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CHAPTER 16A HOMEBUILDING VHF HAM RADIOS VHF Amplifiers & Frequency Generation

2 meters - a band where hams still talk to each other

The last few years most hams seem to have become increasingly obsessed with call letter collecting and FT-8 signal reports. A good reason to get on 2 meters is simply that the guy you're talking to will probably want to tell you about his equipment, his clever dog and his cute granddaughter. Then you get to tell him about *your* rig, *your* dog and *your* granddaughter. In other words, you will have real, human conversations.

R&D exploration with eventual success

Homebrewing 2 meters is difficult. Want to try for a second Nobel Prize? There must be a thousand plans and schematics on-line for building 40 meter QRPs. In contrast, you hardly ever find plans for homebuilt VHF gear. If you have tried to build a 5 watt QRP for 30 MHz, you already know why 144 MHz is so hard. It's not terribly difficult to get a 28 MHz oscillator to work, but producing more than one watt on 10 meters is surprisingly hard. A reader compared these four VHF chapters to a "wild road trip" with lots of unplanned detours and surprises. Previous chapters usually marched through the challenges without encountering so many of my errors and misunderstandings. That's because VHF is just plain difficult! Chapter 16A describes my R&D to build VHF power amplifiers. Chapter 16B describes the evolution of my 2 meter transmitter design(s). Chapter 16C covers building 2 and 6 meter receivers. Chapter 16D describes a 6 meter CW and SSB transmitter.

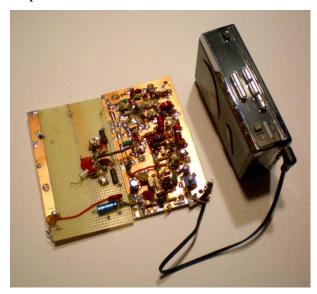
A 2 meter FM signal generator



Finally I have produced a 2 meter transmitter signal generator that generates an FM modulated signal that sounds as good in my 2 meter Icom commercial transceiver as the commercial ham transmitters. Unfortunately, it literally only produces a few milliwatts. That's about 1/100 the

power I'd like to have for actual communication but it's a start. As it turned out, this signal generator was vital for me as a test signal for developing a 2 meter receiver. In the picture above, the RF circuitry is on the left while the audio amplifier and microphone are on the right.

Where I live we have two 146 MHz repeaters that produce strong signals. Unfortunately, most of the time there is nothing to hear but static. To trouble-shoot my receiver project I needed a continuous source of 2 meter FM voice. Although the little LM386 audio amplifier board shown above produces acceptable audio from the microphone, I can't very well talk, hear and tune amplifiers at the same time.



My solution was to drive the FM modulator directly with a Walkman radio shown above. The perforated circuit board ("perf board") on the left of the generator board was one of many failed attempts to produce an amplifier that would raise the output power beyond a few milliwatts. More precisely, they always produced about 200 mVolts open circuit with a 3 pF VHF oscilloscope probe for a load. All my breadboard "power amplifier" stages tuned up perfectly but produced no more than 200 mVolts open circuit ... and sometimes less. Oh, well. They did produce a strong, good quality 2 meter station I could listen to from 6 feet away.

Test equipment required

This project would be extremely difficult without a VHF rated oscilloscope, a frequency counter that covers 0 to 150 MHz and a quality VHF receiver. As you can see in the photo above, an ordinary AM or FM receiver is useful for generating continuous audio to develop and test both the receiver and transmitter. It's also desirable to have an accurate VHF power meter capable of measuring RF power from 0.25 watt to at least 10 watts.

Reliving the Thomas Edison experience

I'm reminded of the story about Thomas Edison searching for the ideal light bulb filament material. He is supposed to have said, "No, I'm not discouraged. Now I know hundreds of materials that don't work." My Edisonian efforts to build a two meter rig have taught me a number of lessons by trial and error. Here are the major ones:

- 1.) Keep component leads short and PC traces wide to avoid unwanted inductance. This isn't critical so long as the wire is only conducting RF voltage, but when significant RF current passes through the wire, the wire's inductance soon becomes obvious.
- **2.)** Use single-sided boards, not double-sided. The extra capacitance to ground doesn't act like coax. It just adds more stray capacitance. When the stray capacitance becomes greater than the capacitors in your L-C tuning circuits, it is difficult to resonate anything above about 50 MHz.
- **3.)** Fiber glass punch boards ("perf boards") with an array of holes every **0.1** inch are an alternative to through-hole single sided boards. Circuits on perf boards are easy to build and can have low stray capacitance. This method preserves the leads of your components to at least 1/4 inch. That way components can be moved or recycled. 1/2 inch wide strips of PC board material can serve as ground and power buss bars.
- **4.)** Use mica, silver mica or NPO ceramic capacitors. Use metal film resistors, not carbon composition or wire wound. These components are "pure" meaning that, above 100 MHz, they will not act like unpredictable combinations of Cs, Rs and Ls. 144 MHz inductors are usually 2 to 4 turns of bare wire and quite "pure."
- **5.)** Use ceramic trimmer capacitors 1.0 cm diameter or larger. Tiny surface mount ceramics are hard to solder and adjust. Plastic trimmers are easily damaged by soldering and may even short out.
- **6.)** Use smaller inductors and larger variable capacitors than recommended. A typical 2 meter amplifier stage schematic might call for a 25 pF variable capacitor and a small 5 turn air coil. I found that a 7 to 100 pF trimmer capacitor and a 2 turn air coil were much more likely to resonate on 2 meters. If all the component leads are really short, the recommended values occasionally work.
- 7.) Use 1 to 3 pF capacitors to connect a scope or counter to your circuit. This makes your instruments relatively insensitive to the signals you wish to observe. However, it is better than swamping the oscillation with a 15 or 25 pF probe. VHF 300 MHz oscilloscope probes have capacitance as low as 3 pF. They improve the sensitivity and usefulness of scopes and frequency counters. A frequency counter and oscilloscope rated for 150 MHz or above will make the project much easier. A 50 MHz scope may display 144 MHz sinewaves but they will be faint and tiny.
- **8.)** Beware of tuning up your 144 MHz amplifiers on 3/4 the desired frequency, 108 MHz. A 144 MHz transmitter based on an 18 MHz crystal will have 36 MHz and 72 MHz artifacts on the signal. The last doubler stage sometimes settles on 108 MHz. 72 MHz + 36 MHz = 108 MHz. As always, the lower the frequency, the larger the sinewave output. The 108 MHz sinewave will be much larger than the 144 MHz output.
- **9.) Beware of amplifier oscillation.** Once you begin to try to amplify your 144 MHz signal, your "success" often turns out to be an oscillating amplifier that is producing a huge sinewave somewhere around 100 MHz. If it's oscillating, the frequency of the oscillation will shift as you approach the circuit with your hand or vary the supply voltage.
- **10.**) A signal on 72 MHz may be easily heard on 144 MHz making you think it's working. Most frequency counters will not respond to VHF signals smaller than about 30 mV peak, so your frequency measurement may be limited to listening to a 2 meter receiver or interpreting a tiny trace on an oscilloscope.

