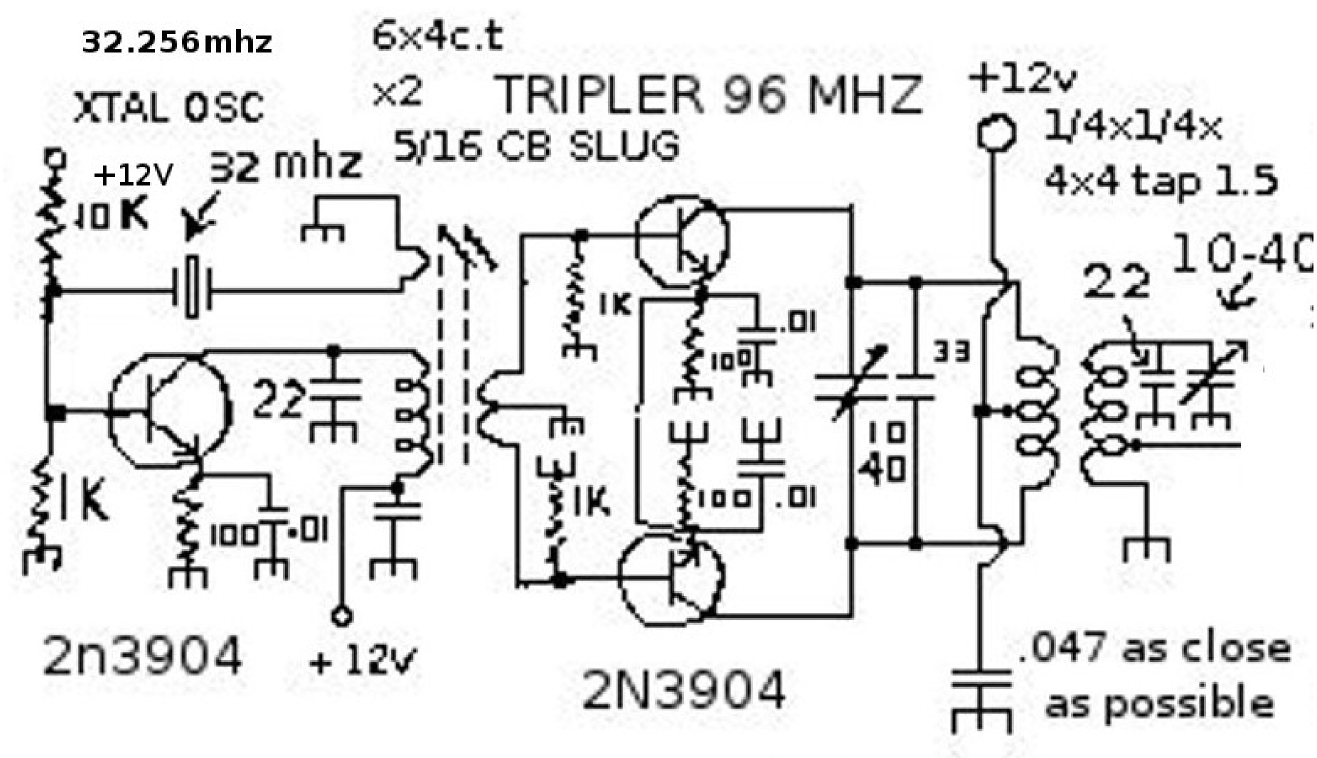
A Spring 2004 VFO controlled AM transmitter used at WSQT drifted maybe 400HZ as it warmed up, which of course is completely unacceptable for AM on 1680 khz, leading to a replacement that heterodyned a 14.318mhz crystal against a 16.000 crystal to give 1682 KHZ, easily pulled to a stable 1680 for AM broadcast use.

The FM band is a little more complex: You might be able to FM a low crystal and muliply it to an FM frequency, but I've never once found a crystal in old equipment that would be useful for that, and good modulation quality would be unlikely. Therefore, a stable crystal oscillator running close to the final frequency and a tunable oscillator making up the difference (or sum) were adopted. The crystal must be far enough from the final frequency that it can be filtered out, and that the “image” signal on the opposite side of the crystal can be filtered out. On the other hand, that frequency must be low enough that the drift of the VFO, one properly set, is not enough to create distortion or muting in digital-tuned receivers. Between 5 and 10 MHZ seems to work well. Typical WSQT “premix” transmitters were able to use the same oscillator settings even between winter and summer in unheated conditions if everything else was working right.

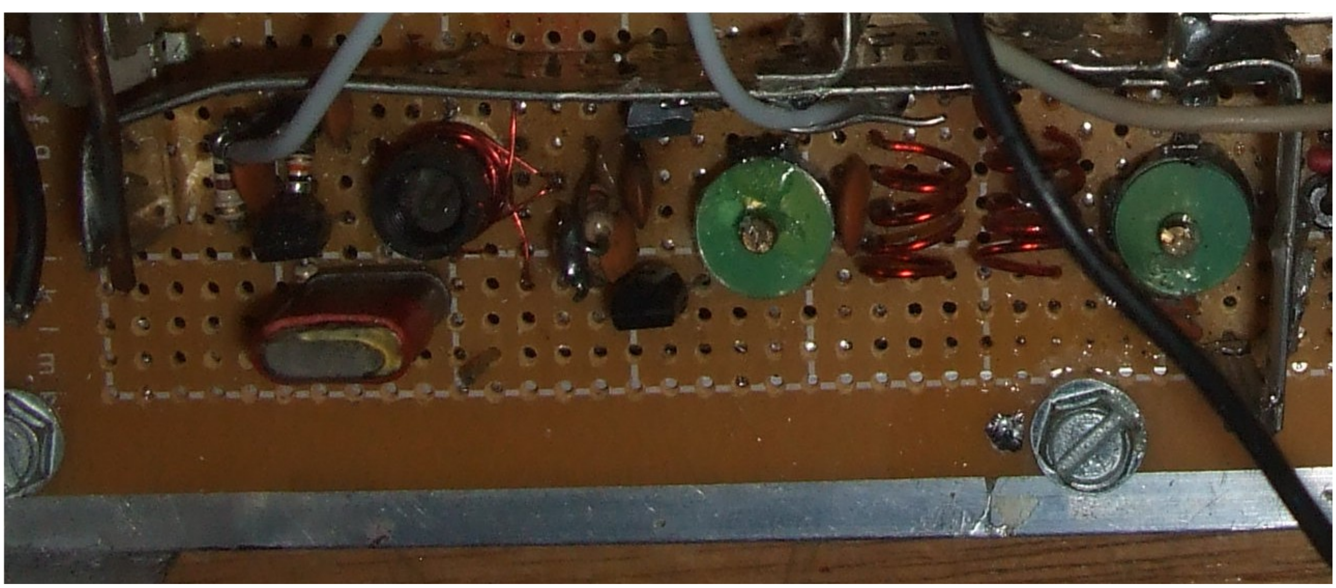


CB Crystals and triplers

A good tripler can give 81 MHZ from 27, or 96 from a 32 MHZ crystal, also fairly common. The tripler's tuning will be critical, as it must not pass the 2nd nor the 4th harmonics of the crystal. For both the tripler and the mixer, doubly-tuned circuits, consisting of two identical coils separated about half their diameter tuned to resonance with appropriate capacitors, must be used. In addition, the tripler should be a “push-pull” design to greatly weaken even harmonics. If you have a crystal requiring a doubler, a “push-push” circuit with the input in push-pull but the output in parallel, would be used to suppress the fundamental and 3ed harmonic. Since you are not using matched transistors, however, this protection is imperfect and you must rely on critical tuning of the doubly-tuned output circuit to do the rest.



Typical crystal oscillator and tripler as used in many WSQT transmitters



Spurious outputs from triplers can make spurious transmitter outputs

The worst problem in premix mirrors that of bad PLL chips: in-band spurious outputs that cannot be filtered. This comes from harmonics of the low oscillator mixing with unwanted harmonics of any frequency multipliers used to run the CB crystal frequency up to 80 MHZ or so.

The tripler circuit can give a clean signal if properly adjusted and was used for years at WSQT without problems, but was replaced when it gave trouble in a rebuild of the transmitter using a 27.12 crystal, for 81.36 MHZ as the tripler output, along with more potent NTE 161 transistors in the tripler in an attempt to improve output. The problem turned out later to be simple: the new tripler made too *much* power, and if you tuned the tripler by mixer output the tripler ended up badly detuned to lower its power, raising the output of undesired harmonics like x2 and x4. This won't happen if the tripler is tuned directly and a resistor used to set the desired output power level. Never try to tune any previous stage by looking at the output from the mixer!

The main difficulty with this circuit is the “spur chart.” Not only the output frequency but also the 2nd and 4th multiples of the crystal can get into the mixer. Once there, they can beat with harmonics of the low oscillator to make weak signals of their own. If any of these appear within about 2 MHZ or the final frequency, the filtering in that double-tuned tripler output, and the use of a low power in the low-frequency feed to the mixer plus a lot of output from the tripler, are the only things that can stop them. Unfortunately, the latter two conditions tend to be mutually exclusive, as the output coils filter best when far apart but give best output at a closer, critical distance that must be found by experiment. The mixer output circuit cannot stop anything inside about 2 MHZ of the center frequency it is set to!

9x overtone crystal oscillators as an alternative to the tripler

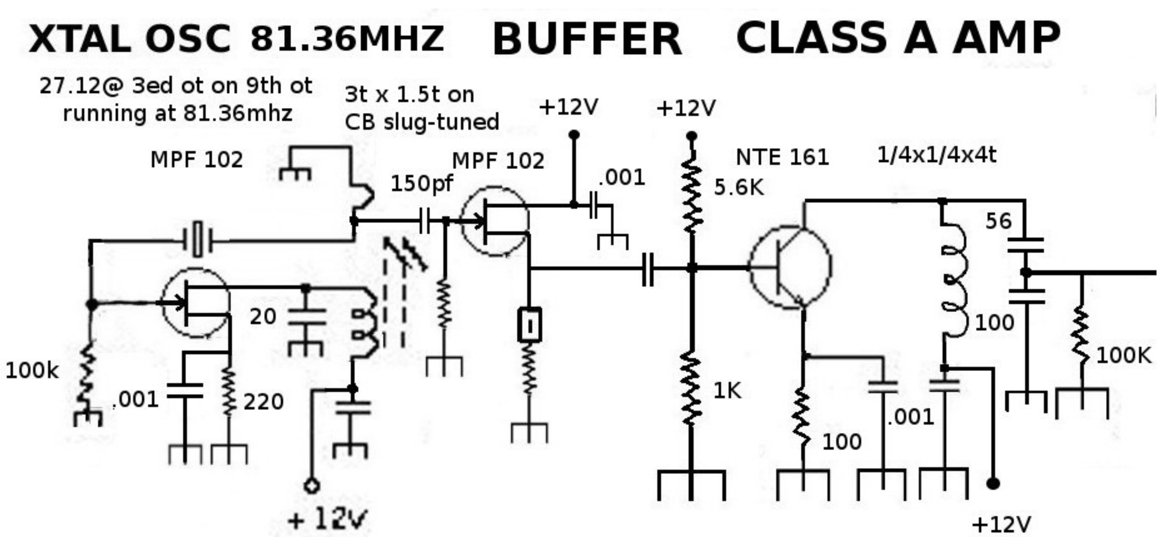
The best solution is not to use a multiplier at all, and run the crystal itself at three times it's marked frequency. Now the spurious outputs must come from 2 times the high frequency and a high multiple of the low oscillator, or else just the nearest multiple of the high oscillator. These are usually so weak as to be difficult to detect from outside the receiver overload distance when running the transmitter into a dummy load. Spurs so weak that they are only receivable by a receiver so close that it makes it's own distorted versions of your signal in most or all nearby channels can generally be ignored as they will not be heard as long as you don't site your transmitter somewhere that people's receivers will get a signal so strong they overload. If you do, you will have other and bigger problems anyway that can only be stopped by moving the transmitter or lowering it's output.

