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.

Update Summer 2013: Radio Shack has again reduced their stock of discrete parts, now the MPF 102 JFET, needed for a stable oscillator, is no longer stocked. Their inductor assortments are gone, their capacitor assortment now sucks. As of now, oscillator transistors, tuning capacitors and the big output transistors, have become parts that must be sourced from Ebay, Craigslist, hamfests, or other sources of used/never sold old stock parts. You also need to get “ferrite beads” from these or out of old TVs, old VCR's and very old computer boards. Newer consumer electronics are contain fewer and fewer reusable parts!

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. Hopefully by the time you can't get parts to build your own exciter board, these become made in such a way as to produce clean enough signals to send to an amplifier.

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. In addition, you will need to be able to check every channel to make sure there are no extra copies of your signal, known as “spurs” going out on the air.

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. That's assuming 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. Some say an FM transmitter running in a row house with the antenna on top will have trouble at almost anything more than 1 watt due to overloading neighbor's receivers. You can't fix that at the transmitter except by moving it, raising the antenna, or lowering the power!

When the transmitter is in use, it is critical that no spurious signal overlapping any other signal be detectable at the first house neighboring the transmitter site. The higher the power and the closer the neighbors, the cleaner the signal must be. Limiting case is when your main signal is strong enough to overload receivers and generate interference inside them. Licensed stations can get away with jamming cheap nearby receivers, you cannot!

You 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 just 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 small-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 to about 68-69 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 an SWR meter to set up your antenna. You can buy one or make one using instructions in the ARRL “Radio Amateur's Handbook.”

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 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. You can get a lot of different values with 10pf caps in parallel, 100 or 150pf in series for 50 or 75 pf, etc but this is a nuisance! If you have a real electronics parts store around, buy a good capacitor assortment there when you begin, you may save $20 or more in buying packs of individual capacitors packed two to a bag later! Don't forget to harvest common values you will use a lot for old junk too-along with all those intermediate values Radio Shack doesn't sell anymore.

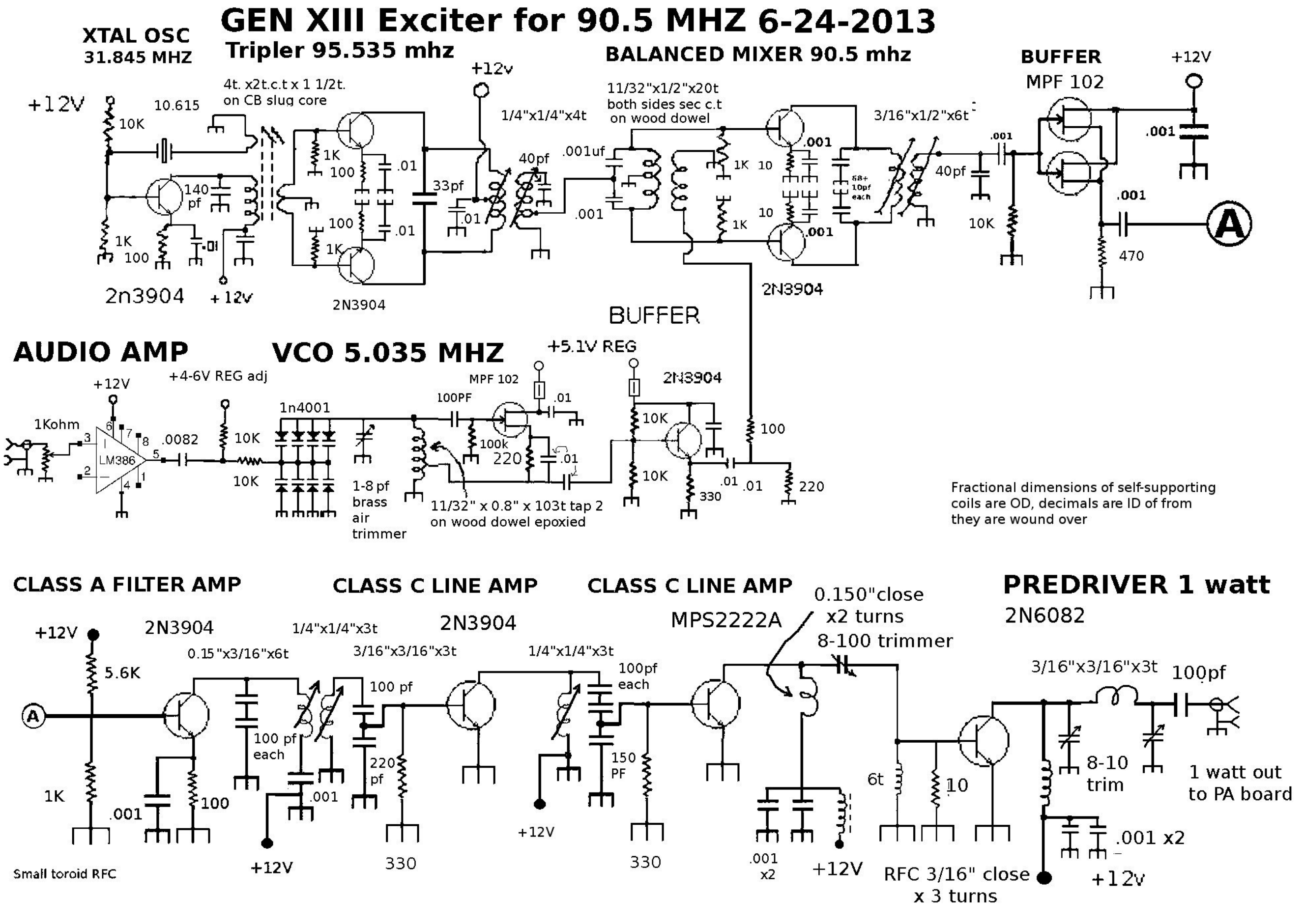
You will find molded chokes and can-shaped chokes with “dumbell” ferrite cores within on old circuit boards, as well as boatloads of resistors and capacitors. Hit the dumpsters, collect old transistor radios, TV, especially things like VCR's and tuners. Radio Shack also has snap-on chokes, you will need one on the audio player's audio cord to keep it from going NUTS when on the antenna!

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. One special note: *If the low oscillator is in the 5-7 MHZ range, the doubly-tuned circuit in the mixer is not enough to stop some of the high oscillator signal from leaking out to the antenna,* and a second doubly-tuned “filter amp” must be used as the next stage. As this stage can only couple out a limited amount of power, one additional stage overall will be needed. This will also give good amplitude limiting in the driver stages and is desirable for that reason as well.