- 11.) VHF transistors with Ft ratings of many hundreds of MHz are fragile. Usually, the higher the Gain-bandwidth frequency, Ft, the lower the breakdown voltages. Looking at the datasheets for various VHF transistors I found collector to emitter voltage ratings as low as 10 volts, but 12 to 20 volts is more common. It is easy to damage them with a brief short circuit or touching a soldering iron to a metal case.
- 12.) Thin VHF transistor leads often do not "stick" to the solder. Tin them before soldering, then after soldering, tug and twist them to be sure they aren't "cold" solder joints. VHF signals often leak right past a cold joint making you think an amplifier stage is working as well as it is going to.
- **13.) VHF power amplifier stages work best with ferrite bead/ capacitor power supply decouplers.** Fine wire-wound inductors have significant resistance and waste power. In contrast, *HF* amplifiers worked best (for me) with resistor/capacitor decouplers while inductor/capacitive decouplers were unstable.
- 14.) Bipolar VHF power amplifiers, 1/4 watt and larger, are fragile and difficult to design. MOSFET VHF power amplifiers are rugged and much easier to design.
- 15.) The most perplexing and frustrating aspect of VHF is that, if your circuit works today, it may quit working tomorrow. Even worse, you won't be able to figure out what changed. Cold solder joints may be a partial explanation.
- **16.) VHF FM voice modulation is extremely susceptible to 60 Hz hum, both on transmit and receive.** In contrast, AM and SSB in the same receiver or transmitter might have no audible hum. The simplest fix is to run your VHF rig on batteries.
- 17.) After initial testing, totally enclose both the transmitter and receiver in metal. Exposed circuitry is more unstable and prone to oscillations. When the transmitter is not fully encased, FM phone is prone to scratching sounds and even harsh continuous noise.
- 18.) And finally, the biggest discovery was that measuring RF voltage and power by using a VHF rated oscilloscope and probe to measure VHF waveform voltage greatly understates the real values by an order of magnitude.

This chapter, Chapter 16A, describes many attempts to build 2 meter amplifiers for the transmitter and a 2 meter receiver. If you're only interested in building a working 2 meter transmitter and don't wish to endure the tedious odyssey I went through to get there, skip ahead to Chapter 16B.

Available 2 meter homebrew designs

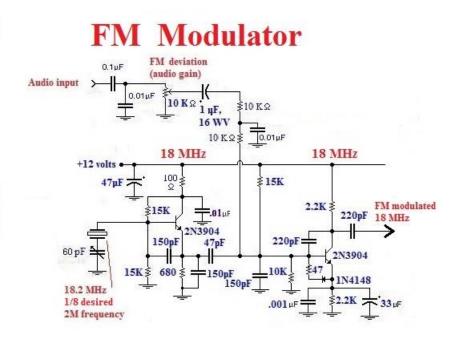
I found several schematics of low power 2 meter transmitters but only two transmitters had construction details: The first one is in the 1986 ARRL handbook. It took 5 amplifier stages to go from milliwatts up to one watt. In other words, at 2 meters each amplifier stage usually only has a gain of 2 or 3, not the gain of 10 we often observe at HF frequencies. Also, the construction was extremely compact with all the little parts mashed together. Building circuitry like this takes patience and a strong magnifying lens to confirm your solder joints.

ARRL handbooks from the 1980s and earlier also have plans for huge, vacuum tube, 144 MHz kilowatt amplifiers. The plans consist of extremely detailed blueprints for sheet metal pieces and brackets to mount the doorknob sized vacuum tubes. The inductors are long, flat plates of metal

that would be appropriate for digging dandelions out of your lawn - heavy duty! For someone like me who couldn't generate one watt, a thousand watts was beyond imagination.

The most useful design I found was at www.qsl.net/vu2msy. The website has a small print label at the top that says "homebrewing." Click on it and look for "2 meter transceiver" among the list of projects. The article also has a design for a 2 meter receiver and a 1 watt to 3 watt amplifier. (The receiver uses magic ICs which defeat my reason for homebrewing.) The one watt transmitter was designed by Dr. Ashutosh Singh, VU2IF. His design is unusual in that it is entirely discrete component construction - no ICs. Also, it has an 18 MHz oscillator and FM modulator that worked perfectly the first time I turned it on. This is the 2 meter milliwatt signal generator in the picture above. I recommend downloading this article and, if you can get the parts he used, make an exact copy of the single-sided PC board layout he used. Who knows? Maybe the entire transmitter will work for you, including a full one watt output.

The FM modulator



The modulator in Ashutosh's transmitter is one of two examples I found of an FM modulated oscillator that uses discrete components - no ICs. Most important, unlike my crude experimental FM modulator mentioned in Chapter 13B, this one generates undistorted modulation in real commercial 2 meter receivers. Notice that both stages of the oscillator and buffer amplifier do not have any tuned L-C circuits. The frequency is totally controlled by the crystal. The oscillator circuit has a 150 pF capacitor that connects the emitter to the crystal, much like a free-running Colpitts oscillator. The emitter is connected by a 47 pF capacitor to a small signal from the audio input. The amplitude of the audio can be adjusted by the 10K potentiometer to determine the "deviation" - the frequency change during modulation. In practice, this deviation determines the audio volume of a signal when it is received by a true FM detector, such as a ratio detector or an FM discriminator.

Custom ground crystals are expensive and take weeks to arrive. To get started, I suggest using an 18.000 MHz microprocessor crystal which can be pulled high with a series trimmer capacitor to give you a 2 meter signal in the CW band. Better yet, there is also a 18.432 MHz

microprocessor crystal available. When multiplied by 8, this produces 147.456 MHz which is near the top of the 2 meter phone band. I was able to "pull" the frequency up to 147.495 MHz which is an official simplex frequency. I bought both crystals at Mouser.com for less than a dollar each.