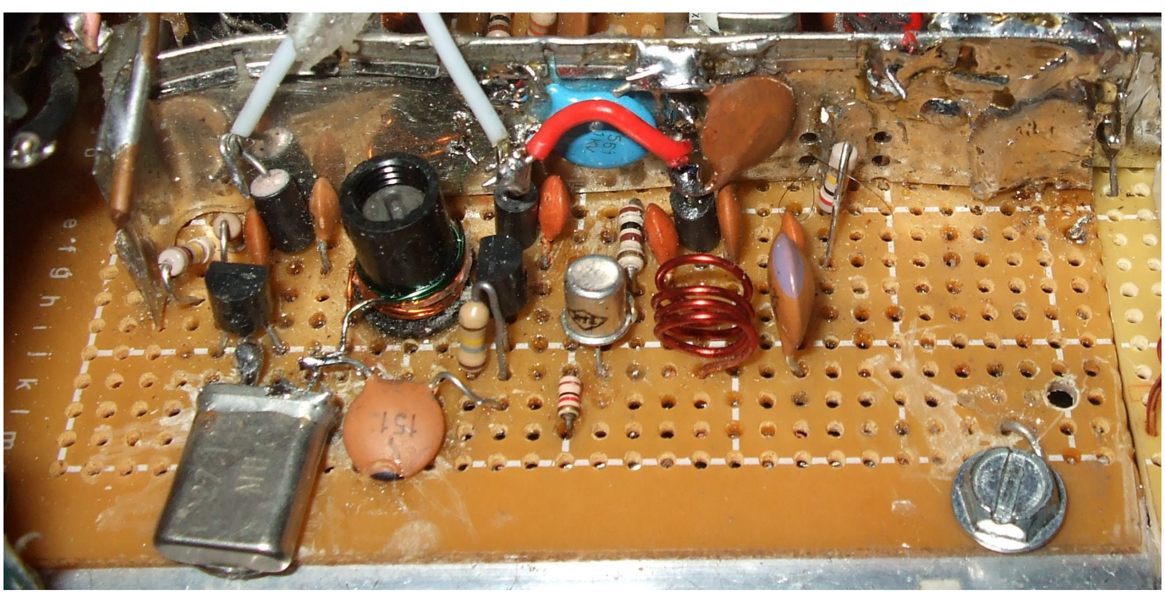
You cannot run a crystal that was designed to run at, say, 11 MHZ at 99, but you can if that 11 MHZ crystal was manufactured to run at 33. Many-but not all-crystals will run at almost exactly 3 times their marked frequency. If the crystal is running at it's fundamental at it's marked frequency, this is usually pretty easy. Most CB crystals that will run at 80 MHZ or so, however, were made as 3ed overtone crystals. They will run at their 9th overtone, but only in a special circuit. Some will either refuse to run at all, while others will pass enough energy around themselves to let this circuit run at any frequency, ignoring the crystal altogether. I've had best luck with 3ed overtone crystals meant for CB use or use in the “low-band” VHF range around 32 MHZ.

Only JFET or MOSFET transistors seem to work on a 9th overtone circuit, If you can find a 27 MHZ or so *fundamental* crystal that is a conventional design like a lower frequency crystal, that might be an exception and in any rate would work very well, giving good output with the JFET. You might have to experiment with how much feedback (top coil winding in the diagram) and even how much coil to how much capacitor to use to get this circuit to work as a 9th overtone oscillator. You can tune the rest of the circuit with the crystal bypassed with a capacitor to get it roughly tuned, then remove the capacitor.
If the crystal won't oscillate, try more or less feedback, if that doesn't work or the oscillator runs without regard for the crystal frequency, try another crystal.

The MPF 102 is a common, cheap JFET available even at Radio Shack. Two are needed: one for the oscillator itself, and a second for a buffer, as the oscillator will stop if you hook it to a bipolar transistor..

I used an NTE 161 as the amplifier after that, but two stages of 2N3904 amplifier would use easier to get parts and probably more output. One 2N3904 amp before the mixer was enough in the rig using a tube final amp used in 2005-2006, in fact. Here's the circuit used in Summer 2012, shown with an NTE161 amp after the buffer:

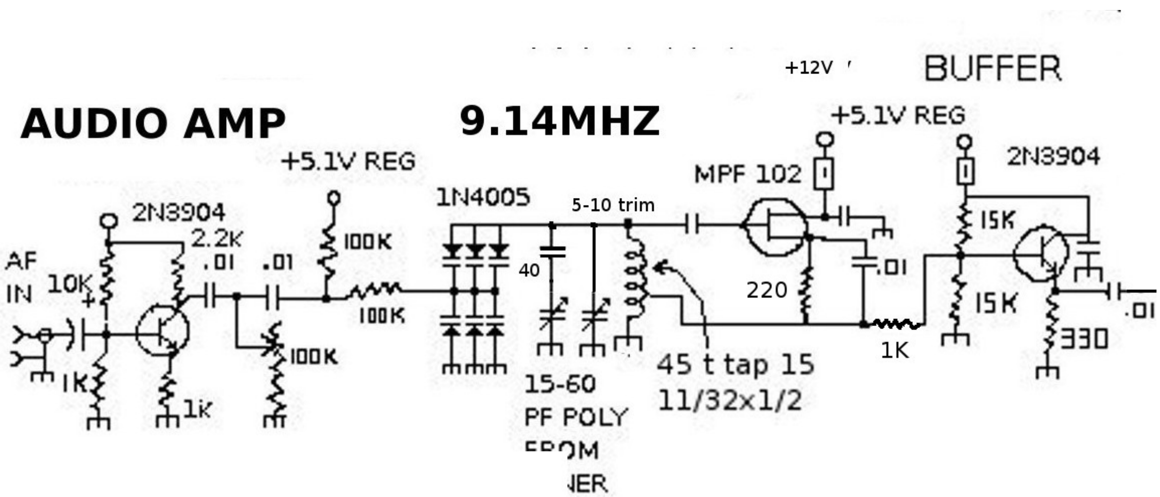


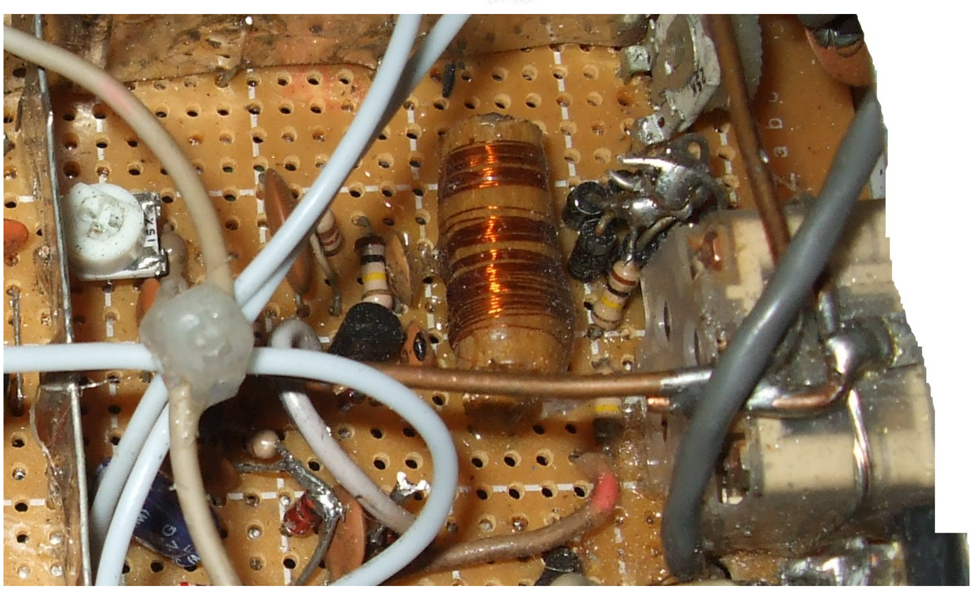


Low side variable oscillators

The low oscillator is the part that allows you to set the frequency to center of the chosen channel, and permits the frequency modulation to be applied. There are a few tricks here to getting the needed stability: The coil should be wound on a wooden dowel rod out of fine magnet wire, then glued in place with epoxy. Solder the wire to coper wire “pins” installed in the dowel rod first, then coat the entire assembly except for the pins with epoxy. This keeps moisture from swelling the wood, which would change the coil dimensions and frequency. It also restrains the windings from moving mechanically, or trying to expand and contract with heat more than the sealed wood. The other issues are the transistor and the capacitors. Disk ceramic capacitors in the tuned circuit must be marked “NPO” or have the black-dipped tops, to indicate a near-zero change of capacitance with temperature. The variables must be good ones, I like re-using one from an old analog-tuned radio. Be sure to use the “FM” side! A small (5-10pf) trimmer can help you center the transmitter frequency later, I've never had trouble from using one. A second standard variable in series with a 10pf NPO capacitor would probably work as well.

This oscillator should against use a JFET like the MPF102. That's because temperature changes affect them less than any other transistor. Use another as a buffer to isolate the oscillator from any tuning changes in the mixer-leaving out out in Summer 2005 meant having to retune for just a 20 degree F temperature change in a non-air conditioned building.





Secrets of avoiding drift in VFO'S

Here is a rewrite of 14 tips for stabilizing VFO's written by an Amateur Radio operator (ham) named "Harris." It has been shortened for spaced and edited to reflect the FM builder's needs.

Secret # 1. Use Junction Field Effect Transistors (JFETs). The first secret of a stable VFO is using a JFET instead of a bipolar transistor. The junctions in bipolar transistors change with temperature-a LOT. I've seen PA and driver bipolar amps that have to be tuned hot and take several seconds to come up to power. If tuned cold, their power will drop for 30 seconds or more as the tuning changed. In an oscillator, it would be your FREQUENCY that would be changing!

Secret # 2. Seal the VFO in a cast metal box. None of the WSQT rigs have done this, but all do put the VFO in it's own shielded compartment. The FCC drift standard for FM broadcast is 3KHZ, but hams need oscillators stable sometimes down to 5HZ per minute, which is AM broadcast crystal territory. They can't get this without a heavy metal box for the oscillator. If you have to go to a frequency above 10MHZ on the VFO to tune your channel, this can help control drift

Secret # 3. Use only single-sided PC board for oscillators. A double-sided PC board is constructed like a capacitor, and changes that capacitance with temperature

Secret #4. Mount the oscillator PC board away from the metal case on standoffs. Same as above, sitting the oscillator board directly on top of metal means capacitance, and the distance to that metal will surely change with temperature

Secret #5. Choose and mount all components affecting the oscillator LC circuit carefully. Make sure everything is soldered down so it can't move, and never cut corners on parts selection here.

Secret # 6. Mechanical variable capacitors should be chosen carefully. The small tuning caps from old FM radios I use seem to be plenty stable for an FM broadcast setup, but would never work in a ham receiver's VFO. They need big brass tuning capacitors. If you have one that will fit, use it.