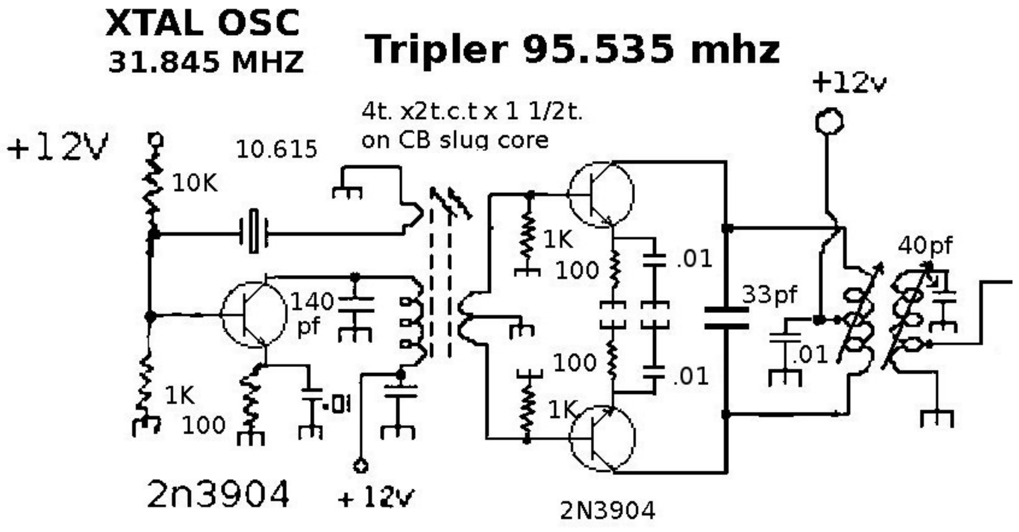


Crystals and multipliers: CB crystals and triplers go together

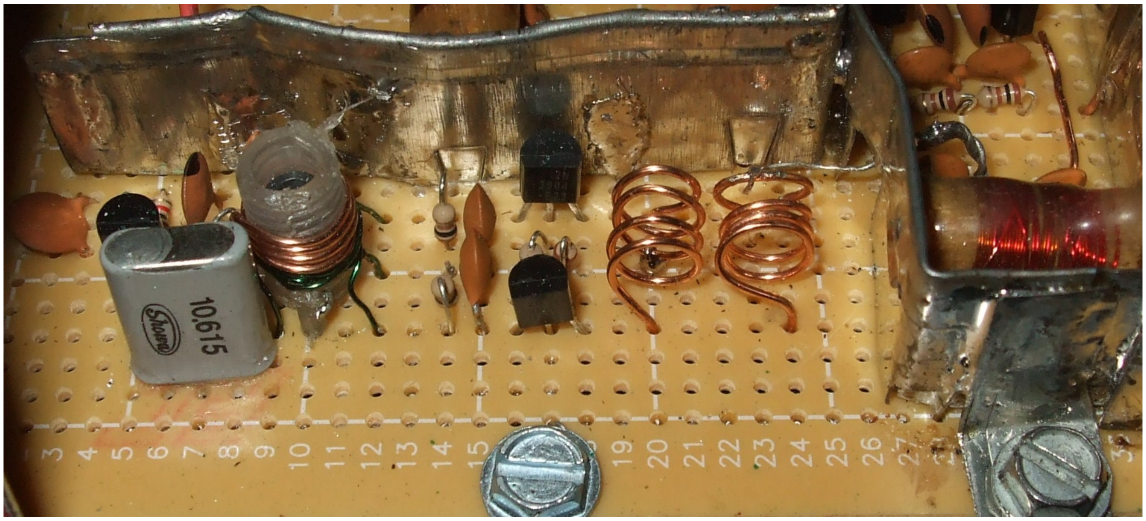
Unless you have a crystal that can run above 80MHZ, (on it's 9th overtone if it is a conventional one), you will need to mulitply the frequency of a lower oscillator up to 80 or 96 MHZ. A 3X multiple is probably has high as you should go, if you can get a 40 MHX crystal a doubler (in push-push) is even better. Some old CB's contain crystals at around 10.6 MHZ that also run well in the 31.8 range on their 3ed overtone, the 27 MHZ ones are cut to run on their 3ed overtones and can often run on their 9th..

A tripler gives 81 MHZ from a common CB crystal on 27 MHZ or 96 from a 32 MHZ crystal. 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. Without matched transistors, however, this protection is imperfect and you must rely on critical tuning of the doubly-tuned output circuit to do the rest.

A tripler likes high drive and some back bias, thus the 100 ohm emitter resistors.



Typical crystal 3ed overtone oscillator followed by a tripler as used in many WSQT transmitters



Spurious outputs from multipliers can cause 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 main difficulty with this and similar circuits is the “spur chart.” With a bad tripler,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, you will hear them unless you cut the low oscillator drive way back and sacrifice mixer output. As a result, the tripler's output must be very clean. You get this with good tuned circuits, no overloading, and enough yet not too much drive.

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 2012 rebuild of the transmitter. The then new setup used 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 the coupling (*not the tuning*) used to set the desired output power level. Never try to tune any previous stage by looking at the output from the mixer.

In 2013, a new transmitter was built. This time around, no crystals capable of 9th overtone operation were available that would allow a low oscillator frequency under 10 MHZ, so a tripler was used again. With it's secondary tapped at ½ turn out of 4, and the primary and secondary could almost touching (they are side by side layout), it gave plenty of drive to the mixer without saturating it. If the mixer had needed reduced VHF drive, increasing the separation of the primary and secondary coils would have controlled it with ease. The resulting signal was very clean, and the theoretically-expected X2 and X4 tripler product spurs were undetectable in a receiver when all stages through the 1 watt predriver and a dummy load were run for testing with the receiver only about 2 feet away. On the other hand, due to the low oscillator running at a little over 5MHZ, a doubly-tuned filter amp after the mixer was needed to keep traces of the tripler output frequency out of the amplifers and antenna.

9x overtone crystal oscillators as an alternative to the tripler

The best solution is not to use a multiplier at all, and run a 27-32 MHZ crystal at three times it's marked frequency. You will only be able to do this if one of your CB crystals will run this way, try the 9x overtone oscillator with the crystals you have and find out. If it works, you have a lot fewer possible spurs to chase down and suppress.

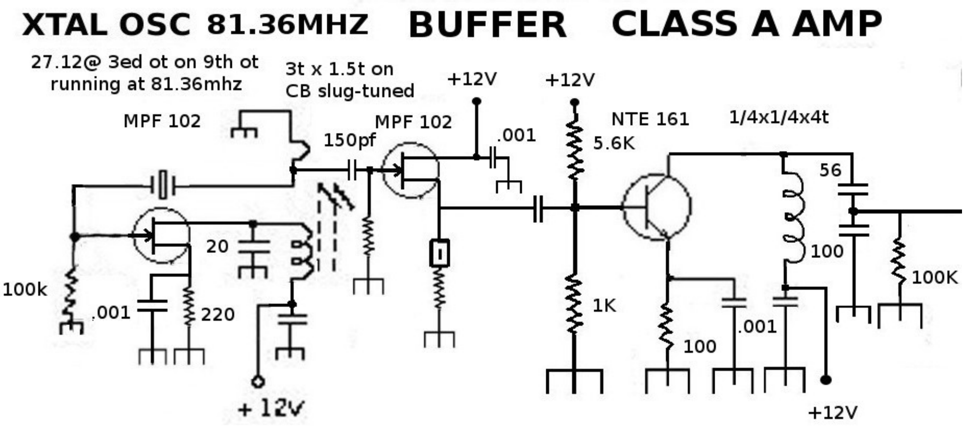
This is true overtone operation, where the crystal vibrates in layers and the RF circuits operate at the same frequency the crystal is running at, not a harmonic of the crystal vibration frequency. The advantage is no energy from any subharmonic of the output frequency is generated.

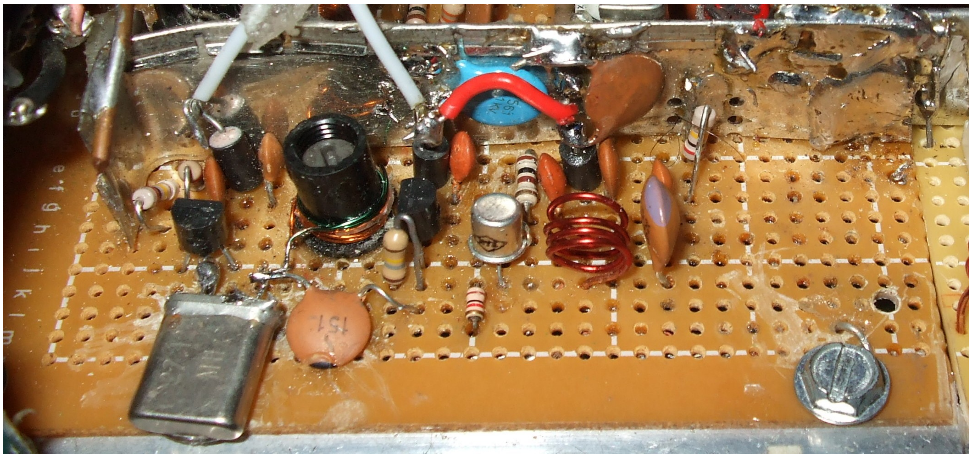
Now the spurious outputs must come from 2 times the high frequency and a high multiple of the low oscillator, or else just the nearest multiple of the high oscillator. These are usually so weak as to be difficult to detect from outside the receiver overload distance when running the transmitter into a dummy load.