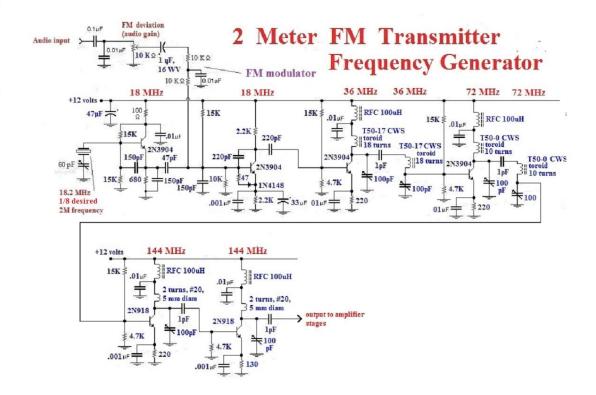
Narrow band FM can be detected with a product detector

If you have an all band HF ham receiver, tune to 17 meters and listen to the signal. My oscillator is at 18.2 MHz and easily heard. The modulation sounds quite good when detected by a product detector, just as though it were an SSB signal. The interesting phenomenon is that the deviation control controls the frequency of the modulation, so you must adjust the deviation to match the real frequencies of the original audio waveform. If incorrectly adjusted, the audio will have too much treble or bass. The modulation at 18 MHz is an example of "narrow band FM modulation." The test set up I used was illustrated earlier. A Walkman radio provided audio for the test. When you switch your HF receiver detector to AM, you will hear a strong carrier at 18 MHz but there is no audible modulation. That's logical because the amplitude doesn't vary, just the frequency.

Notice that when the 18 MHz signal frequency is doubled three times, the FM deviation increases 8 times. This means that a 500 Hz speech frequency will be moved to 4 KHz. This is now "wide band FM modulation" and needs an FM detector to produce useful audio. It is logical that a product detector shouldn't be able to detect clear speech with wide band FM. Eventually I discovered that, although distorted, wideband FM speech was sometimes understandable using the product detector.

Raising the 18 MHz signal up to 2 meters

The 2 meter FM generator schematic shown below is the signal generator half of the transmitter design. Using Ashutosh's circuit I was able to construct a single-sided board prototype. I ran the generator output open circuit with no antenna and could hear the signal clearly around the room. Voice and music are quite clear when received by my Radio Shack handheld scanner radio or an Icom 2 meter handheld transceiver. Following the 18 MHz oscillator and buffer, four amplifier RF stages multiply the frequency to 36 MHz, 72 MHz and finally 144 MHz. Listening to the modulation at 146 MHz, the frequency deviation control behaves like a volume control. Deviation = audio loudness. Although it wasn't easy to get it working this far, eventually it submitted to patience and a few minor circuit changes.



Starting with an 18 MHz crystal oscillator, 5 more transistor stages were needed to reach a reasonably pure 146 MHz signal. The RF output power of this device is a few milliwatts. VHF transistors and amplifiers often work below 0.6 volts peak (on the oscilloscope). My mental image of how bipolar transistors work seems quite reliable for audio frequencies. At HF RF frequencies the same rules of thumb are useful, but we have to be ready to accept and compensate for deviations from what we expect.

There is an article in Chapter 6B about calculating static DC operating conditions for transistors. This math model works fine for audio frequencies. However, when applied to HF frequencies, the load on the collector is often an inductor with essentially zero resistance. When the results of the calculations are compared with the real static voltages, there are significant differences. Positive current seems to emerge from the base of a NPN transistor which shouldn't be possible. As you'll see shortly, when you measure the DC voltages at the collector, base and emitter of an operating VHF amplifier, you get really crazy answers. These are just measurement artifacts, but the fact remains ... homebrewing is weird up there!

One of my reliable rules of thumb has been that a signal needs to be greater than the base to emitter voltage in order to be "noticed" by the transistor. VHF transistors often *seem* to violate this principle. For lower frequencies, like 36 or 72 MHz, adding a little forward bias to the base will usually increase the gain somewhat. As the frequency goes higher, the extra bias heats the transistor but doesn't always increase the VHF signal.

The generator circuit above ends at a 1 picofarad capacitor at the lower center. This is where my R&D temporarily stalled. Trying to raise the power level up to watts is really tough. I tried to

build the rest of the original one watt transmitter circuit on the same little circuit board. Each amplifier stage purified the sinewave, but didn't raise the open circuit voltage level. To observe the output from each stage, I attached the oscilloscope probe to each transistor collector with a 1 pF or 2 pF capacitor. The "capacitor" was sometimes just two little pieces of hook-up wire twisted together 1 or 2 turns. After I bought a pair of 300 MHz oscilloscope probes that have just 3 pF capacitance to ground, my oscilloscope and frequency counter performed much better, (but still inaccurate).

In the original design, the last amplifier stage had an antenna matching network to deliver the power to a low impedance load, like 50 ohms. This matching circuit seemed to work, because I was now able to deliver the usual 200 millivolts output through a short piece of 50 ohm coax to an external amplifier board.

Don't apply too much supply voltage!

If you power your prototype with a variable lab supply, you should make a habit out of always applying voltage starting from zero and increasing the voltage while watching the current. In a generator circuit like this one, there is always a threshold voltage where the circuit begins to produce an output waveform. As you continue to raise the supply voltage, there is usually a supply voltage at which the output waveform RF voltage stops rising. This might be 8 volts, 10 volts or somewhere above 12 volts. Don't get curious and go over the design voltage of your project! Yes, it may continue to increase the output level - maybe even above 200 mV peak! But soon there will be an abrupt crash when you kill a transistor. Avoid the temptation.

Crystals also die

This past year I had 2 dead crystals. One of them died in this 2 meter FM generator. There was no obvious reason. Suddenly there were no sinewaves, even at 18 MHz. The DC voltages on the transistors were all normal, so I eventually concluded that the crystal was defective. Before you look for a replacement, try re-soldering it. The other dead crystal was in a commercial VHF radio receiver. It was used in the frequency reference oscillator for stepping the signal down to the IF frequency. In both cases the crystals were inert when I tested them in the crystal tester described in Chapter 13A. Replacing the crystals fixed both units.

The Great VHF Power Amplifier Mystery

I had a terrible time learning how to generate any sinewave higher than about 50 MHz. Consequently, I wasn't surprised that I was also unable to amplify ephemeral 2 meter signals to more than millivolts. Larger signals inevitably involve significant current flowing in wires. The trivial inductance of a centimeter of wire soon becomes overwhelming when the current rises. I needed to find some new ideas on how to do this.

How do those cute little handheld transceivers generate 5 watts of 144 MHz signal?

For decades the only commercial ham radio I owned was a Kenwood TH-21 handheld 2 meter transceiver. Years ago I visited a wonderful museum in Minden, Nebraska. It has huge buildings full of ancient airplanes, cars and antiques of all sorts. There is even a small exhibit on old time ham radio. In the display was a 2 meter handheld transceiver, a Kenwood TH-21, just like mine. Ha! My one and only piece of commercial ham gear was a priceless antique. My Kenwood eventually died, and because I didn't know how to fix it or homebrew VHF, I replaced it with an

Icom.handheld. The new handheld works beautifully but is a software nightmare - Too many modes and features! If you accidentally touch a button, suddenly you're on 440 MHz, memory bank 6, "p-skip," "t.scan" and heaven knows what else. Another difficulty is that the keyboard is designed for elves with tiny fingers.