Secret # 7. Varactors are the most stable tuning element: Another option is to not use ANY tuning capacitor at all, and put a pot in the line to the modulating varactor to fine tune the frequency within one channel. Don't try to tune farther than that with the modulator diodes or you will run out of voltage for the AF modulation peaks combined with oscillator RF peaks, though. Add or remove small NP0 capacitors to get to your channel this way, or start with any variable, then take it out and measure it's C if you have a capacitor testor. They change frequency with temperature as much as 10 times less than tuning capacitors. This means don't blame the modulator for drift unless you didn't use regulated voltage to it. *Note: Other authors disagree with this,* saying they got MORE drift using varactors, but since an FM oscillator already has to have varactors, might as well use them. All but one of the WSQT oscillators used 1N4001, 1N4004, or 1N4005 ordinary rectifier diodes as varactors, they work fine, giving about 10pf per opposing pair at 5.1V/

Secret # 8. Use only NP0 fixed capacitors in oscillators. When selecting fixed capacitors, look for type

C0G
(formerly known as NP0). These are supposed to have minimum temperature change. Use these for ALL fixed capacitors affecting the LC circuit.

Secret # 9. Use multiple C0G(NP0) capacitors in parallel to achieve a given value. They warm up fast, then settle down.,

Secret # 10. Temperature compensation for the LC circuit. Never used in for FM broadcast, but again, hams use it to get far better stability than ever needed for FM broadcast with that +-3KHZ standard under our 75 khz FM modulation. An oscillator with this might be able to get enough stability to work the FM band directly, with no mixer and no premix, if also in a cast aluminum box and supplied by a precision-regulated supply. Haven't tried this, it might work.

Secret # 11. Use ONLY "air core" inductors. Toroids and slug tuned coils are fine in crystal oscillators(like the 9x overtone oscillator elsewhere in this document) but are very temperature unstable. Air core actually means no metal, no conductors, and no magnetic materials inside or near the coil. Ceramic and wood forms should be fine. Always epoxy the windings in place so they don't move and change your frequency! If a wood form is used, cover it completely with epoxy so it doesn't absorb moisture and swell, changing the value of the inductor. This is what is used in WSQT low oscillators and seems to work very

Secret # 12. Voltage regulation: You can't run any VFO for any purpose without regulating the B+ voltage to the transitor or it will be very unstable. This goes double for the modulator bias voltage. Best system of all is to use what are called "precision zener diodes," which are actually IC's that are used just like a zener diode but are far more precise. The LM317 type voltage regulators are also more precise than zeners. Most FM transmitter designs I've seen use ordinary zeners, there have been WSQT transmitters that did not have to be retuned between winter and summer use in unheated buildings using them. If you run on batteries though, make sure the zener voltage is far below your battery voltage or you will get bad drift. This means if you need 8 or 10 volts for a varactor tuned, no tuning capacitor setup, you will need an IC type voltage regulator.

Secret # 13. The VFO should draw as little power as possible. The less power drawn, the less heating that occurs inside the VFO box. Also, the less power drawn, the easier it is to build a precision voltage supply to drive the VFO. That is why the VFO was designed for a 500 ohm load rather than 50 ohms like most ham RF circuits. The VFO as a whole should draw less 20 mA DC. 10 mA would be even better.

Secret # 14. Forget tube oscillators, even in tube amplifer setups. They drift ALL OVER THE PLACE. The 2005 WSQT tube setup made 55W, everything up to the driver was transistors. The PA was a pair of 6146-B tubes simply because nobody associated with the project had any access to good VHF PA transistors at that time, while these tubes are used in AMPEG bass amps. In 2006, a rebuild got 100W out of that setup but it was not deployed.

MIXERS

This is the component that makes a heterodyne or premix transmitter possible. Many designs exist, but I prefer the singly-balanced mixer using transistors instead of diodes. The common diode ring doubly-balanced modulators do a better job of keeping low oscillator fundamental output away from the output port-but perform worse than singly-balanced mixers in terms of keeping harmonics of the low oscillator out. In Summer 2004 experiments at WSQT with diode ring mixers were abandoned due to severe spurious outputs that appeared to be simply the 11th harmonic of the low oscillator. Needless to say, this was never deployed in the field!

When WSQT broadcasts switched to FM for good in 2005, something better than a straight variable oscillator setup was needed, and that proved to be the singly-balanced (push-pull) mixer using transistors. Either JFETS like the MPF102 or bipolar transistors like the common 2N3904 can be used. Do not try to use high-gain bipolar transistors like the NTE 161, they are hard to keep from oscillating in some circuits and are very easily destroyed in a mixer for some reason. I burned out two pairs of them trying to build a higher gain mixer with NTE 161's. In my experience bipolar transistors give better output, best results have been with the 2N3904, available at Radio Shack.

Here's how it works: the output from the crystal oscillator's amplifier or tripler is fed to both sides in parallel, and must be the stronger signal. It switches the transistors on and off. There is no output with just this signal, as each transistor's signal is cancelled by the other. The low oscillator's signal is fed in push-pull, in this case by a tuned transformer made from a 10.7 MHZ IF “can” taken from an old radio and rewound. It's internal capacitor is removed, and a center tap between two identical external capacitors in the output is the feedpoint for the high signal. The low signal unbalances the circuit, and the result of this is that only the mixing products of the two signals can escape-in theory.

Since the output is in push-pull, the high oscillator signal is cancelled in the output, making the job of the output tuned circuit as a filter far easier. Otherwise, this would be the strongest signal and much harder to block. The low oscillator output is effectively shorted in the output by the tuned circuit, and even harmonics of it (but NOT odd harmonics) are reduced by cancellation just like in the tripler.

You might find you can tune to the high frequency oscillator s signal in some cases, but you will be more easily able to tune to that frequency plus or minus that of the low oscillator. The output circuit makes sure only one of those, not both plus the high oscillator, gets out. It is a double-tuned circuit and the whole thing looks a lot like the tripler. *This is the most critical circuit in the whole transmitter-tune it wrong and you will broadcast on the wrong frequency or on several at once!*

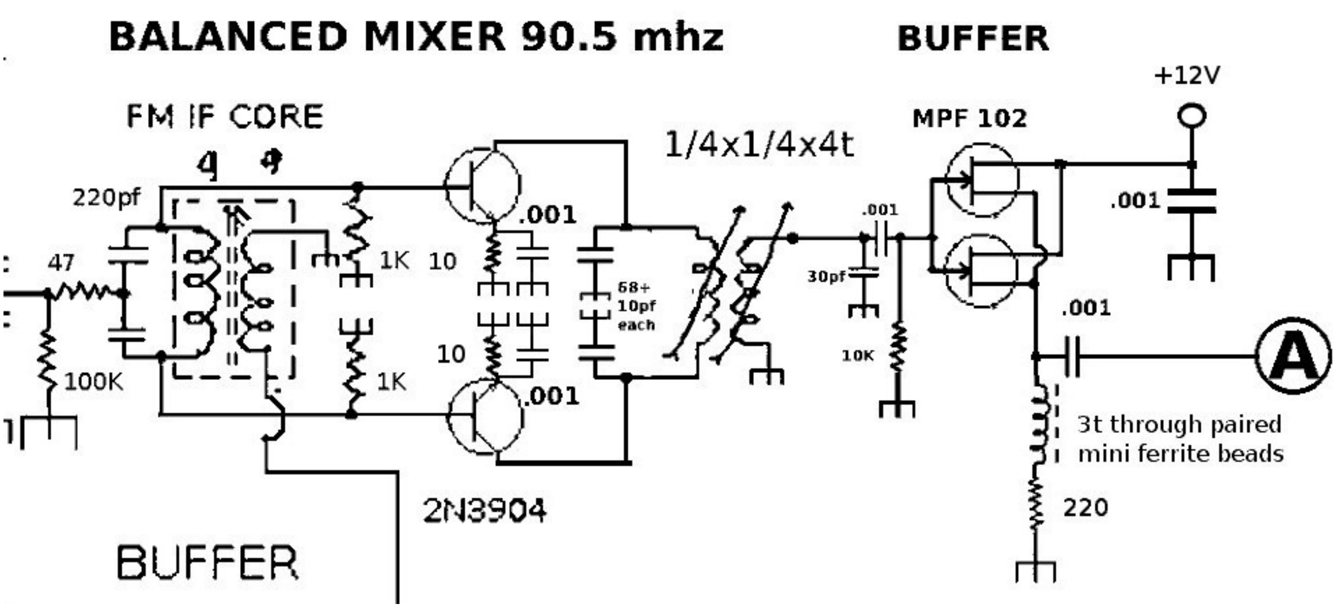
Like the tripler, the balance is rarely perfect. If it was, no spurious signal created by even harmonics of the low oscillator would escape, and if it's anywhere close you won't be able to tune the output circuit to pass the high frequency input frequency . Still, if the high signal is clean, harmonics of the low oscillator are usually too low to be heard. If the high signal is strongest, the strength of each mixing product is in proportion to amplitude of the low oscillator signal or harmonic making it. That means higher harmonics make weaker unwanted outputs.

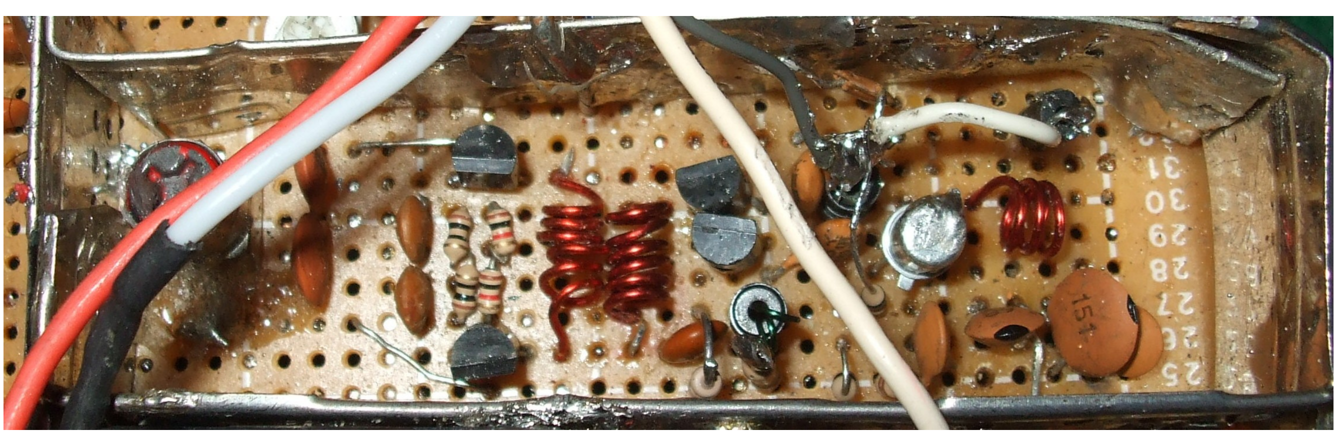
You will need a voltage divider in the line from the low oscillator to adjust levels. You might find you need a resistor between the crystal frequency amplifier (or tripler) and the mixer as well. The high frequency input should be about 10 times the power of the low frequency input, or about 3 times the voltage as measured with a small diode in series with an electronic voltmeter.

Never run either input so high the mixer transistors saturate, or the output will drop, as the other side then has less influence. If you have extra power available from the crystal frequency amp or tripler, first tune to resonance, then use resistors to lower both inputs until the mixer output is at it's highest. Never try to tune the crystal frequency amp or especially a tripler by watching the mixer output, or you will tune it far from resonance and feed harmonics or unwanted multiplier products to the mixer. That will cause spurious signals in the mixer output.