The problem is this requires a crystal cut for overtone operation in the first place, as those cut for fundamental operation can't be run over their 3ed or sometimes their 5th overtone. Some crystals in the tiny flat cans seem not to be able to run at any overtone, possibly due to the way they are cut. 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. The MPF 102 is a common, cheap JFET formerly available 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. 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 Summer 2012 9th overtone direct oscillator/buffer/amp circuits





Low side variable oscillators

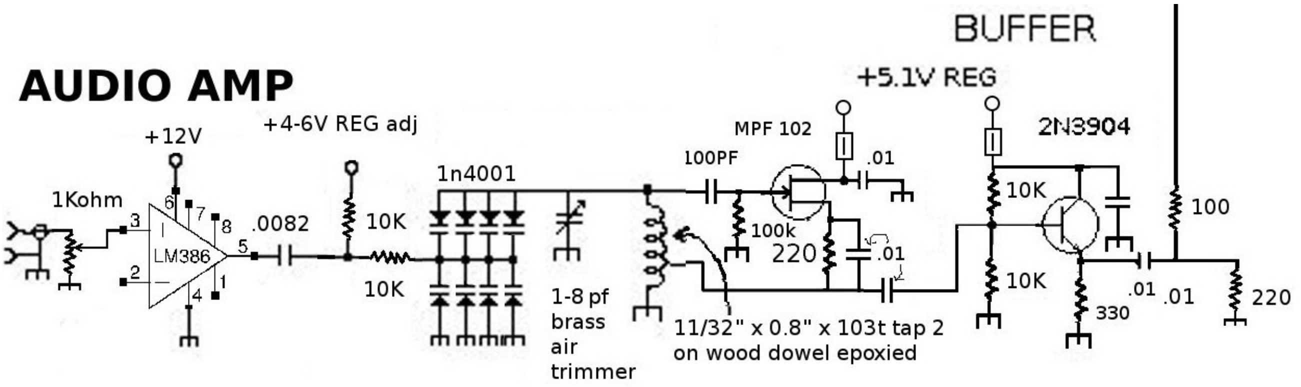
The low oscillator is the part that allows you to set the frequency to center of the chosen channel, and permits the frequency modulation to be applied. There are a few tricks here to getting the needed stability: The coil should be wound on a wooden dowel rod out of fine magnet wire, then glued in place 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.

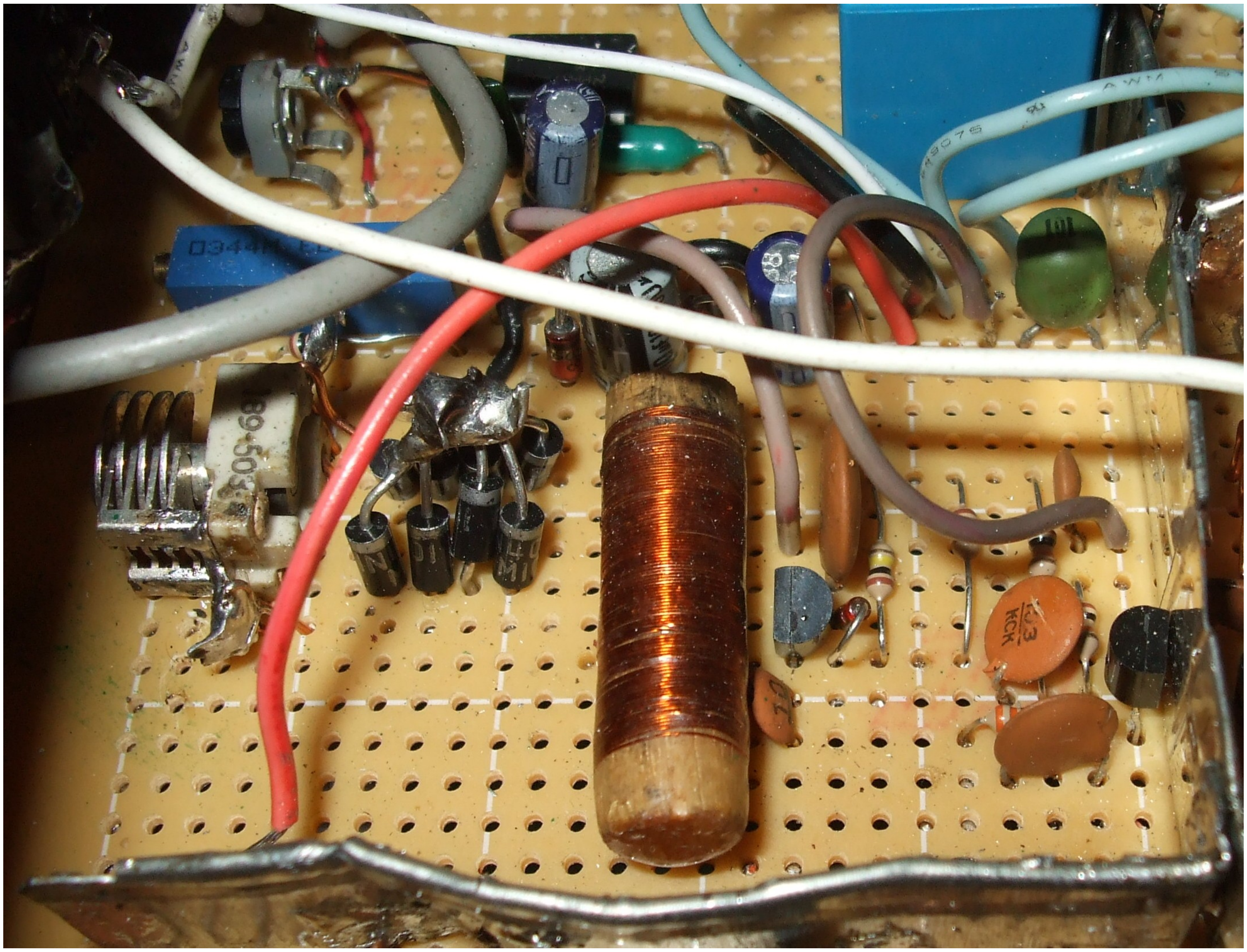
This oscillator should again use a JFET like the MPF102. That's because temperature changes affect them less than any other transistor. Use another MPF102 or a small bipolar transistor in source/emitter-follower configuration as a buffer to isolate the oscillator from any tuning changes in the mixer.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

There is one other critical aspect of the modulated oscillator: the modulator itself. Both free-running FM oscillators and phase-locked loop oscillators are known as “voltage controlled oscillators or VCO's and are tuned by varactor diodes. These change their capacitance in response to changes in the DC back bias level. They are now hard to buy-but common 1N4001 through 1N4004 rectifier diodes have been used for decades as varactors and can be found anywhere. In fact, their tuning is a near-match for some formerly sold varactors and their design is a temperature stable “linear junction” as opposed to a “hyper-abrupt” junction. A single 1N4001 at 5V is about 13pf, reaching 15pf at 1V and 10pf at 11V. Zener diodes are also useful as larger varactors, but I've never tested using them this way for temperature stability. None are linear, so the needed change of voltage must be kept small.

In addition, the varactors must have enough DC bias that the combination of the peak RF and peak modulating voltage never drives them past zero and into conduction! Otherwise, the current they then draw will move the center frequency on modulation peaks. This causes a maddening inability to get full audio volume without distortion, and makes all receivers seem incredibly sensitive to the exact centering of the original carrier signal. During the design of a new transmitter in 2013, this was addressed by using a separate, higher voltage source for the varactors. This had been done in a 2005-2007 design to allow tuning by a potentiometer, this was also included again as a fine tuner. The result was greatly improved audio “punch” that could have made weak signals that could not be listened to in certain places with the 2008-2012 transmitter usable, and may explain why so much RF power was needed beginning in 2008. In prelimary tests before even accurately centering the carrier, the audio was clearly much stronger than before prior to distortion, even with a badly off-center carrier that would previously have caused severe distortion on all audio peaks. Also, using as small a tuning capacitor as possible and getting the coil close to its theoretical value maximizes modulator sensitivity, reducing the amount of audio signal needed, thus raising the minimum voltage when negative audio and RF peaks cooincide.