A fellow in my ham club was so frustrated by his similar Yaesu handheld, he gave it away. Eventually I managed to program mine to be a usable *SIMPLE* radio, like the old Kenwood. The most useful software feature on the Icom is "lock mode" which allows you to turn off the 1,000 modes you don't want. To learn more about how real engineers turn milliwatts into watts, I took the old Kenwood apart. Unfortunately, I don't have a schematic of the design and I didn't learn much.



Notice the tiny 1/8" diameter copper coils, the 1/4 inch ceramic trimmers and square slug-tuned transformers. It has a digital frequency synthesizer using at least 8 crystals. The other side of the board has still more miniscule parts and complexity. This transceiver dates from about 1990. It's definitely old technology. To avoid becoming discouraged, maybe we shouldn't compare our work with modern electronics! Most disconcerting to me remains the 5 watts output. The major lesson this unit seemed to teach is that VHF circuits must be tiny with closely spaced parts.

Building experimental "power" amplifiers

When operating above 100 MHz, I have read that ordinary resistors, capacitors and inductors sometimes act like unpredictable combinations of all three components. *Use mica, silver mica or NPO ceramic capacitors. Use metal film resistors.* These components are relatively "pure" meaning that they have little inductance or unwanted capacitance. Surface mount, square, silver mica capacitors and metal film resistors are ideal because they have no leads and virtually no stray inductance. 144 MHz inductors are usually 2 to 4 loops of bare wire. If the wire is relatively thick, like 20 gauge or so, the resistance will be trivial. I was surprised to read that good old carbon composition resistors begin to have significance internal capacitance above 100 MHz.

Before you go nuts throwing out all your old parts, wait until you've developed a transistor amplifier stage that produces a 144 MHz sinewave. Assuming you have an oscilloscope capable of displaying a 100 mV output waveform, swap your present capacitor or composition resistor with one of the recommended type. I didn't notice any significant changes. I don't know whether to be disappointed or pleased.

Use ferrite beads or small wound ferrites for supply decoupling

VHF power amplifier stages work best with ferrite bead/ capacitor power supply decouplers. Many-turn, fine wire-wound inductors have significant resistance and waste supply voltage. In contrast, for *HF* amplifiers below 30 MHz, resistor/capacitor decouplers worked best for me.

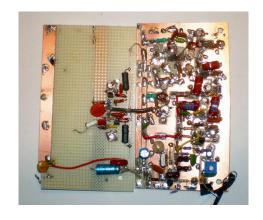
HF inductor/capacitor decouplers were unstable and often went into "noise mode." The small, encapsulated RF chokes have thin wires and significant resistance. Resistive loss just decreases voltage range and gain. Notice that the 3 watt amplifier design described below uses 4 big ferrite beads instead of a wire wound RFC.

Another way to make low resistance RFCs is to wind a few turns of #22 wire around a ferrite toroid such as an FT-37-61 core. "F" means ferrite. "T" tells you that the core is a toroid. The number 37 or 50 (as in FT-50) is the diameter of the toroid in fractional inches. That is, 1/2 inch = 0.50 inches. "61" is the type of ferrite - its inductance per turn.

VHF driver boards

Below on the left is an experimental amplifier board I built to increase my 200 millivolt 146 MHz signal (hopefully) up toward 12 volts and one watt. After 3 transistor **common emitter stages** of amplification I successfully raised the open circuit output voltage up to ... 200 millivolts.





My frequency counter was too insensitive to measure the frequency, but since the sinewave peaks were about 75% as wide as the 10 nanosecond marks on the oscilloscope screen, I assumed that it was on the right frequency. The modulated signal from my FM generator was loud and clear on my Icom handheld and the Radio Shack handheld VHF receiver.

In another attempt I built 2 stages of common emitter amplifier constructed on fiberglass perf board instead of PC board. Strips of low inductance PC board along the edges supplied 12 volts and ground. This construction eliminates the stray capacitance to a conventional PC board and allowed the parts to be as close together as possible. This circuit produced an open circuit output signal of perhaps 0.5 volts peak - a voltage gain of 2.5! I was thrilled. The signal was now strong enough for the frequency counter to measure. It indicated a nice solid, stable reading of ... 109.28 MHz. What?

I was puzzled by this strange frequency until I realized that it was exactly 3/4 of the correct frequency, 145.7 MHz. In other words, the amplifier had resonated on the combination of 72 MHz plus 36 MHz artifacts and come up with the sum, roughly 108 MHz. Or perhaps it was just 3 times 36 MHz. If you read the previous chapter on sideband, you may remember how various frequency components often re-emerge after multiple mixer stages, long after you thought they had been filtered away. When I retuned the amplifiers extremely carefully, I managed to get the stages to resonate at 146 MHz. As usual, *the higher the frequency, the smaller the output*. At 145.7 MHz the amplifier produced ... 200 millivolts.

In two other attempts I built 2 stages of **cascode amplifiers** on the perf board and a single-sided PC board. With cascode amplifiers, a grounded emitter stage feeds directly into a grounded base amplifier so the two outputs are directly added, one on top of the other. My thinking was that the coupling between the transistors was as tight as possible. The output of this amplifier was about one volt peak and I was overjoyed to find an apparent solution. Then I realized that it wasn't amplifying. It was self-oscillating at about 100 MHz. I was eventually able to tune it to resonate at 145.7 MHz and it produced 200 millivolts.

JFETs: On-line I found a schematic for a low power 2 meter transmitter that used two JFET stages for the initial amplification following the frequency generation stages. I assume the JFET amplifier stages are supposed to generate a signal voltage measured in volts rather than millivolts. The final amplifier stages were bipolar transistors that raised the signal up to a few watts, or so they claimed. JFETs are class A voltage amplifiers with no bias resistors at all. That sounded ideal. It's impossible to apply the wrong bias currents because there aren't any.

The JFETs were BF244s, which I had never heard of. I looked them up and they were rated at 500 MHz plus. I compared them with J310 and MPF102 specifications. The specs looked pretty similar, but apparently I don't know much about JFETs. I copied the first JFET stage using identical resistor and capacitor values but used a J310, then later, an MPF102. The amplifier tuned up properly but reduced the signal to 100 mV - useless!

Just to try everything, I built a **Darlington transistor amplifier**. A "Darlington" is two transistors combined to multiply the gain. The two collectors are soldered together and the emitter of one transistor is soldered to the base of the other. The remaining free base becomes the base for this combination transistor. If the gain of one transistor is 10, the gain of two of them working together should be 10 times 10 = 100. This trick often works at audio frequencies, but I've never seen it work at HF or higher frequencies. And of course, it didn't - 200 mV as usual.