Do saturate at least one amp after the mixer, though, to get rid of any amplitude modulation coming from the low oscillator. This makes a much better sounding signal with less “splatter” into neighboring channels.

I've found an output buffer of 2-4 MPF102 JFETS to work better than anything else for coupling the mixer to the amplifier chain that will bring the signal to broadcast strength. Very little mixer load that would broaden the tuning, yet 10-20 MW of low-impedance output that can drive bipolar transistors.





Output Amplifiers and their circuits

The rest is just the same kinds of amplifiers used in any other transmitter. Higher power amps, over a 100 mW or so, generally use some variant of the L network as input circuits, output circuits, or both. Unlike tubes and small transistors, the impedances are impractical to match with the normal parallel-tuned “tank” circuit. That's because to match a 1 ohm output from a 72 watt 12V power transistor would require a 7.2 ohm tank circuit across a 72 ohm output for a Q of 10, which would work, but you would not be able to couple the transistor to it tapped far enough down, as the coupling would be too weak. Instead, one arm of the circuit, usually the inductor, is disconnected from ground and hooked directly to the transistor collector(or other low impedance to be matched). The impedance ratio of 72-1 would not use an 8.5 ohm tank circuit, with the transistor in SERIES with the coil. Putting the coil in series is the “lowpass” configuration, always used at a PA output to reduce radiation of harmonics by the antenna. It does require a blocking capacitor, usually placed after the network where current is least. The L network's own capacitor in series is the “highpass” configuration, is sometimes used between stages for shunt feed of DC through the coil and using the capacitor to block DC, for one of the lowest possible part counts.

They key to understanding the L network is this: Since there can be only one current at a time in one conductor, two impedances connected to the end of a conductor in parallel are exactly the same as two, lower impedances in series, no matter whether they are resistive, inductive, or capacitive. Therefore, the effect of the input capacitance of a power transistor is to make the resistive part of the input impedance lower, while demanding extra inductance in the series arm to tune out the equivalent series capacitance. An 0.5 ohm capacitance paralleled across an 0.5 ohm resistance would look the same from a conductor hooked to one end of both as though they were an 0.25 ohm C and 0.25 ohm R in series. For 10 ohms C across 1 ohm R, maybe a driver transistor's input, you get the series equivalent of somewhere around 0.8 ohms R in series with about .1 ohm C. Both come out to about 0.9 ohms, about 90 percent resistive in this case.

There is a mathmatical formula for this, works only if you know how much capacitance is in the input and the output of each transistor. EXCEPTION: One impedance L, one impedance C anywhere near resonance-then the currents cancel in parallel or the voltage cancels in series, thus the tuned circuit behavior.

The L network's parallel arm can also be seen by this “one wire” principle, being a resistance across a capacitance or in some cases an inductor. The L network itself is simply a tuned circuit with one resistive impedance (or power source) in series and the other in parallel. A 1 ohm transistor output in series with the inductor of a 10 ohm L network would match to a 100 ohm output, but we use 52 or 75. Lowering that output impedance to 75 would lower the “Q factor” or just “Q” of that series tuned circuit between the transistor and ground from 10 to 7.5, thus raising the impedance seen by the transistor from 1 ohm to 1.33 ohms. Lowering the load on one end raises it on the other.

Computation for L networks is simple if you know the impedances and they are resistive: Multiply them, take the square root, that is the impedance of the L network. Since you rarely know the input impedance of a transistors, however, you will have to experiment, starting with values of about 1 ohm

for driver imputs, about half that for PA inputs. For the output, the resistive part of the impedance is simple: the square of the input voltage divided by twice the desired power output usually works. You can compute in advance with the “Smith chart” if you know how to use it and know the complex impedances of the devices, but you can get by without that.
Whenever the output impedance of a transistor is higher than the load impedance and these impedances are high, like in small-signal stages, output circuits look and work a lot like those that tube amps use.

Ordinary parallel-tuned tank output circuits can be used, tapping down on the output side for an impedance match. The doubly-tuned circuit works well when high selectivity is needed, and can be tapped down on. A smaller coil that is NOT tuned also works in the singly-tuned, transformer-coupled circuit. The turns ratio is not exact and has to be found by experiment as coupling of the turns is not 100% when singly tuned.

L networks can be used with the parallel arm facing the transistor, or a Pi-section network, which is just two L networks with their series arms connected. The total series arm impedance in the Pi network must not exceed the square root of the product of the load and source impedances, or you would be looking a two L networks with a Q of less than one, which won't work. The “T-network” is two L networks with their shunt (parallel) arms combined, usually into a single capacitor or inductor. This is used a lot between two POWER transistors, as the output of one needs to be on the series arm, and so does the input of the next. It does not have the same maximum impedance problem as the Pi network, as its impedances are greater than those of one L network, those of the Pi less than those of one L network. The T is used when practical reactances (XL and XC) must be greater than those of a single L network, the Pi when the Q must be greater than that of one L network.

For coupling between two RF power transistors, just putting the previous stage across the parallel arm and the input of the next in series with the series arm (generally the inductor) would theoretically work but require impractical values of L and C. This works fine between small signal transistors, but gets impractical for power transistors.

To match a 12 ohm driver output to a ½ ohm PA input, using devices where the interelement capacitances are small enough not to be close to these values, would require a 2.44 ohm L network, the square root of 6! That would be about 730pf of capacitance, and barely over .004uh of inductance. Just getting a pair of capacitors to handle the current would be a problem.

The T network matches up to an arbitrary value, then back down again for a reasonable amount ot L and C in this case. On the other hand, the higher the value of that arbitrary point, the greater the Q needed to match it. Since all capacitors and inductors, even traces on the board, have their own resistance, the maximum possible or “intrinsic” Q becomes a smaller and smaller multiple of the Q actually used, so the efficiency goes down as well as the circuit becoming more selective as the arbitrary centerpoint is raised If the loaded Q is only half the unloaded Q, the efficiency of the circuit is only 50%, as that means the inherent resistance in th circuit is as high as that of the load!

This problem gets especially bad in driving such transistors as the MRF247, an otherwise excellent 75 watt device. It is designed with an “internal matching network” to raise the input impedance in its design range of 137-175 MHZ. Two low Q networks, one inside the transistor, make it possible for a communications amp to cover a band without retuning and add efficiency. Unfortunatley the turn around and LOWER the input impedance, often by a lot, at half frequency. To drive the MRF247 to 70 or 80 watts from 2008-2012, I had to design around a 1/10 ohm input impedance, using two 125pf mica compression trimmers plus 4 75pf wire leaded mica capacitors as the capacitor and a 1 inch trace on the board with a 1/8 inch half turn “speed bump” of copper strip as the inductor. It worked, but I suspect it also used up half the driver power in heat, lowering the gain of the device by 3db or half.

Optimizing amplifiers

If you can get really good performance from each amplifier stage, you can sometimes reduce the number of such stages needed. This is usually considered a subject for experts, with inexperienced workers advised to use more, lower gain stages. In 2005, some WSQT designs required 3 or even 4 small signal stages between the mixer's output buffer and the 1W predriver to work. Recent designs required only two, using the NTE161 instead of the 2N3904 in the first stage. The NTE161 is a touchy but very high gain device, able to deliver as much as 15dB of gain at 200MHZ, or theoretically over 18dB of gain at 90MHZ. Be careful tuning with these or similar devices-momentary shorts to ground anywhere in the output circuit will destroy them! Bipolar transistor gain goes up 3dB with every halving of frequency until reaching a maximum, as the current gain does the same while voltage gain stays nearly constant. If you have these or similar VHF small signal transistor, you can save a stage, maybe two, in the overall design.

It really doesn't take a lot to make a small signal transistor amplifier *really* work, though sometimes getting it not to oscillate can be a chore. Getting them to work well, with the maximum gain your transistors can offer and good efficiency can be quite another story. In the summer 2012 WSQT transmitter rebuild, several designs were trued in the line amps after the mixer and in the driver. For a single-stage to predriver design, the mixer was followed by 4 MPF 102 JFETS, giving about 30MW of power at a low impedance that can drive a small bipolar transistor directly. All other designs use 2 JFETS and required that that stage be forward biased, which gives maximum possible gain. Using the NTE 161 helped get more gain here, but to run without forward bias needed a 4 JFET mixer output anyway.

If you can't get NTE 161's or other VHF high gain transistors, use 4 MPF102's in the mixer buffer and two stages of 2N3904 amps, then a single MPS2222A driving a 4PMS2222A predriver for similar results. Same tips below apply, you just don't get as much gain or efficiency.

For a Class C VHF amp under 1 watt, I have found these items to be the key to maximum gain:

1: DC conditions must be exactly right, just like a tube. That means a true grounded emitter with either a ten ohm or no resistor/capacitor network, it means a choke or shunt fed input circuit with zero DC resistance to ground, and of course no DC losses in power supply RF chokes. *If there is a surplus of drive to the stage and it is output you are after, a 10 ohm resistor paired with a .001uf capacitor will prevent overheating and make any thermal runaway problem self-limiting.* These also make a stage more resistant to destroying transistors from mistuning or oscillation-use them if you can, delete them if you must. In any event, 2N2222 stages without heatsinks will almost always need them to prevent overheating, even when a 2N3904 stage would not.

2: Output circuits must be adjustable both for resonance and for impedance matching, yet reasonably low loss. All coils in the signal path need to be wound from large enough wire. A small signal stage can use #22, a 1watt stage needs something like #18 or so, 5-10 watt stages need #14 wire or thicker, and big PA stages should use wide traces on the board or loops made from at least 3/16 inch copper strip. It takes untold hours to match impedance by cut-and-try, though once that's done an adjustable circuit may show no power improvement. If you use a fully adjustable circuit you won't be tempted to cut short the process of finding that perfect match. Real world note: on power stages, *you may have to cut and try coils to avoid losses caused by excessive circuit Q* that results when using a coil of convenience with a second trimmer capacitor.

For small signal circuits matched by tapping down on a pair of capacitors, making one capacitor adjustable and then squeezing or spreading the coil is often enough. Even a pair of fixed capacitors and the squeezable coil can be used. Spreadable coils work very well with #22 wire, but with heavy wire have to be set with tools, no good for adjusting resonance, and requiring shutting down to change an impedance match.

I used fixed caps and squeezable coils in the mixer and the high oscillator amp. These, however, did not require gain optimization, in fact they had too much and all inputs to the mixer had to be reduced anyway.

The usual way to get adjustability for both impedance and resonance in an L network is to use two variable capacitors: One in the capacitive arm, the other in the inductive arm, partially resonating a higher than normal inductance. This is good when the shunt arm faces the collector and the series arm faces the load. For matching up to a load, with the shunt arm facing the transistor, a lower Q circuit with less loss can be made with the second capacitor between the shunt arm and the load, lowering the coupling. In both cases a larger than normal inductor, often a convenient size, is used. Don't make the inductor any bigger than you have to though! This is because the loss of the coil increases in direct proportion to the length of its wire. In high power stages you might experiment using this adjustable system, find out what shunt capacitor value gives the best results, then remove the larger coil and resonating capacitor, then cut and try coils until you get the same results with better efficiency and durability.

Many say to avoid shunt feed through RF chokes and use series feed though the coils to avoid low frequency oscillation, but this is almost impossible when pi or L networks are used. The choke can, however, be a resonant curcuit formed by a low inductance coil and the output capacitance of the transistor if it is known. This circuit also works when a transmission line must be inserted between stages on different boards.