Summer 2013 audio amp, low oscillator, and buffer as of 6-24-2013





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 plus or minus 2KHZ, 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. Small brass air trimmers are stable, I've used one as a trimmer to pull a crystal on an AM setup to center frequency with no issues.

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. That will make the diodes conduct on peaks and raise the frequency of the low oscillator. 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 13pf each (6.5 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.

And one more: Make SURE varactors are never, ever biased into conduction! Otherwise “carrier shift” on modulation peaks will result, forcing a substantial reduction in modulation and audio power! Using as little tuning capacitor as possible will maximize modulator sensitivity, reducing needed AF voltage.

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 multiplier 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. 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. Until 2013 I used 10.7 MHZ IF “cans” taken from old radios and rewound. Internal capacitors were removed, and a center tap between two identical external capacitors in the output was the feedpoint for the high signal. A center tap in the coil provided and RF ground, In the 2013 build an “air-wound” coil on wood and epoxy just like the oscillator coil was used instead, it is easier to make and gives better balance. It was computed to resonate with 500 pf across it, from a pair of 1000 pf capacitors. While this is fixed-tuned, it came out plenty close.

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 a push-pull 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!*

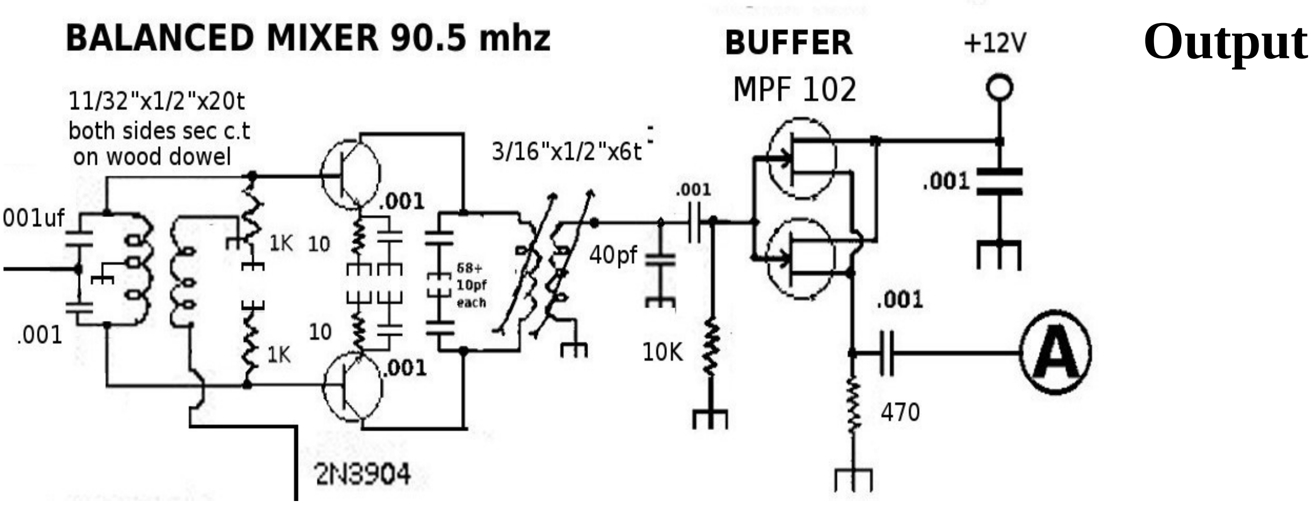
Like a tripler, the balance is rarely perfect. If it was, no spurious signal created by even harmonics of the low oscillator would escape, and if it's anywhere close you won't be able to tune the output circuit to pass the high frequency input frequency . Still, if the high signal is clean, harmonics 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.

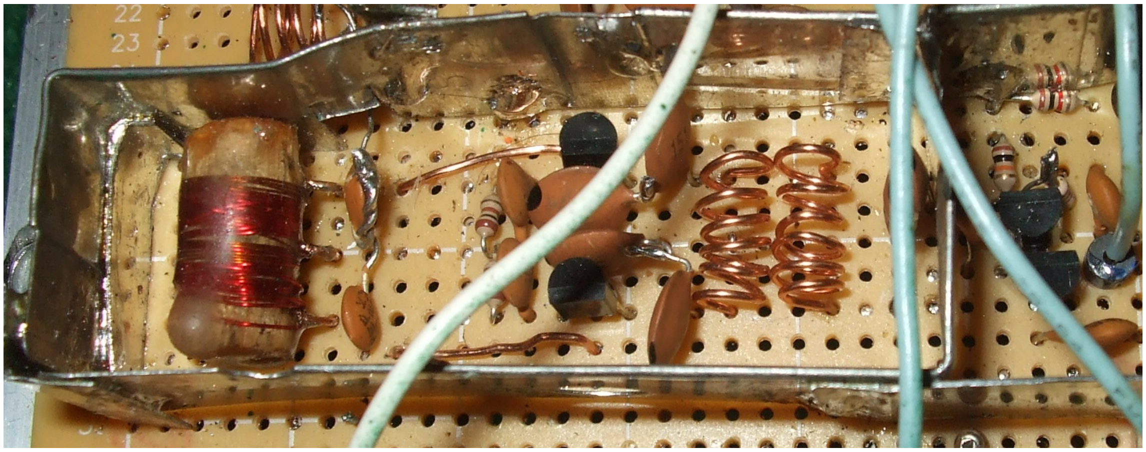
You will need a voltage divider in the line from the low oscillator to adjust levels. The high frequency input should be about 10 times the power of the low frequency input, or about 3 times the voltage as measured with a small diode in series with an electronic voltmeter. Never run either input so high the mixer transistors saturate, or the output will drop, as the other side then has less influence. If you have too much power available from the crystal frequency amp or tripler, first tune it to resonance, then reduce coupling or 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 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 MPF102 JFETS to work better than anything else for coupling the mixer to the amplifiers that follow it. Very little mixer load that would broaden the tuning, yet 10-20 MW of low-impedance output that can drive bipolar transistors. If more output is needed, 4 MPF102's can be used, but they are getting harder to find and another 3904 amp stage might be easier to get parts for!

The mixer and buffer used in Summer 2013 as of 6-24-2013:





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 now 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. A 100 ohm capacitance paralleled across an 100 ohm resistance would look the same from a conductor hooked to one end of both as though they were a 25 ohm C and 25 ohm R in series. Both are 50 ohms with a phase angle of 45 degrees as far as that single wire is concerned.

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 mathematical formula for this. It works 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 gives currents that cancel in parallel or voltage that cancels in series, which is how all tuned circuits work.

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.

When 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. This is always used in WSQT mixers, multipliers, and “filter amps.” A smaller coil that is not tuned also works in a singly-tuned, transformer-coupled circuit but is not as selective. 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 that can 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. Unfortunately they 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.

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. A 40-50 watt design in Summer 2012 required only two, using the NTE161 instead of the 2N3904 in the first stage, and a half watt only from the predriver. 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 transistors, you can save a stage, maybe two, in the overall design. On the other hand, they are much more likely to oscillate if your layout isn't the best.

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 used 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.

On the other hand, the lower gain of the common 2N3904, still available at Radio Shack, lends itself better to the inexperienced builder, as it is much tougher and also more stable. The lower gain means it is less likely to oscillate, though it still can if the circuit is really bad, has poor decoupling, or especially in the case of too much inductance in shunt-feed RF chokes. The latter is recognizable by making nasty white noise in receivers tuned anywhere near the operating frequency. Smaller chokes, smaller bypass capacitors, and resistors in series with large bypass capacitors and across larger, secondary chokes are the cures for this, presented here in the order in which they should be tried.

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 1 watt 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 steel tools, no good for adjusting resonance, and requiring shutting down to change an impedance match.

A common 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 addition to this loss, the circuit can get too selective and difficult to tune quickly with too much inductance. 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.