Another desperate "hail Mary" attempt was an amplifier based on a **dual gate MOSFET**. Dual gates worked in the converter and in one of the IF amplifiers I used in Chapter 13. Maybe it could produce a low voltage boost for the first stage of a power amplifier. With the gain control gate wide open it barely produced 200 mV. With less than +12 volts on the control gate it produced less than 200 mV.

Regenerative amplifier stage

I was impressed by the large output from amplifiers that unexpectedly begin to self-oscillate. Consequently, I tried a tuned, oscillating transistor amplifier, very similar to the regenerative receiver concept. If the feedback and input coupling are balanced properly, the output sinewave will track the input sinewave. Since we're working with FM, the amplifier doesn't need to track varying amplitudes. The amplifier is amplifying its own signal, so there are no impedance matching and bias issues. The good news was that it worked. The bad news was that at 145.7 MHz it only had a gain of 1.2, about 250 millivolts peak. Also, it was unstable and tended to either oscillate between 60 to 120 MHz or go into full chaotic "noise mode." In conclusion, the gain was a little better than usual, but not worth the instability.

The "200 mV phenomenon"

OK. I have been having fun saying that every one of my amplifier amplifiers had exactly the same open circuit output. I was exaggerating. Sometimes it was as high as 350 mV, or somewhat less than 200 mV. The point is that *above a certain low voltage*, *there was simply no more gain*.

I gradually realized that this is partly an example of transistors having more gain for little signals than they do for large signals. The circuit time constant is too long and the sinewave simply can't rise much above 200 mV before it must fall back down. Another explanation is that tiny voltages produce tiny currents so stray inductance isn't much of an issue. Bigger voltages produce big currents which convert stray inductances into significant RF resistance and cause voltage drop. Also, transistors have more gain - higher Hfe - for little signals than they do for big ones.

You may recall that I exploited this phenomenon in Chapter 7C for the broadband VFO. When the VFO tuned the high end of its 30 MHz range, the output voltage was much too low to operate the mixer stage. I solved the problem by amplifying the signal with 4 stages. After 4 stages the 30 MHz signals became more equal to the low frequency sinewaves. I explored the big-versus-small signal phenomenon in Chapter 17A, in an article on SSB amplifiers named, "Compression by accident."

I'm running my amplifiers with a 12 volt supply. This implies that the maximum sinewave a class A amplifier could support would be nearly 6 volts peak. If I had a sinewave that large, would that represent 1 watt? Of course if the tank circuit resonates and it works properly, it will generate much more than 6 volts peak. Recall that our HF QRPs had to produce 22 volts peak to drive a 50 ohm load to 5 watts. It is possible that the output impedance would be so high that little current would flow and the output power would still be milliwatts. A stepdown transformer can lower the output impedance to match the low impedance of a transistor base. My few attempts at VHF transformers had the same performance as using a 10 pF coupling capacitor. The difference was that VHF transformers were mechanically hard to build.

How successful driver amplifiers connect the stages

I studied the driver amplifier stages in the various VHF transmitter circuits: Once the millivolt range is exceeded, the drivers always use new transistor driving strategies. They often drive the bipolar transistors with capacitive dividers. One capacitor drives the base as before, but another capacitor of about 30 pF goes from base to ground. The collector-to-base capacitor is often variable. In my limited experience this does nothing good, even with both capacitors variable. In another method the collector tuning capacitor, instead of going to ground, goes directly to the base of the following stage. This sounds efficient and clever. I have managed to make it resonate like that, but the power output of the driven stage was always disappointing.

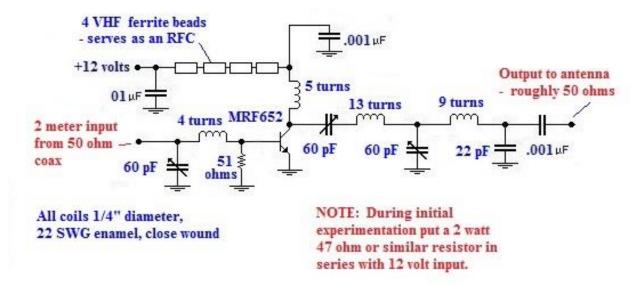
How the professionals do it

I scoured the web for more homebrew 144 MHz transmitters and found an Italian ham's design. It featured a high resolution frequency synthesizer with all the complex, mysterious ICs needed to perform that feat. What was most amazing, and most annoying, was the driver amplifier section that raised the power from the frequency generator. That entire section of circuitry was done with a little round, 8 mm wide, button-like IC with 4 pins. In case you're interested, it is a MAV-11 broadband 50 to 2000 MHz amplifier chip. It costs \$3 to \$12 each, depending on which version you buy. The ham was required to place a resistor in series with the 12 volt supply line - Oh, the complexity! He put in his milliwatts, received 12 dB power gain, then used the output pin to directly drive his power amplifier section. At least his final amplifier looked like the final amplifier described below:

A 3 watt power final amplifier

If I couldn't build an amplifier that delivers more than a 200 millivolt 146 MHz sinewave open circuit, why did I think I needed a one watt to 3 watt amplifier? After seven or eight failures I was hoping for more ideas to get past 200 millivolts. The same www.qsl.net/VU2MSY article contains the plans for a 3 watt amplifier stage that can be added to Ashutosh's one watt transmitter. Notice that one watt times a gain of three equals 3 watts. He only reached 3 watts even though he had a 35 volt DC power supply to work with. The original 3 watt amplifier was designed by Avinash Missra, VU2EM.

2 meter 3 watt amplifier



The schematic had 2 features that interested me. First, the amplifier received its input through a coax cable. It was designed to do what I had been attempting with my external amplifier boards. Also, it had a built-in π -type antenna tuner for driving coax leading up to a remote 2 meter antenna. The circuit was laid out on a single-sided PC board with wide margins around the traces. The original design used a 2N3553 power transistor. It was powered by +35 volts, although the text encourages the builder to tune it up on +12 volts first to avoid damaging the transistor.



I used an MRF652 transistor which I bought many years ago for a portable HF amplifier that I never finished. The MRF652 is designed to produce 5 watts at 500 MHz using a 12.5 volt power supply. Like any amplifier above a quarter watt, you'll need a heat sink to control the temperature of the transistor. The MRF652 has a threaded stud for bolting onto a heat sink. In order to make experimentation easy, I installed it with the threaded stud facing upward. The cylindrical body of the transistor is about 3/8" diameter and is mounted in a hole through the board. The 4 leads are 2 emitter tabs, one collector tab and one base lead. The collector tab has the corner clipped. These tabs are soldered to wide board traces as seen above. I built a heat sink out of a piece of aluminum angle that can be fastened to the threaded stud on the top of the board, as shown above. If the amplifier ultimately proves successful, I could unsolder the transistor and turn it over. If placed on the bottom of the circuit board, the heat sink could be as large as I like.