Big power amps are a special case: Sometimes you will do well with using a second adjustable capacitor between the L network and the filter, but if you don't want to waste power in small diameter coil wire (even #14 is too small here!) you will be using hairpin tanks or traces on the board. With board traces you have to cut-and-try, attaching the variable capacitor at different point on a trace with extra length to get it right. This is enough of a nuisance that driver outputs, not PA inputs, should be the point of adjusting that match.

If you use a board trace for the PA output inductor you will have to use a variable capacitor match after it. If you use a hairpin of 3/16 inch copper strap, however, that is adjustable! If you squeeze it narrow, its inductance is reduces, if you push it round it's inductance rises, though not over a wide range. Build them so you can try different lengths, adjusting them will tell you which way to go until you get close enough to get it perfect. Why bother with this? Because using a big fat mica capacitor with no steel in it instead of a mica compression trimmer with steel parts can save a watt or two in losses. Those trimmers can handle a ton of power and work in bit PA amps, but they do have steel in them, and steel is lossy. ***WATCH THESE TRIMMERS IN USE FOR CORROSION:*** I had an 80 watt MRF247 destroyed by a corroded mica trimmer that heated in use, detuned from the heat, and damaged the PA transistor. Several replacement transistors were destroyed as well before I found the corroded capacitor.

RF Chokes

The key to sucessful use of RF chokes is not to use too much inductance, (or you get low frequency "hash" oscillation), to make sure the same chokes are not paired with the same amount of capacitance on both input and output of any device, and to make sure chokes don't couple to each other.

I've had especially good luck with the little square RF chokes in a Radio Shack "inductor assortment" purchased a few years ago. Each choke has a tiny ferrite toroid wound with a few turns of relatively thick wire. I don't know what they were designed for, but the only place I found they didn't work was at the mixer coil center tap choke, which has to handle the low oscillator signal. They seem to be excellent for VHF use, and toroids contain the magnetic field. They are considered to be "self-shielding" in that aspect, very resistant to unwanted coupling. If you have some tiny ferrite or powdered iron cores, try winding your own. If you get "hash," reduce the number of windings.

Emitter resistors and doing without them

A lot of designers use a resistor and capacitor to ground in the emitter circuit of small bipolar transistors.

I found emitter resistor/capacitor networks to be absolutely necessary in the mixer and in triplers to control heating of 2N3904's , which are not really meant for VHF service. This is true also of straight amplifiers using the MPS2222A in most cases unless heatsinks are used.

This resistor has the disadvantage of reducing gain in a Class C stage, although in a Class A stage it does not reduce gain in any way when the capacitor is present to bypass RF. This is because the voltage drop through the resistor adds back bias, which is added to the 0.6V conduction threshold of the transistor and thus increases the driving voltage requirement by the same amount. Over several stages, this can really add up. In one case, getting a single stage NTE 161 bipolar line amp and a 4 MPS2222 predriver stable and cool enough to remove these resistors meant the difference between 45 watts and nearly 60 watts coming out of the power amps, which of course never use external emitter resistors. Power amps were an MRF646 driver and another MRF646 as the PA.

On the other hand, this resistor and capacitor can stop oscillation at low frequencies, caused by the fact that bipolar transistors have much more gain at audio through low shortwave than they do in the FM band. A capacitor that has little impedance to 90 MHZ has ten times as much at 9MHZ and 100 times as much at 900KHZ and will sometimes shut down oscillation at those frequencies. It does this by bypassing the emitter resistor at VHF while *not* bypassing it at low frequencies. If it does not, keep them anyway until you fix the problem, they may save a transistor. As said before, they also work wonders to control overheating.

They can also stop "thermal runaway" of devices like the MPS2222A and 2N3904, which work at VHF with 6-10dB of gain but tend to leak current. The hotter they get, the more they leak-and the hotter they get. For a 4x 2222 predriver the solution is aluminum tube heatsinks, and exactly the right amount of drive. Too much, they get hot from "saturation," which slows them down and makes them get even hotter from still more leakage. Not enough, you lose power. The right amount is just enough to make those aluminum tubes hot to the touch but not so hot as to be uncomfortable or cause a burn. You can get 1 W from 4 of the Radio Shack MPS2222's that way.

A 2N3904 small signal stage could also be heatsinked, but using an emitter resistor means the more leakage, the more back bias, and therefore less leakage and they stay cool. I've never been able to get more than about ½ to 3/4W from 4 mps2222's with emitter resistors, so I put those in heatsinks and have occasionally have to replace them. A small fan blowing on those heatsinks should prevent overheating failures,

Often the real best solution is another stage, not removing these resistors from existing stages. That approach with the same power amps gave 65W from the power amps, and the twin NTE 161 second stage, with a 10 ohm emitter resistor, was fully saturated with 55 mW drawing for the pair. It was driven by a single NTE161 in Class A, with just two MPF102 JFETS instead of 4 (two were destroyed in removal while making the mixer more compact to fit the stage. If you are short on gain, can't fit another stage, and have good stability though, removing emitter resistors from class C stages (NO forward bias!) will often do the job.

A note concerning the MPS2222A and 2n3904's: These are very durable and available at Radio Shack. The 2N3904 can be very cheap in a pack of 25! It can pay to use them in the line amp stages exclusively, adding the necessary extra stages for gain. You also won't be replacing them like small signal VHF transistors that seem to blow at a touch. At moderate drive levels they work fine without emitter resistors, but above about 50ma they need either an emitter resistor or a heatsink (aluminum tube) to prevent thermal runaway. AVOID generic 2N2222's, they have only a 250 MHZ “transition frequency” intead of 300MHZ. That is the frequency at which current gain drops to unity. That means the Radio Shack MPS2222A has a current gain of 3.33 at 90 MHZ, while the generic 2N2222 will have a current gain of only 2.77. This is of course multipled by the circuit voltage gain.

A note about the NTE161 and similar VHF transistors: these offer incredible amounts of gain, as much as 15 or even 18 db at 90 MHZ. Some of them, like the NTE 161, get this performance by being as small as possible, with as little extra base layer thickness as possible. This makes them vulnerable to blowout from excess collector voltage on signal peaks. I have rarely lost them in Class A stages, but they seem to be expensive popcorn in Class C stages. Use them in low power stages only to protect them unless you can get intermediate sized and/or 1W driver versions.

STABILIZING AMPLIFIERS

The number one cause of hissing white noise oscillation in bipolar transistor amplifiers is too-large RF chokes! Too much choke impedance can also create oscillation in the AM band that just seems to be impossible to stop until the choke inductance is reduced.

The impedance to ground at both the collector and base of a bipolar transistor amplifier for audio, ultrasonic, and low frequency RF to ground needs to be low, but not zero and somewhat resistive to damp out low frequency oscillation.

Freescale semiconductor has published literature concerning transistor power amplifier design, and much of it is applicable to any shunt-fed stage that must use RF chokes. They recommend that the inductive impedance of collector chokes be no more than 3-7 times the resistive impedance of the circuit at the point of connection. Remember that this is an inductance and adjusting the tuned circuits will easily compensate for it. The bypass capacitor must also be relatively small, about 1000pf seems to work well. BE sure to avoid series resonance with the choke, however.

The small bypass capacitor allows a high Q, undamped path to ground for the inductive current the choke flows at operating frequency to hold down circuit losses. It also forces low frequency current to take another path. A second choke is used here, generally wound on ferrite and of intentionally low Q, and paralleled with a resistor of about 10 ohms in power amps. On the other side of that choke and resistor are a larger RF cap, maybe .01 or .1 uh. That capacitor controls tendencies to oscillate at frequencies around 1 MHZ or so. If you get hissing white noise you will need to use electrolytic capacitors in the 100-220 uh range to decouple the power supply and provide a path to ground for frequencies as low as a few kilohertz.

You will almost always need to run “losser” resistors in parallel with RF chokes in the base circuits of small signal amplifiers, these place an upper limit on gain to reduce the tendency to oscillate. These can be as high as 1,000 ohms in small signal stages, reduce them if you have trouble. When not optimizing gain, using them as the DC return can save use of an RF choke at the expense of gain. This can stop “hash” oscillation caused by chokes with too much inductance, but so can using the right chokes. Between 100 and 220 ohms seems to work well in small signal stages.

On power amps, another stabilizing technique can eliminate the need for a base losser resistor if the stage is stable at operating frequency. That is to use a small choke , just like in the collector circuit but not the same impedance, in series with a capacitor to ground. Then a larger, ferrite, low-Q choke provides a DC path to ground, while forcing low frequency energy through another 2-10 ohm resistor. 10 ohms is usually recommended.

The emitter resistor/capacitor networks discussed earlier also control low frequency oscillation in small signal stages , but are never used in Class C PA amps and avoided in drivers because they cost power and gain. Use them if you need them or you have transistors that need them to control heat. They are always used in Class A stages, of course.

PA FINAL AND DRIVER AMPLIFIERS

Amplifier transistors can be a sticky problem for the FM builder. There are a lot of them on Ebay, the selection is always changing, so avoid circuits that require one particular type and cannot be adjusted to use another!, The WSQT exciter detailed later in this publication has very adjustable driver stages, so it can push any common VHF or UHF transistor to its rated output or more, up to 80-100 watts if you can find a big enough transistor that still gives 10 db of gain at 90 MHZ. The 6 legged power transistors all have internal matching networks, making 170 MHZ VHF devices hard to drive at 90 MHZ but usable. Most UHF power transistors are 6 legged with internal matching networks, but the UHF matching network has little effect at 90MHZ, so these devices are easy to use. The 4-legged VHF transistors do not have internal matching networks, all work well at 90 MHZ. Avoid the SSB/shortwave ham type transistors, they work poorly at 90MHZ, though presumably better than the IRF510 from Radio Shack will.

You can often drive a PA with another transistor of the same type, or you can use a smaller one of about ¼ to 1/6 the capacity if you are buying it separately. The smaller one will usually be eaiser to drive and have less capacitance, as long as it is not an older device with less gain,

All the devices designed for higher frequencies will give higher power and usually more gain at lower frequencies. The exception is that input circuits required for internally matched devices at or near half their design frequency are not themselves efficient, lowering overall gain. The gain of the transistor itself rises 3db, a doubling of gain, with every halving of frequency.

The MRF 646 is common but a little delicate. It is rated for 45 watts at 470MHZ, I've gotten 60 and even 70 on occasion from them at 90MHZ. It specifies 4.8 to 5.4dB of gain at 470 MHZ, figure 10-11 dB of gain at 90. The MRF648 is similar to the MRF 646, but rated for 60 watts instead of 45, should be good for 80 watts or so at 90 MHZ. There is also to more expensive and newer MRF 650, another 47-MHZ device, rated for 50W, a little more gain, and much better protected against damage from a mismatched circuit.

The larger MRF 648 has become common at the time of writing, a little cheaper than the MRF 646 and a LOT cheaper than the MRF 650. It is rated for 60W at 470 MHZ and will easily make 80 watts at 90 MHZ. I highly recommend the MRF648, it is the most powerful of the MRF646/MRF648/MRF650 family as well as the cheapest at this time.

I have yet to test an MRF 650-too expensive and not as powerful as an MRF648, but better protected against failures from mismatched antenna/output circuits.

The big VHF MRF247 is damned hard to drive with its internal matching network designed for 170 MHZ, but will make 80W at 12.5 volts and should be good for 100 watts on a 13.8 volt power supply from AC. Not as good a choice as the MRF640 in my opinion, often about the same price. Harder to drive but better protected against damage from a shorted antenna.