Another point about “stripline” traces on printed circuit boards: If you want to duplicate one that worked before, the length, width, board thickness, and degree of connection between front and back side copper must all be duplicated. If inductance is too high, you can easily shorten it. If inductance is too low, you must interrrupt the trace and insert a small hairpin half-turn “coil” of copper sheet as wide as the trace. It looks like a speed bump almost, about 1/8” to 1/4” high often works for me in this situation.

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 big 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 damaged by a corroded mica trimmer that heated in use, detuned from the heat, and damaged the PA transistor. The MRF247 is tough, it lost maybe 10-15 watts of available output when used in another PA but did not die outright. Several replacement transistors were destroyed entirely 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. It's also important 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. This reduces the chance of oscillation at a frequency of a few MHZ, with the chokes becoming the resonant circuits for the oscillation.

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

It is common practice even in Class C stages use a resistor and capacitor to ground in the emitter circuit of small bipolar transistors. In Class A stages higher value resistors in the same circuit are used to set the idling current.

I have 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 except when using heatsinks are used or when the drive is too low to saturate them.

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 2012 experiment,, 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 100 times as much at 900KHZ and will sometimes shut down oscillation at lower 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.

Emitter resistors 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 prevents overheating failures and was used from Fall 2012 to Spring 2013.

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. 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 30ma 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.

Sometimes when a 330 ohm or so resistor is the DC base return path, the resulting back bias will prevent thermal runaway by forcing any leakage current to flow from the base, bypassing the emitter-base junction and all of its gain. The back bias will be less than expected due to this leakage current.

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 330 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. WARNING: the stabilizer resistor in the PA collector choke circuit gets very hot if the PA oscillates or any previous stage feeds it low frequency energy. It it dies with a spark, it can take out the PA transistor! Be sure to watch it for heating while first tuning up. If it heats at all, you have a problem with spurs, either from oscillation in the PA or in an earlier stage. Fix this, don't go on the air until that resistor runs *cold.*

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 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 easier 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.

I recommend either the MRF648 or the MRF247 for outputs in the 80 watt range. The MRF247 is incredibly tough if you get the real Motorola version, while the MRF648 is easier to drive. Actual gain seems to be similar. I've gotten 70 plus watts from an MRF247 that was previously overheated until it cooked off it's heatsink while running with a corroded capacitor in the output network.It lost some output, but could still be pushed to over 70 watts even after being damaged if it was clamped directly to the PA heatsink.

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, will give 80 watts or more at 90 MHZ. There is also to more expensive and newer MRF 650, another 470-MHZ device, rated for 50W, a little more gain, and much better protected against damage from a mismatched circuit. It should be nearly as tough as the MRF247, assuming you get the Motorola and not the “UK” variety. I've not yet tested one due to the higher cost of the MRF650/

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. The MRF247 VHF transistor remains popular with hams, sometimes being pushed to 100 watts at 2 meters (144 MHZ) with 13.8 volts.

The big VHF MRF247 is considered 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. If you are going after 80W, though, you would have to overdrive the MRF648, giving similar gain-and the two become almost interchangeable at 90 MHZ. Even the same imput circuit can be used, though the driver output L network should be a *higher* impedance for the MRF247 as the lower imput impedance will be inverted by its input L network. If the driver has power and drive to spare, the exact same interstage circuit may work with just a minor retuning for either device.

The sheer toughness of the MRF247 thus gives it the edge at powers over 60 watts.
There is one exception: all three of these devices have been made by several makers. The ones labeled “UK” will perform as well as the others in these circuits but are delicate. Buy them only if much cheaper than the Motorola versions-and never buy just one. Of course, a bag of them sold cheap can be a great deal if you don't have almost constant antenna troubles. Matched right, even the UK versions will run and run. Just be sure to initially tune at half voltage when building with them!

You won't quickly damage any of these (with the possible exception of some of the UK versions) 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 becomes 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 of 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 miles of 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. Best practice is simply to use tuned/coupling circuits that actually need that much capacitance and let the transistor supply it. Even 1W predrivers will work using big PA transistors if this is done. Why use big transistors this way at all? Because a pack of 5 MRF648's or MRF 646's may cost less than or the same as one 1W device, one 10W device, and one 80W device while giving you two spares!

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 will be able to deliver more than that because of losses in the interstage coupling circuit.

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.

Mount drivers over 5W on the same heatsink as the PA or another external fansink, or the inside of the case will get too hot and the oscillator will drift.

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. If you don't get enough inductance to resonate with a pair of the trimmers you have, adding a “speed bump” strap inductor about 1/8” to 1/4” high across a cut in the stripline will solve the problem.

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.

The predriver will usually need to make about 1 watt to drive a 2 stage bipolar PA to 80-100 watts. This is more than a single MPS2222A can make. You can either get three PA style transistors and use the third one as a 1 watt stage or connect 4 MPS2222A's in parallel for a 1 watt stage. The former is much more efficient and makes much less heat, the latter is easier to stablize but requires improvised heatsinks with a small fan blowing on them to survive. The 2012 rebuild used the MPS 2222A array, the 2013 rebuild a single 2N 6082, a 25-40 watt VHF transistor. In 2011, a single UHF type MRF646 was used. It's entirely possible, in fact, to simply use 3 MRF646's out of a baggie of them purchased over Ebay, each driving the next, to get from about 150 mW all the way to 60 watts or more.

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 60 or more watts at 12.5V.

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, some but not all samples will go as high as 70-80 watts
MRF648-80 watts
MRF650-untested ($$$) should be good for 65, maybe 70 watts but possibly 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.

On the other hand, big ones like the MRF247 don't have to resort to overdrive to make 80 watts plus, so for high powers the MRF247 ends up with about the same gain as an overdriven UHF device.

The MRF247, used for an 80 watt setup for years by WSQT, is a good example of an otherwise excellent device whose matching network makes it hard to drive. The very low input impedance means the driver to PA circuit has a very high “loaded Q” and thus poor efficiency due to limited “intrinsic Q.” L et 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 interrupting 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.

When I used a damaged but still usable MRF247 in 2013 after blowing an MRF648 in testing, it worked in the same circuit as the MRF648, and the slightly higher inductance used in that amp with the longer stripline seemed to help the driver's efficiency, probably be eliminating the array of wire-leaded mica capacitors used alongside the trimmers from 2008-2011.

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.

Again, all of the devices above are almost interchangable in the PA circuits discussed here, and even some (but not all) samples of the MRF646 will overdrive to the 70 or 80 watt level. All will make 60W with ease, all day long.

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 Intermittent 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 intermittent service, however, you will need the strongest signal you can generate just to get heard, here's how to get it. Just be sure to have spare PA output transistors on hand, as it takes time to order them!

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.

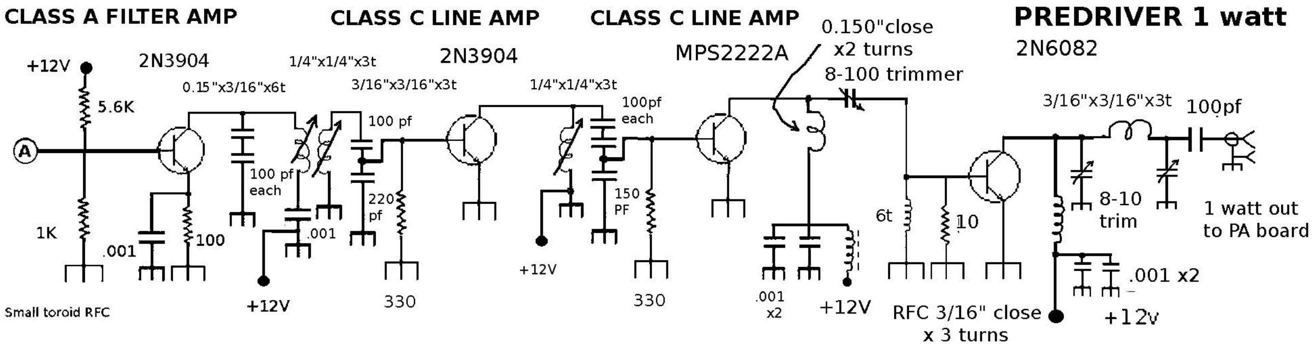
Warning: Always begin tuning dual transistor PA amps at half voltage! They can oscillate in push-pull mode, and if that starts up at full supply voltage it is really easy to blow one or both transistors. At half voltage you can forget about this, let it oscillate at first startup, and experiment with 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.