When I first powered it, it tuned up properly on the 200 millivolt RF input with no forward bias. Notice that the base-emitter junction voltage barrier doesn't prevent it from amplifying a tiny signal. Curious! The power supply current was modest for such a large transistor, about 40 milliamperes. It produced a voltage gain of 2.5 into a 51 ohm, 1/2 watt resistor, about 500 millivolts. That was a huge improvement over my usual 200 millivolts peak with a 3 pF load. I looked away for a moment, but when I glanced back, the circuit was suddenly drawing 0.5 DC ampere. That was the current limit of the lab power supply. The transistor was quickly overheating. So, following Avinash's advice, I protected the circuit by putting a 39 ohm, 2 watt resistor in series with the power input. Now when it ran away, I hoped no harm would be done. **Wrong.** Before I knew it, it not only ran away again, but destroyed the PN junctions - irreversible avalanche breakdown. I had a replacement transistor but I didn't try it again until I knew more about this runaway problem.

This reminds me of my MRF454 HF amplifier adventures in Chapter 12. I was never able to explain all those runaways. On the other hand, none of my MRF454s died. Eventually, after many failures, my prototype 100 watt HF amplifier stopped running away. It was as though I had to invest a certain amount of exasperation to be worthy of a working amplifier. I eventually built two of those MRF454 HF amplifiers which have been reliable ever since.

I looked up the price of new MRF652s and learned they are now ridiculously expensive - \$38 each! Another distributor wanted \$78 each. Absurd. This amplifier probably doesn't have a future

with MRF652s, even if I ever do generate one watt at 144 MHz. I didn't learn much about VHF amplifiers from this except that perhaps construction with wide traces and wide blank margins is better than thin traces. I also learned that VHF bipolar transistors are often FRAGILE! As usual, I should have studied the fine print. The MRF652 collector-to-base breakdown voltage is 36 volts which sounded more than adequate. I didn't notice that the collector to emitter breakdown is only 16 volts. That's too close to 12 volts for comfort.

Another lesson is that, when you tune up a fragile transistor final amplifier, start with a series resistor in series with the supply and increase the voltage on the transistor VERY slowly. Often it will produce an output with 4 or 6 volts DC and tune up with the correct sinewave across a dummy load resistor. But when you increase the voltage, the waveform may abruptly shift to large, crazy, multi-frequency waves. This is the operating mode, a.k.a. "noise mode," that can kill a transistor. These wild waveforms can usually be tamed by careful tuning. Slowly raise the voltage again and repeat the process multiple times until you reach your target supply voltage.

The power gain of this design inspired me to build the same design with low power transistors. In short, it didn't work at all. MRF652s are obviously very different than 2N2369s, 2N2857s or even 2N3866s. I added forward bias, but the bias only heated the small transistors without any apparent amplification.

The data sheet for the 2N3866A had a "test circuit" that was quite similar to the above 3 watt amplifier. It was easy to modify my mini-output stage to match the test circuit *exactly*. This circuit at least delivered 200 mV ... whoopee. However, it was remarkably unstable. The input series variable capacitor had to be adjusted perfectly to prevent noise mode. The test circuit had a low frequency R-C shunt filter on the +12 volt Vcc supply node. It was 10 ohms in series with a $0.012\mu F$ capacitor going to ground. It was just like a treble-reducing filter in an audio amplifier. This filter made adjustment less critical. However, my more crude amplifiers easily achieved the same 200 mV without noise mode and finicky adjustments, thank you.

Experimenting with various VHF bipolar transistors

When I started this project I assumed that the good old 2N3904 and 2N2222 transistors would switch too slowly to build VHF circuits. Consequently all my early attempts used VHF transistors that have Ft ratings like 300 or 500 MHz. I often swapped different VHF transistors into a circuit to see which one produced the most gain. They were all disappointingly similar. There were no magic transistors.

Finally, just for fun, I tried 2N3904 and 2N2222 transistors. They produced 146 MHz signals that were perhaps 80% as large as the VHF transistors. It turns out that the Ft for the 2N3904 is typically 300 MHz. The 2N2222 is rated at 250 MHz. They often work at 100 MHz and higher. One advantage of the 2N3904 that I have learned to respect is they're difficult to kill. If you accidentally touch your soldering iron to the little TO-92 plastic case, you will melt the plastic a little, but the transistor keeps working. The VHF transistors I experimented with mostly had little metal cases, such as the TO-72 and the larger size TO-39. If you accidentally touch your soldering iron to those cases, they conduct heat directly to the little chip inside and may fry it.

Also, VHF transistors seem more fragile electrically. When struggling with a circuit, I often had a VHF transistor suddenly lose its gain. Usually when I checked the transistor P-N junctions,

the transistor seemed intact. I wasn't aware of applying too much voltage or shorting it. This failure almost never happened while using the old 2N3904 and 2N2222 in HF circuits.

Along with the VHF crystals I also inherited a collection of VHF transistors. Ones that worked the best were: **2N918**, **2N2857**, **2N4124**, **2N2369**, **2N3014**, **2N3866** and **2N5109**. Type 2N5551 has an Ft of 300 MHz, but it produced half the output in the same circuits. If your experience is like mine, be prepared to ruin several transistors.

Another aspect of VHF transistors is the price. Unlike 25 cent 2N3904s, many of these cost \$8 or \$10! The price varies wildly from one manufacturer to another, \$1.00 here, but \$8 there. The same transistors rated for military use, "JAN" part numbers, are crazy expensive. Similarly, the price the distributor Digikey charges can be quite different, higher or lower, than the same part bought from Mouser. Jameco doesn't carry VHF transistors other than some small JFETs like the J310.

How to test a transistor

How do you confirm that your transistor is dead and belongs in the waste basket? Ideally your volt-ohm multimeter has a test mode for diodes and transistors. Test mode is usually indicated on the mode switch by a diode symbol. In this mode a test voltage of about a volt is applied across the red and black leads. When the red lead is applied to the P-side of a PN junction, the display will read numbers like, say 0.654 volts or 0.713. (positive to P conducts) These voltages are the typical forward conduction voltages of silicon diodes or the base-to-emitter voltage of silicon transistors. You should see this normal voltage offset reading between base-to-emitter and base-to-collector with any undamaged bipolar transistor. If the reading says "0.029" or "0.000," your transistor is dead. When the leads are reversed, the display should read "OL" - infinite resistance - no conductance. Also, if all the readings, forward and reverse, are "OL," the transistor has failed. Apparently we are "Out of Luck."

If you don't have this diode junction test mode on your multimeter, then perform the same test using the 1 megohm resistance range on your meter. Forward conduction resistance will read hundreds of thousands of ohms in the forward direction and the reverse conduction resistance will read "OL." So far, I have not found a way to test loose, used VHF transistors that seem intact, but have mysteriously lost their gain.