You won't quickly damage any of these with a disconnected antenna at 90 MHZ, as the “L network” match inverts that to appear as a short, and they will simply dissipate the maximum input power as heat, having enough cooling to take it. A shorted load, however, gets converted to a very high impedance and inductive as well, making high voltage spikes that can kill an unprotected device like an MRF646 in seconds. Usually this kills some but not all of the internal junctions, leading to a permanent partial power loss. Protected devices like the MRF247 and MRF 650 will take it longer. The lower the frequency you use the device at, the worse the problem. I would suggest ordering several copies of any transistor you use, you are almost certain to kill at least one, especially if you are new to this!

All these devices are bipolar transistors, not MOSFETS as MOSFETS need more than a 12V power supply, If you will be operating in a place where the electricity is turned on, RF MOSFETS have much more gain than bipolar transistors, can be more efficient but harder to stabilize.

There is one other MOSFET worthy of mention: the IRF 510 power MOSFET available at Radio Shack. It makes an excellent AM band power amp, though the driver will need to be modulated too for best results. In the FM band it is extremely hard to use but can be made to work, giving 10-15 watts output with 6-10dB of gain. Efficiency is poor, never topping 41% in my tests. If you only need 10 watts, can use two 12 volt batteries in series or one AC power supply, and know what you are doing around RF power amps, this can mean being able to go to Radio Shack, buy one or two IRF 510's, and have a working power amp tomorrow if you already have either rotary ceramic or mica compression trim capacitors.

The 23 watt dual IRF 510 circuit shown at the end of this publication actually contained one mistake, in the input circuit. The use of the L network instead of just a 2 turn by ¼ inch diameter by ½ inch long coil across the input prevented the use of “neutralization,”a circuit used to cancel the inverse feedback capacitance of a tube or a MOSFET. In tubes and some transistor circuits neutralization is used to prevent oscillation, but at 90 MHZ with the low frequency IRF 510, it operates in the “unilateralization” mode, preventing the input power from being sucked into the output across that same capacitance by high frequency phase changes. With neutralization that amp would have made 30W, as each IRF510 is capable or 15W. The circuit used for this is simply a ¼ inch by ¼ inch by 5 ½ turn coil of #22 wire in series with a large DC blocking capacitor, from gate directly to drain. It only works with a much lower inductance to ground in the input circuit, otherwise it will cause oscillation at a lower freqeuncy. It is the “direct” form of neutralization, where the inductor makes a resonant circuit with the feedback capacitance inside the transistor. At lower frequencies that does not take place, and the 2 turn coil resonating at operating frequency with the input capacitance also makes a voltage divider that shuts down low frequency feedback through the neutralization coil.

Use of the IRF 510 at VHF, even in the 6 meter (50MHZ) ham band, is almost unheard of, but a single IRF 510, 10W output amp was used at WSQT in Spring 2005 at 87.9, and the same transmitter was used in New Orleans after Hurricane Katrina, giving nearly citywide coverage over that flat terrain. A second IRF 510 design giving 15W was used for a month in fall 2005 after arsonists torched the main location, and again in June 2006 after that location was abandoned for good.

Drivers

Most of the UHF devices mentioned above can be driven with a second device of the same type if you happen to have two of them or they are simply easier to find on Ebay than one large and one smaller transistor. Do pay special attention to stability when using a full size PA transistor as a driver, it does have a lot more capacitance than a smaller device. The driver capacity is simply the desired PA output divided by the expected PA gain. Always allow a safety factor, as gain is not the same from transistor to transistor, and coupling losses may run higher than expected. If you intend to push the PA with drive for maximum output, the driver transistor should be capable of about ¼ the PA output or the rated driving power for the device at its design frequency. If your PA device is a UHF device large enough to produce the desired output at rated power, it will need about 1/10th the output power as drive delivered to the base, the driver device should be able to deliver more than that if needed.

As said elsewhere, the driver should be mounted on the same heatsink as the PA or otherwise on a heatsink whose fins and fan are outside the transmitter's enclosure. Drivers smaller than 5 watts output can be mounted on fansinks inside the case if and only if all the hot air is ducted to the outside of the case. Otherwise the hot air will heat the inside of the case, causing the oscillator to drift enough to harm reception.

The driver will almost always be coupled to the PA by a T network. The driver itself will have an L network to an impedance higher than the driver impedance, as this is necessary to get real-world usable values of inductance and capacitance in the PA input. I've had good luck with between 50 and 100 ohms, but do not expect that the finished and tuned circuit will necessarily be the value used in initial design! This is because manufacturers do not list the input impedance for either 175MHZ or 470MHZ devices in the 88-108mhz FM band. The lower the input impedance at the base strap on the case, the higher the impedance at the other end of an existing L network.

There's a trick to setting the impedance match given this unknown input impedance: The smaller either coil in the T network is, the lower the impedance presented to the driver collector. The PA base impedance will drop a bit with increasing power fed to it but otherwise is a constant. Power can be saved by using a trace on the board as the inductor of the PA base L network side of the T network. A ¼ inch wide trace, 1 inch long seems to work well with the MRF646 and MRF648. You can cut this trace long and try different attachment points for the mica compression trimmer to vary the inductance, then cut off the excess by dividing the trace at that point. Adjustment for impedance match is then made by trying different coils for the driver output L network, as these are far more easily changed without moving other components.

The driver input circuit is also an L network if fed by a transmission line. Usually a single turn is all the coil needs here, with the capacitor adjustable around the range of 150pf or so.

In some cases the predriver collector can driver it directly, needing only an RF choke and a blocking capacitor if it is on the same board as the driver. In fact, there is much to be said for a single long board of predriver, driver, and PA on one long heatsink on the back of the case if the case you use is wide enough to accommodate this layout.

PA Transistor selection summary:

UHF TRANSISTORS, DESIGNED FOR 470 MHZ:

Why UHF devices? There are plenty of these on Ebay. They are easier to drive than 174 MHZ parts running at half frequency, where the internal matching networks common on devices over 40 watts make the input a very low impedance.

I especially like like the MRF646, MRF648, and MRF650. All will give over 10dB of gain at 90MHZ, all can produce 45 or more watts at 12.5V. The MRF 650 has a little more gain and a 50 watt rating, the MRF648 has the highest power rating at 60 watts at its original 470MHZ, and even the MRF646, rated for 45 watts is sometimes good for 60+ at 90 MHZ with 12 volts and enough drive.

RATED POWER AT 470 MHZ:

MRF646-45 watts
MRF648-60 watts
MRF650-50 watts, has output circuit mismatch protection.

POWER AT 90MHZ BY WSQT TESTS WITH OVERDRIVE AT 12V"

MRF646-60 watts
MRF648-80 watts
MRF650-untested ($$$) should be good for 65, maybe 70 watts but more durable than the others.

The MRF 650's (and MRF 247's) output mismatch protection can save a transistor if you get a shorted load. A shorted load is transformed into a very high impedance by the L network, and combined with the RF choke can make high inductive voltage spikes that cause reverse (zener breakdown or avalanche) conduction in the collector-base junction. In protected devices this current spreads across the entire junction like in a zener diode, doing little harm. In many other devices, it concentrates in a single point and destroys it, causing permanently reduced power output.

VHF DEVICES FOR 174 MHZ:

VHF transistors designed for more than 40 watts have a problem: Their internal matching networks, with as much as 2000pf of capacitance, cause a very low input impedance anywhere near half their design frequency. This can be as low as 1/10 ohm in some cases! The UHF devices don't have this problem as 90 MHZ is far less than 1/2 of 470 MHZ, and their internal matching networks contain only a few hundred pf of capacitance.

The MRF247, used for an 80 watt setup for years by WSQT, is an example of this. It made great power, but that very low input impedance meant the driver to PA circuit has a very high “loaded Q” and thus poor efficiency due to limited “intrinsic Q.” let me explain this: The previous stage will have an output impedance of 7 ohms or so. This could be matched to a 1/10th ohm next stage directly with a single L network, except for one problem: impractical component values. That L network would be just 0.83 ohm, which is 7 times .1, square root of that figure, as an L network is always computer. That would require over 2,000 pf of capacitors-and an inductor if just .0015 uh, which is maybe the inductance from the transistor's case to the end of the base tab, just 1/8 inch or so away. You'd never attach the capacitors!

In the 2008-2011 MRF 247 amp, I didn't have VHF chip capacitors, so I used 2 125pf trimmers paralleled by 4 75pf micas, one on each side of each trimmer, to two attachment points for about 500pf as used. That resonated with about an inch of trace on the board with a "speed bump" inductor of 1/8 strap copper 1/8 inch high by 1/8 inch long interrrupting it. That was about a 3 1/2 ohm circuit. This is 35 times the 1/10 ohm input impedance, for a loaded Q of 35! It gave an easily matched 120 ohm parallel side connection but was lossy. A trace on the board or a strap gives good Q compared to a wound coil, but those trimmer caps have steel in them and run warm in some drivers and hot in PA service, though they work. For a 90 percent efficient input circuit, the unloaded Q of the circuit would have to be 350, but with these parts won't go anywhere near that, 50 to 100 being the best I could hope for. At an unloaded Q of 50, loaded Q becomes 20 instead of 35, meaning about 40 percent of the driver's output is dissipated as heat, lowering the gain of the circuit by that same 40 percent.

Although the MRF247 can show more than 10dB of gain at 90 MHZ, that's based on power delivered to the base junction, not the top of the input L network, so it took a driver output of about 15 watts (when tested by itself) to feed that beast, meaning 25 watts plus from the battery for the driver, plus 140 for the PA, meaning 14 amps and a ton of heat at 12.5V and 80 watts out.

Of course, if power consumption is a non-issue, a pair of MRF247's in parallel can make 150 watts, or even make 200 watts on a 14 volt power supply if you want to push them! A 646 with the drive and loading backed off a bit would drive them with ease, requiring about 35-40 watts with the input circuit losses involved. A pair of MRF 646, 648, or 650 class devices could make 90-100 watts at rated power and voltage, more if pushed.

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PUSHING POWER TO HIGHER LEVELS

It's possible to push many transistors well above rated power in short duration service, just as it is possible to do with tubes. RF tubes, especially in the 100W to 1KW class, have two ratings: Continuous commercial service (CCS) and Intermittant Commercial and Amateur Service (ICAS). That is due to shortened tube life at high temperatures, higher voltages, and higher currents. I will now posit that the same could be true of some transistors, except that the odds of failure increase rather than the mean time to probable failure being reduced.

Never push any device that must run 24-7 with utmost reliability! For "12V" transistors in this kind of service, use a regulated 13.8 volt supply if the device was meant for a car, a 12.6 volt (or whatever the datasheet calls for) regulated supply if it was meant for a base station. In these cases, I would recommend staying under the rated power in all cases, especially if you don't have a spare PA transistor or it is difficult to retrieve the transmitter to install it.

For intermittant service, however, you will need the strongest signal you can generate just to get heard, here's how to get it.

Higher power by overdrive:

There are a lot more 50W class VHF and UHF transistors on Ebay than there are 100W devices. Those transistors that are designed for for higher frequencies (UHF) can be driven harder than needed to reach their rated output for about 3/2 their rated output with enough drive. They can handle the drive needed to reach their rated power at 470 MHZ while running at 90 MHZ, with an additional 7-8dB of gain.

This overdrive works just like a guitar amp: A Marshall stack with a 50W rating is rated with a sine wave input and no clipping into a dummy load. Plug in a guitar, turn both distortion and master gain all the way up, you get more like 75 watts. This has been measured again and again.