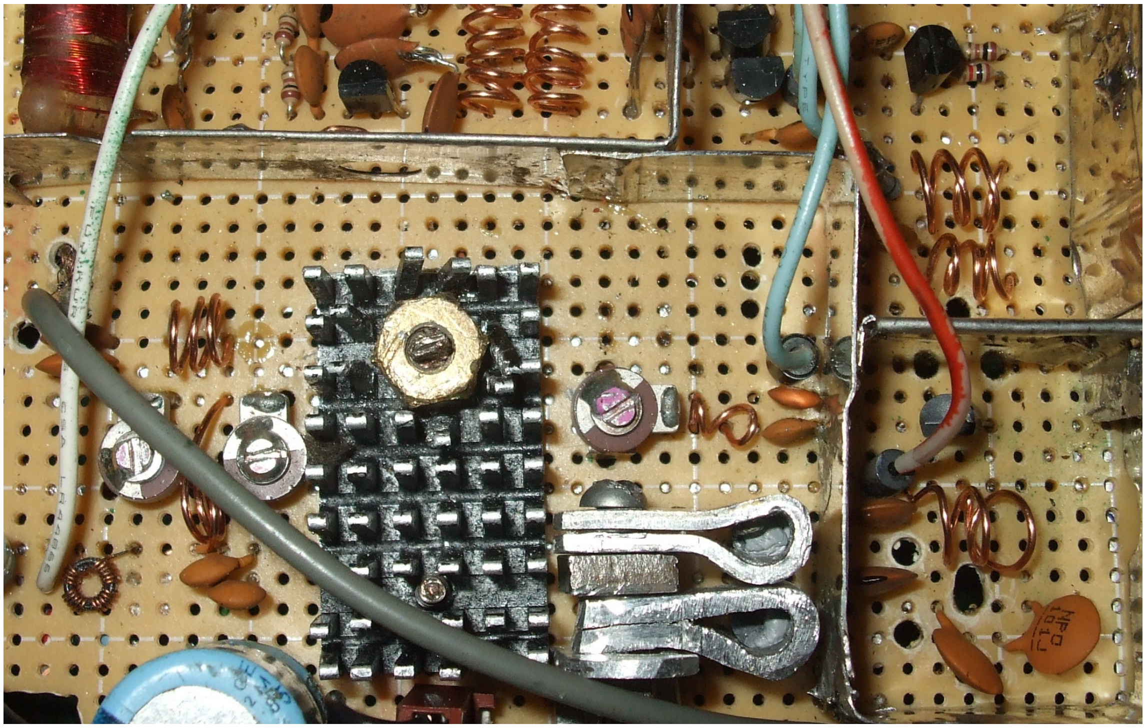
A note about layout and cooling

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 heatspipes 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 7-10-2013:





A note concerning aligning/tuning power amps:

It is a good idea to pre-check the input circuits and the filter for resonance before trying to run and tune the amplifier for the first time, then fire up on half voltage to adjust the output stages and check for any instability/oscillation/"hash noise." Initial tuning on half voltage can save a transistor, it will almost certainly save a driver or PA stabilizing resistor from being burned up.

This is especially important when using suspected delicate devices like the "UK" versions of MRF (anything) transistors, or any dual transistor setup. It was half voltage tuning that made it possible in April 2008 to make a dissimilar dual transistor amp work without first destroying both of the transistors, the only ones I had! The UK version MRF 648 used in the Summer 2013 rebuild was tuned and stabilized at half power and works just fine now that it is past that critical period.

You will do all this adjustment on a "dummy load" with a string of three small signal diodes in series connected to the hot side and to a capacitor, allowing probing voltage peaks there to indicate power output. Use an insulated tool only to adjust the capacitors while the circuit is running or you will get falsified results-and even RF burns.

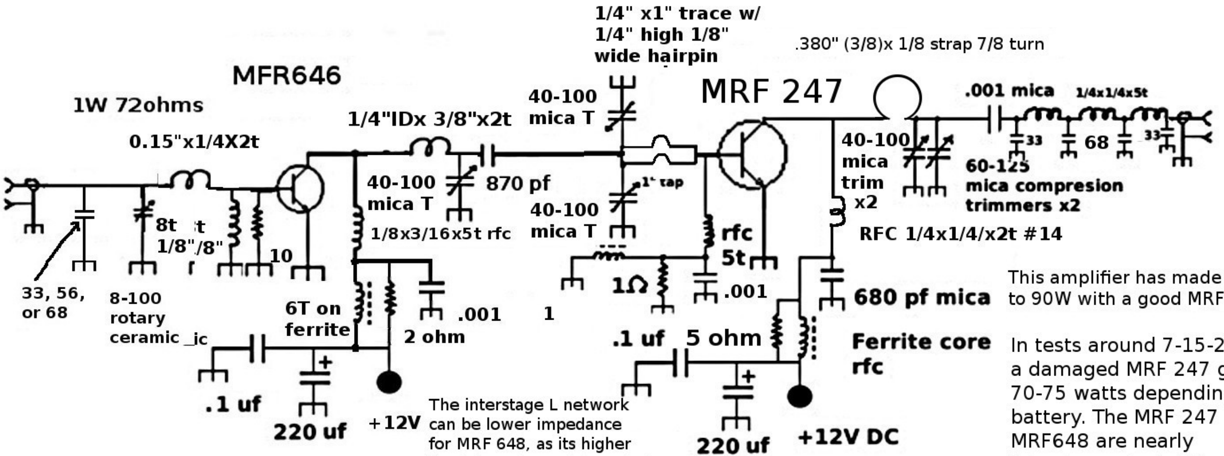
First, connect a transmission line from the predriver (1 watt stage) to the filter, the PA input circuit, and finally the driver input circuit and adjust these circuits for resonance, peaking the reading obtained with a diode probe on a digital volt meter. Do this with the coupling capacitors between PA and filter and between driver and PA removed. Next, make sure the input circuit gives about the same peak as the predriver running into a dummy load. If it does not, change the amount of inductance and return until it does. You can get away with it being a bit high by increasing loading on the predriver and vice-versa, but watch for overheating it, and if you "get lost," put it back on the filter/dummy load and retune it.

One the imput curcuits are roughly tuned, put the coupling capacitors back in the circuit and peak the output circuits on the small amount of signal leaking through. Next, hook only the driver to a 6V power source (half voltage) , turn on the exciter, and then the 6V power. Peak the output circuit, then repeak the input circuit. Turn on a receiver and make sure you are not getting any white noise or extra copies of your signal. The output power from it will not hurt the PA one bit. Finally, turn everything off and connect the PA power lead to the 6V source and repeat this process with the final amp stage. When everything is right, expect to get about ¼ of your expected power (half output voltage) at half voltage, with NO hissing or extra copies of your signal. Finally, connect a 12 volt source and recheck everyhing, touching up the tuning as needed.

If you don't have the heatsink fans running yet, the heatsink will soon get hot. If the dummy load is made from 14 1 ohm resistors in parallel in two rows (a recommended inexpensive design) it will get very hot very fast under power, only apply a few seconds of full power at a time. This load starts at 72 ohms, same as your Cable TV RG6 feedline and a dipole. It will drop under use and heat to about 68 ohms. With a 3 diode string, a capacitor at the probe pickup (open circuit) point, and a 68 ohm load, an electronic voltmeter connected between the diodes and ground will read about 102.5 volts at 80 watts. That is peak voltage, add 1.8 volts for the 0.6 volt per diode drop, then multiply by 0.707 for sine wave "root mean square" power, square the result, and divide by your measured impedance for your power reading.

PA used in Summer 2013 rebuild.