Why doesn't my amplifier stage resonate?

One trick I learned was that the 2 meter VHF schematics I examined usually had L-C components like 5 or 7 turns of air core coils tuned with 25 pF trimmer capacitors. When I built these, they didn't resonate and the amplifier was inert. I learned to use much smaller inductors, usually 2 turns of #22 wire, 3/8" in diameter or 4 turns 1/4" diameter. When I tune them with 100 pF trimmer capacitors, they nearly always resonate with two obvious maximum points. Remember that, if the output signal has a maximum at only one place on the trimmer capacitor screw, it means that the L-C is close to resonance, but your capacitor or inductor are too large or too small for the desired resonant frequency. Perhaps the success of my 100 pF trimmers and smaller inductors tells me that my circuits have too much stray inductance? Perhaps my component leads and circuit board traces are too long.

Lessons from FM radios

So why do our little VHF handhelds, cell phones and TVs work so well? Examining the few

examples of VHF circuit boards I own, at first I saw no obvious reasons why they work. My first guess was that the stray inductances and capacitances have become part of the design. Looking at portable FM radios - 88 to 110 MHz - I noticed that the coils are tiny and could have been wound on a match stick or perhaps a pencil. They are typically 4 to 10 turns, the larger the diameter, the fewer turns. They are often wound on a tiny cylinder of fibrous, cotton-like material. The little coils are usually potted in what looks like hardened beeswax. The beeswax preserves the form of the coil. If the windings were loose, they could be compressed or stretched like an accordion, thereby detuning the L-C resonance.

The FM VHF circuits were on single sided boards and were (relatively) widely separated from other components. Back when I briefly worked with microwave directional couplers I read about "microstrip" PC boards which were built on 2-sided boards. The traces were engineered to form a sort of coaxial cable-like relationship with the ground plane on the far side of the board. This technique allowed microwave currents to travel distances along the board like coax cable without significant power and voltage loss. This made sense to me. So I was surprised to see single sided boards or two sided VHF boards which had little or no ground area. In other words, the ground traces were skinny little strips, just like the traces above ground. This minimizes stray capacitance from ground. The main lesson I took from this was to *use single sided boards*.

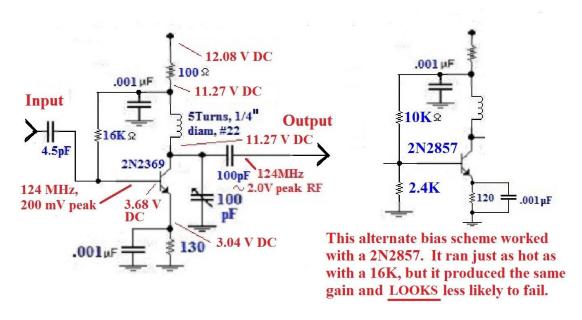


I made an amplifier stage using single-sided board with drilled-through holes. Unfortunately, the performance wasn't better than the perf board or gouge boards I have been using. Also, throughhole boards take much more time to build than the other methods.

It is better to amplify and die than never to have amplified at all.

A big advance FINALLY came when I eliminated some of the transistor protection against overheating and runaway. Virtually every VHF transistor amplifier circuit I could find has a base-to-ground resistor or inductor to make sure the transistor has a way to turn off. When the base resistor is removed and forward bias is increased, sometimes the gain soars. Yes, the transistor runs hot, but so far I have only destroyed one or two of the small transistors. I tried adding base-to-ground resistance back in, but even high resistances caused significant loss of gain. Using this new trick, I was able to complete my 2 meter converter for the Chapter 7C receiver - See Chapter 16C. The circuit below shows the transistor amplifier stage in the 2 meter converter that was able to generate a 2 volt peak 124 MHz reference signal for the conversion. The alternate biasing scheme with the 2N2857 appears in a circuit on page 31-30 in the 1986 ARRL handbook. It is part of a 144 MHz transmitter converter.

A successful VHF amplifier stage



Beware of VHF waves affecting your test equipment

Notice the static DC voltage readings on the diagram. These measurements were made with the RF input disconnected. When the amplifier had RF on the input and was operating, I got crazy readings. According to my multimeter, there was no DC voltage drop across the 100 ohm resistor. The collector DC voltage read higher than the supply voltage. The base DC voltage was about what I expected, but the emitter voltage read 6 volts! In fact, with the voltmeter disconnected and both its leads 18 inches away, it read about 0.6 volts DC when I turned on the 124 MHz drive. The voltmeter was a receiver! When I turned off the 124 MHz input signal, I got readings that made much more sense. Also, and this might be real, with no input RF signal the current drawn from the power supply decreased to one third its operating level.

This over-biased circuit has enabled me to build a total of 4 working amplifier stages. Unfortunately, whenever I put two of these in series, the second stage produced hardly any gain. It usually just reproduces the voltage on its input. Once again, even with optimum forward bias, transistors have much higher gain for little signals than big ones. "Big" is obviously more than one or 2 volts peak input. Unlike low frequencies with a resistive load, I can't put a DC volt meter on the collector during operation to measure the operating point. When I do, I get wild readings - like DC voltages greater than the supply voltage. Of course with the input turned off, the zero resistance in the little coil makes all bias levels look the same - 11 volts or so.

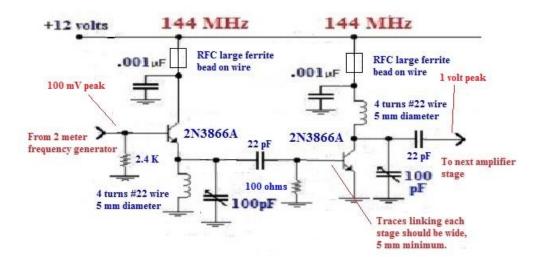
Occasionally transistor specifications will give the collector DC current with corresponds to the ideal level for class A operation. If you know this number, a 100 ohm resistor in series with the choke decoupling circuit could allow you to measure the collector current with no input RF signal to interfere with your volt meter reading.

Another way to go beyond 200 mV

I noticed that a 2N3866 transistor was used in Ashutosh's transmitter as the driver for his final amplifier transistor. Using a 2N3866 I reproduced the amplifier stage he used as closely as I could. Unfortunately it had the usual result - no power or voltage gain. Later it occurred to me that the output from my 2 meter generator seems to be very high impedance. That means that it is all voltage and no current. Therefore I needed an extremely high input impedance to receive this signal efficiently. My idea was to use a transistor impedance transformer - an emitter follower amplifier stage. This amplifier design has a very high impedance input with a very low impedance output. In other words, *it converts voltage to current*. The voltage gain of these amplifiers is always less than one. I used the high current output to drive my usual grounded emitter amplifier stage.