The same thing happens with a "switched" amplifier, and an overdriven VHF FM amp works the exact same way: a near square wave current pulse contains about 1.41 times the energy of a sinusoidal conduction pulse. Again, I've measured UHF devices putting out about this much more than their rated output, again and again.

I've not seen this with VHF devices, either because they were saturated at rated driving power or because the driver could not transmit enough driving power through the half-frequency internal matching network of the MRF247. Of course, the MRF247 makes 75 watts to begin with, you may not need any more than that anyway.

Higher power by voltage:

Most transistors designed for "12V" service have a maximum collector-base instantaneous voltage rating of 36 volts. Normal operation would go to twice the power supply voltage on each positive peak, so that means the "instant blow point" for most transistorized devices meant for 12V service is about 18 volts.

Most 12 volt amps will work fine on 14, making more power but of course being closer to failure if a bad antenna match or other problem generates voltage spikes. I've heard of hams pushing some amps awful close to that 18 point failure threshold.

Simply using the 13.8 volts every car mobile transmitter PA is designed for isn't really pushing the amp, it's just not leaving anything on the table. If using AC power, I recommend this, and suspect that the 80W MRF247 transmitter of 2009-2011 would have made 100 watts on such a power supply. Many hams report such power from the MRF247, and at 144 MHZ instead of 90.

For a homemade transmitter, I would NOT recommend more than 14V on a 12 volt device, simply due to the likelihood of voltage spikes if the output circuit has any problems and the danger of this or a shorted load destroying the transistor. The exception is devices with unusually high collector-base voltage ratings listed on the data sheet. I once ran an NTE 235 final, a device meant for 5-6W, at 10 W with a 30 volt supply, taking advantage of it's 65 volt base-collector voltage rating. Sure enough, an antenna problem took it out, leading to the development of the 10-15W IRF 510 rigs, which used 24-30 volts(that's a 100V device, though poorly suited to VHF).

Higher Power with dual output transistors in parallel

This is the best way to get more power than one common device can deliver. With 45-50 watt transistors now common on Ebay, this means you can get 100 watts for less than 100 dollars worth of transistors and no touchy overdrive or overvoltage tactics. In 2008, fed up with getting no more than 35 watts from a 20 watt UHF device, I rigged up a parallel circuit with it plus the output transistor from a VHF marine radio. Not even the same devices, but could run at the same impedances and divide the power. The circuit was simple: Common capacitors and individual inductors in both input and output L networks, wound coils of convenience, a matching capacitor in the output circuit and an additional pi network to match the input. Little attention was paid to tuned circuit efficiency, yet it made 55 watts, the most I had gotten from transistors to that date.

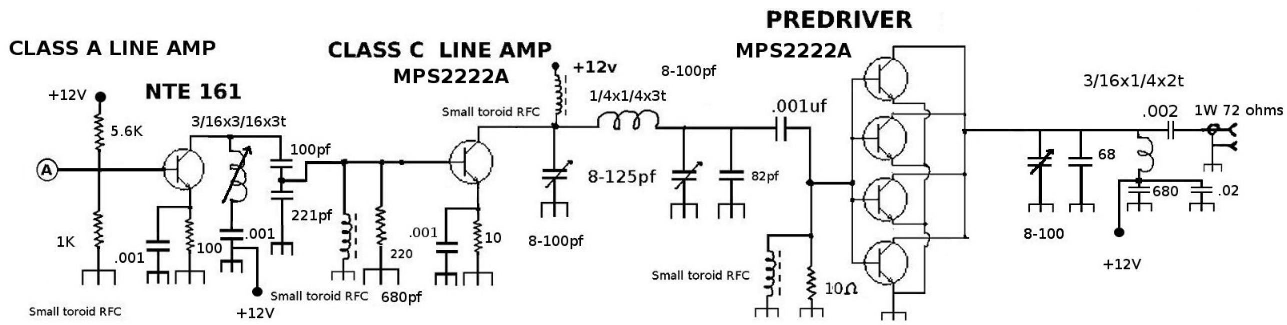
Warning: Always begin tuning dual transistor PA amps at half voltage! They can oscillate in push-pull mode, and if that starts up at full supply voltage it is really easy to blow one or both transistors. At half voltage you can forget about this, let it oscillate at first startup, and experiment with chokes and damping resistors until it runs smooth and stable. Only then try it at full voltage. That was how I got a two dissimilar parallel device amplifier working and on the air in Spring 2008.

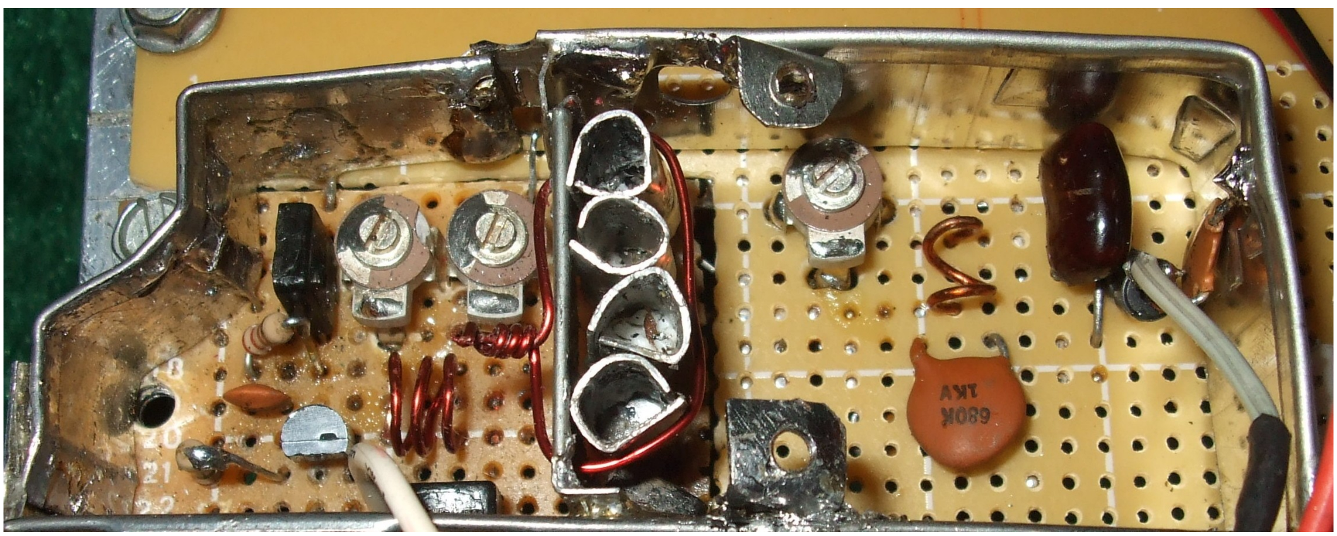
A note about layout and cooling

Never put the driver on the same board as the small signal stages if it makes more than about 6 watts unless the main heatsink can be reached from the small signal board! A small driver heatsink would have to be vented entirely out of the case in order not to heat up the air inside until either the oscillator drifts or something overheats. Exactly twice did I try to run a setup with a driver on the main board and no fan duct to the outside of the case. In one instance the oscillator drifted off the channel center after about 45 minutes with a 5 watt driver on the board. Installing a fan duct to the outside of the case made that board stay on frequency. In the second instance a board with a 10 watt driver and a fairly large but internal heatsink get so hot it started oscillating and had to be shut down after just 5 minutes! This could not be duplicated on the bench but was obviously a thermal issue, so the driver was moved off the main board, back to the PA board on the main heatsink like in 2008-June 2012.

The heatsinks to use are massive computer heatsinks that do NOT contain heatpipes. You can't drill into heatpipes or their working fluid escapes and the heatpipe is dead. Big Pentium 4/Athlon 64 era finned aluminum or copper heatsinks with 80mm or larger fans are the way to go. Use the biggest you can get that doesn't use heatsinks and has a large square bottom to accommodate both driver and PA. IF you have to use separate heatsinks, they must both be outside the case, with big fans. Two way radios often don't need fans, but broadcast radios ALWAYS need them, even at 5 watts or so!

RF Amplifer chain as used by WSQT 9-03-2012:

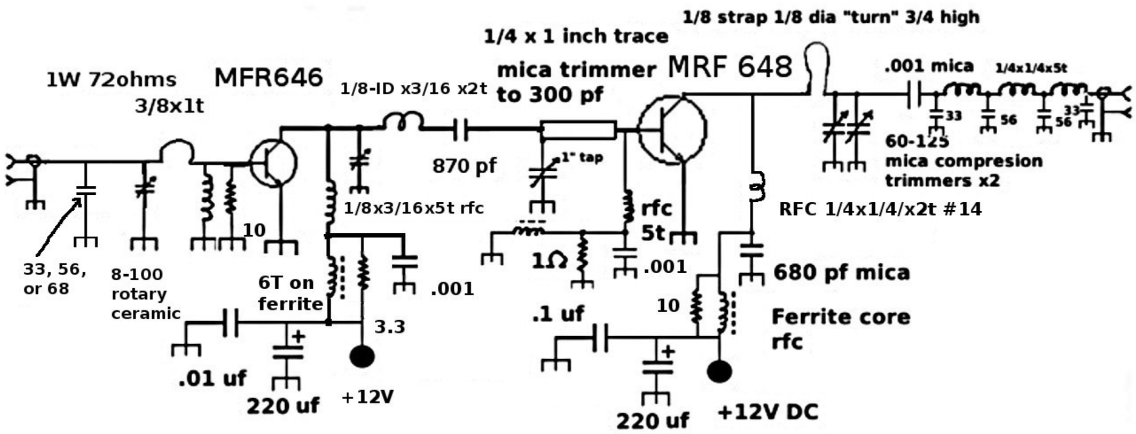


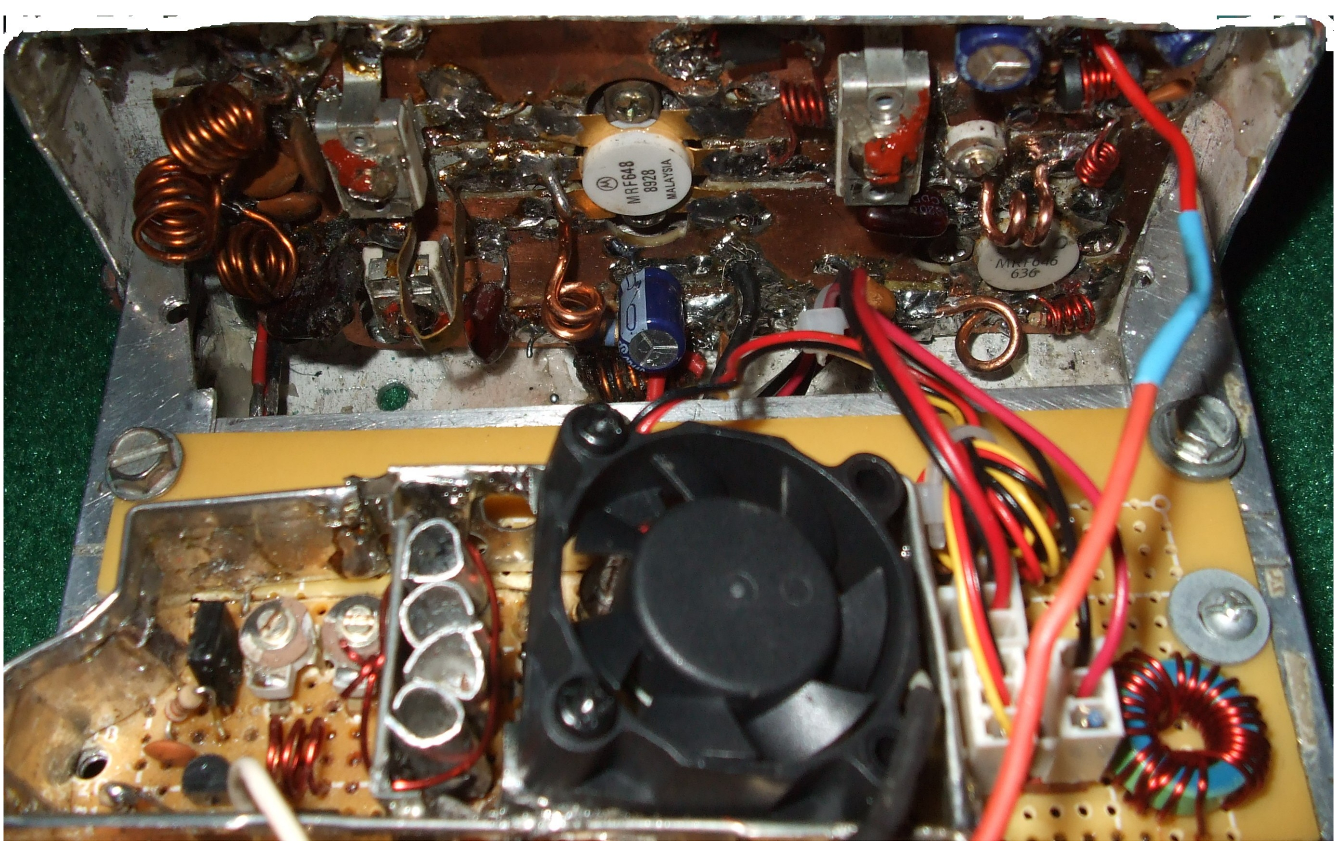


The predriver cooling fan has been removed in this picture to show the output circuit, you can see the mounting tabs

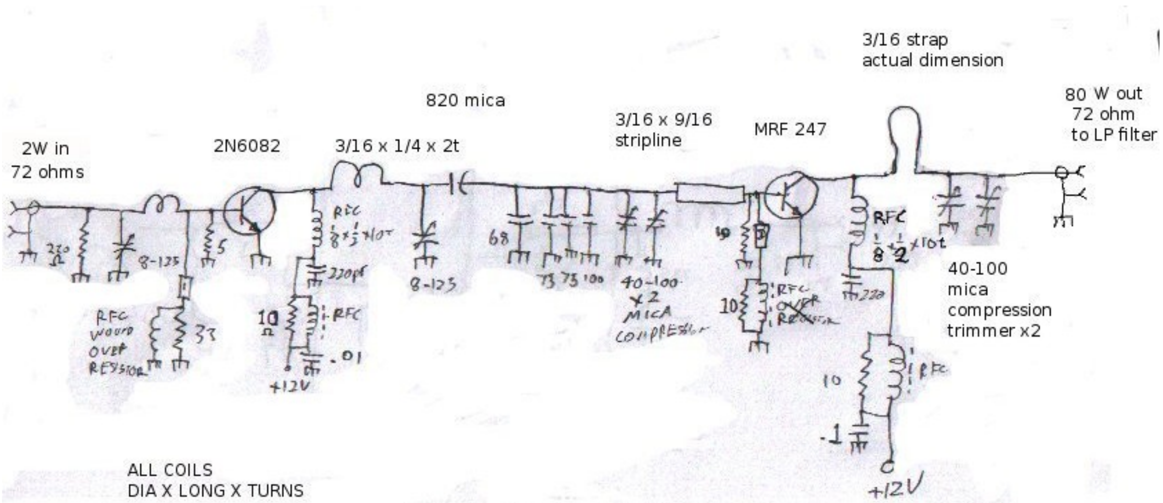
The first stage (Class A) line amp is in the mixer photo as it is in that compartment.

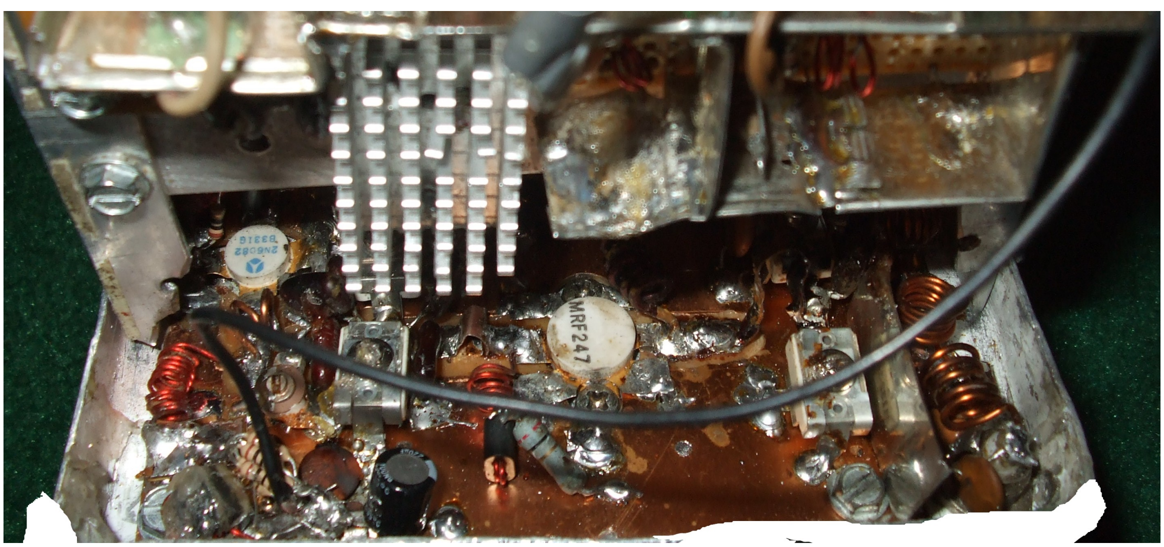
80-85W PA for MRF 648 w/ MRF 646 driver



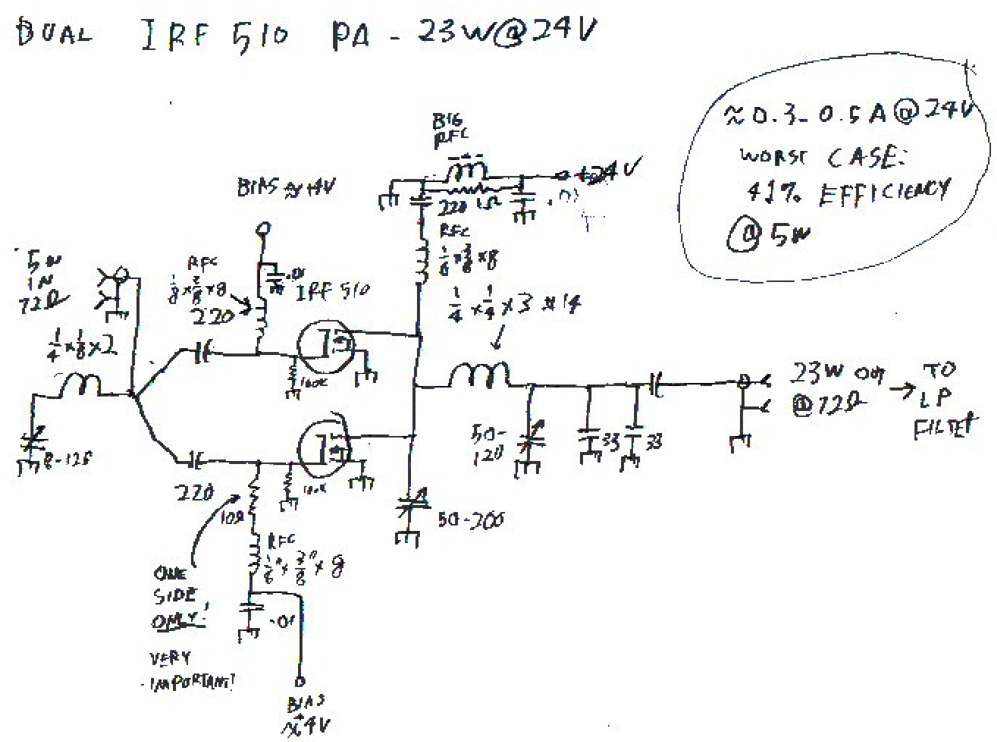


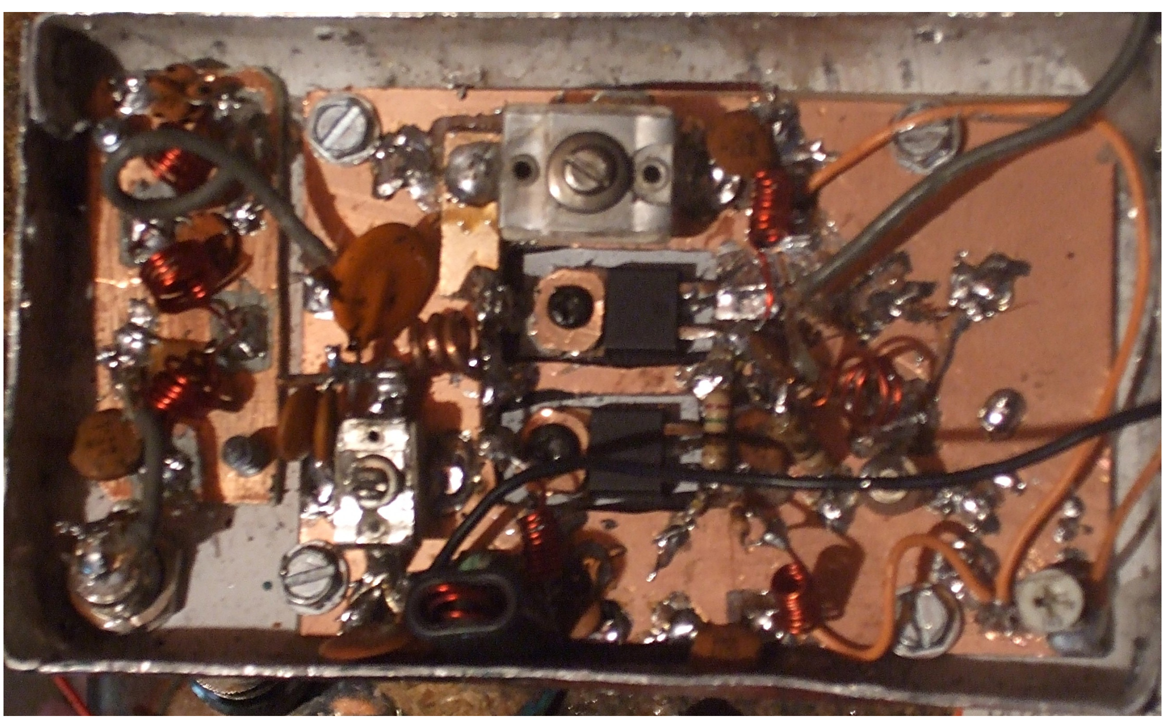
2008-2011 70-80W MRF 247 PA





A 23W dual IRF 510 PA: Hot running, high power consumption but works...





The April 2008 55W dual transistor amp:

Yes, this worked with two dissimilar transistors. The design concepts here could yield a 100 watt amp from a pair of RMF 646/648/650 class devices, or 150 watts plus from a pair of MRF 247's. A LOT easier to make work with two identical devices, but I recommend tuning these up at 6V until you get all the parasitic oscillations out,m then turn up gradually on a regulated power supply if you have one.