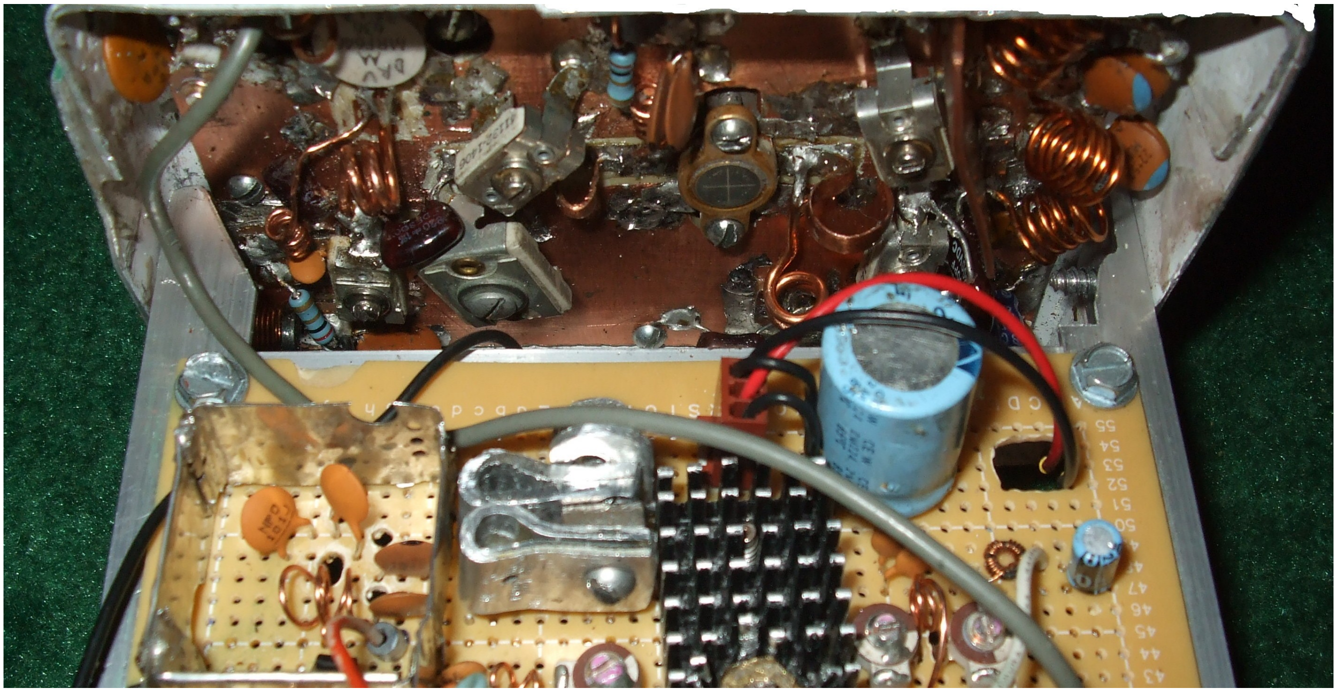
60-90W 90 MHZ PA for MRF 247 or MRF648



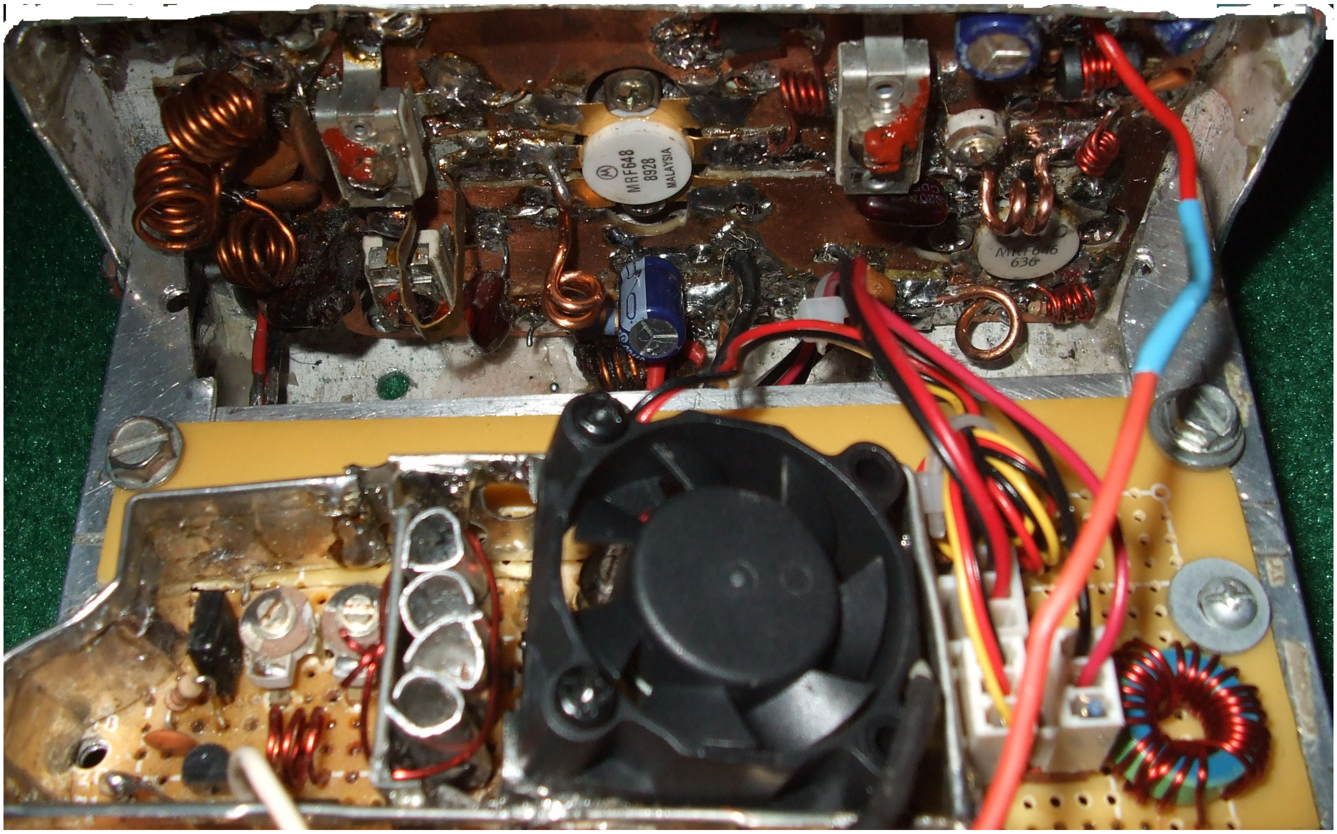
The interstage L network can be lower impedance for MRF 648, as its higher input impedance is inverted by the same input circuit

This amplifier has made up to 90W with a good MRF648.

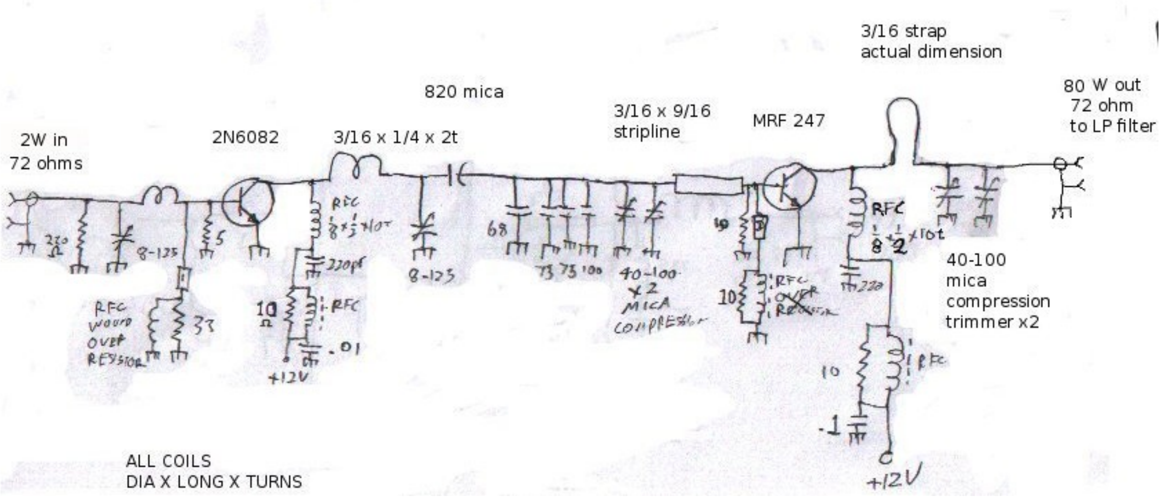
In tests around 7-15-2013, a damaged MRF 247 gave 70-75 watts depending on battery. The MRF 247 and MRF648 are nearly interchangabe in this circuit

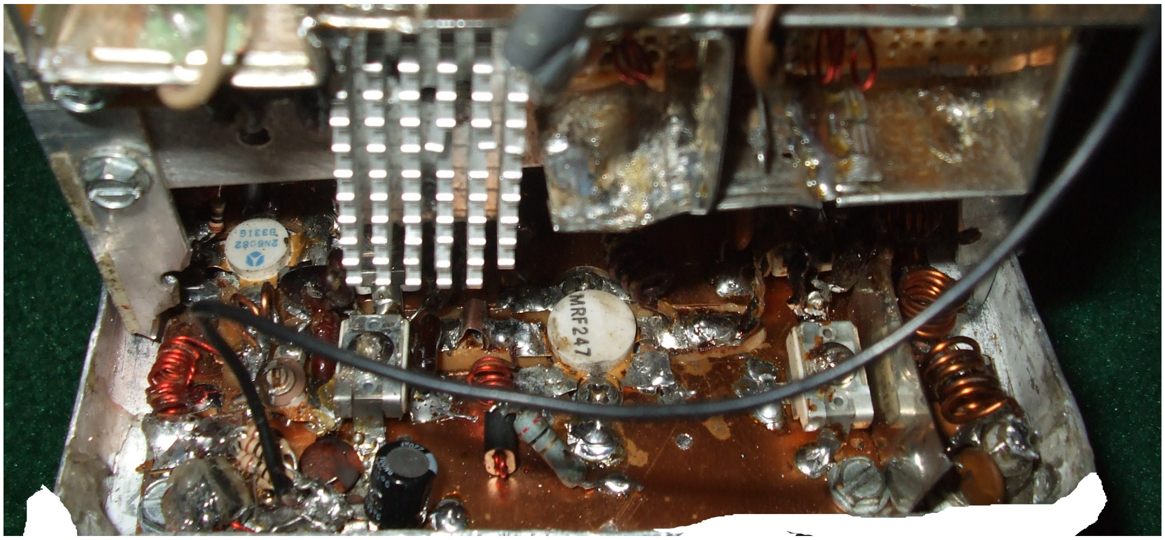


PA used in Summer 2012-Spring 2013:

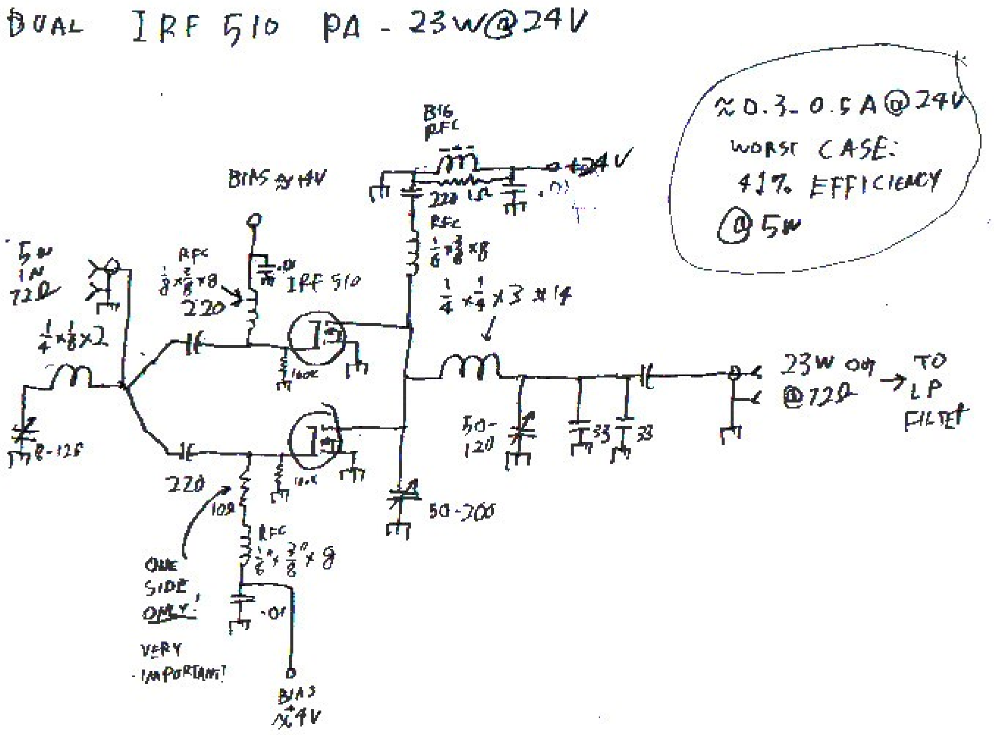


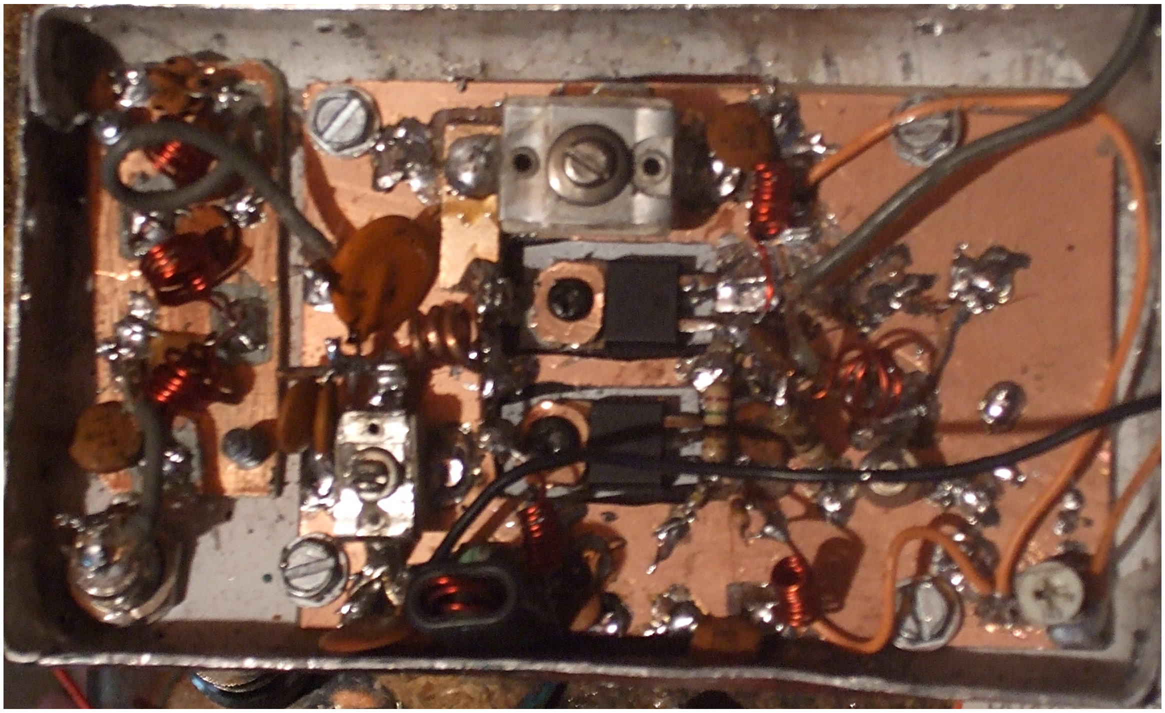
2008-2011 70-80W MRF 247 PA





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.