A friend of mine worked as an engineer for Collins Radio in the 1970s. Aside from their famous line of HF ham radio equipment, Collins made some the world's best VHF/UHF aircraft electronics. Collins used to buy huge quantities of the JAN military version of 2N3866s. The 2N3866 seemed to be their favorite transistor. When they received a shipment, they hooked them up to a high DC load, put them in a temperature chamber and tortured them for a month. The transistors that survived the test were used in their production products. The rest were thrown out.

High Gain Amplifier - Emitter follower drives the usual common emitter stage.



Notice that the 2N3866A doesn't need forward bias resistors. It just needs a base resistor to help insure that it doesn't run away when overheated. The base resistor can be startlingly small - 100 ohms - without any noticeable loss of output. 2N3866As are different! Much to my delight **the experiment worked**. A 100 mV peak input as measured on the base on the left produced a one volt peak output. Naturally the next experiment was to put two of these double amplifiers in series. As usual the second amplifier pair produced no additional gain. Darn!

I also tried to use this double amplifier to drive the same 2N3866 stage that Ashutosh used in his transmitter. It produced the same result - no gain - one volt peak input, one volt peak output. I also tried driving another grounded emitter stage with the same result. While building this I confirmed that using **very wide traces** to transmit an output signal into the next stage produced

another 10% of gain. The 22 pF coupling capacitor in the center above had almost zero free wire lead to minimize stray inductance.

Notice that a 2.4K resistor is not really "high impedance." I was expecting it to work best with no base resistor at all. Even though my idea worked, the theory that inspired it was not entirely correct. The phenomenon of an incorrect hypothesis producing a useful result is not rare. To say it another way, ... try everything!

Applying the high current bias approach to the 146 MHz transmitter

I applied the same 2N2857 transistors and bias scheme to four of my 146 MHz transmitter amplifier stages. Two of the four stages amplified for real. One stage was in the amplifier board and the other was in the generator board. For no reason that I could discover, the other two stages remained in "no-gain mode." The amplifier board as a whole generated a 146 MHz sinewave output of 3 volts peak! I connected it to the "3 watt amplifier" board and the final amplifier produced 1/8 watt output into a 51 ohm 1/2 watt resistor. Wow! That might be enough to trigger my favorite repeater. It was late at night, so I quit for the day.

The next evening I fired up the breadboard and ... all the amplifier stages had returned to "200 mV mode." I removed the 2N2857 transistors and measured their PN junction forward voltages. They were identical to the measurements I made before they were used. I can't explain why these amplifiers are so unreliable.

2N3866 VHF transistors

Mouser offered 2N3866 transistors on sale for \$5 each and had a "new product" label next to them. This was the transistor that Ashutosh used to drive his final output transistor in his 2 meter transmitter. I had looked for them before, but had never found any at a reasonable price. 2N3866s resemble the 2N5109 in package and frequency response, but have twice the continuous power and current ratings. Even better, the collector to emitter breakdown voltage is 30 volts instead of 20 volts. These specifications mean that they can stand lots of heat, mistuning and wild oscillation. The Mouser on-line catalog said they had about 3,800 in stock. I thought about it for a day, but when I looked again, they only had 900. They're popular! I bought 10 of them. As I become more desperate to make this project work, my definition of a "reasonable price" keeps rising.

I rebuilt my three stage amplifier board using 2N3866As. In short, they don't respond to the bias trick I used with the 2N2857 and 2N2369. They work with no forward bias but do need a base resistor. They can easily tolerate high currents of 100 - 200 mA and survive without an emitter resistor/capacitor. The gain from each stage is rather small, but with three stages in series I got one volt peak output. I fed this into the "3 watt amplifier" which has an antenna tuner output. It produced a whopping 14 milliwatts output into 51 ohms.

I was becoming desperate to build a one watt 2 meter transmitter.



As you can see, I resorted to **vacuum tubes** to try to generate a VHF signal greater than 200 millivolts. I theorized that the high plate voltage and proportionately low currents should minimize the problem of unwanted stray inductance. Also, I remembered that in the 1950s many ham clubs built simple 2 meter rigs from a set of standard plans. The club members lined up for pictures with their homebrew vacuum tube transceivers. The transceivers were cube-shaped, a bit larger than a basketball and apparently worked well around town - without the aid of repeaters. If dozens of ordinary hams built these, was it really as difficult as my experience?

For my vacuum tube amplifer I used a 6AK5 pentode because they were VHF amplifiers commonly found in ancient TV sets. I also conveniently own 4 of them. They're rated for 400 MHz and tolerate up to 180 volts plate voltage. This should make the tube currents roughly 1/10 the currents needed in equivalent transistor circuits. If the first amplifier stage worked, I had room on the PC board for 2 or 3 more stages.

My power supply was made mostly from components out of a 1935 radio. Notice the huge dual rectifier tube and gigantic old 80 microfarad, 450 volt DC electrolytic capacitor. The supply delivers 250 volts of poorly regulated DC and the 6.3 volts AC needed to power the glowing filament. The filament heats and activates the cathode and makes the tube conduct. Because 250 volts was too high and the regulation was poor, I used an 02A gas regulator tube to produce ripple-free, 150 volts DC. The 0A2 works like a fixed Zener diode and conducts at 150 volts. If I wanted a different voltage, I'd need a different gas regulator part number.

I tried several tube versions of the same transistor circuits I had been testing. It took several attempts and a great deal of fussing, but I eventually achieved ... (Drum roll, please) ... literally, 200 millivolts peak! That really surprised me. Once again, the amplifier had a voltage gain of ONE. I assumed, or at least hoped, that it would produce a gain of at least 2 or 3. Wrong. I was beginning to wonder whether my tube amplifier could amplify *any* frequency. I rewired it for 28.6 MHz and tried again. The voltage gain at 28 MHz was 1.75. With 2 volts input, I got 3.5 volts output. My guess was that tiny RF antenna signals, a few microvolts, would be amplified many times. Perhaps these tubes, like the transistors, work well with VHF microvolts but poorly with VHF "big voltages," like "2?"

One watt output? Not as hard as I thought.

It turned out that my amplifiers weren't so feeble after all. The biggest difficulty has been that my power measurement fails at VHF frequencies. *I had been building adequate amplifiers for months and didn't know it.*

Ever since I began building ham gear, I have been measuring power using an oscilloscope and dummy loads. I measure the sinewave peaks, multiply by 0.707 to convert the voltage to RMS. I square the RMS voltage and divide by the dummy load resistance. I have an ancient Heathkit HF power meter, but it doesn't work well for QRP power levels - the needle barely moves. I doubt it would work at all for VHF. Consequently I have been using my new VHF rated scope for measuring tiny VHF transmitter outputs. I assumed that, if I use a 3 pF VHF "300 MHz rated" probe with a modern oscilloscope rated for 150 MHz, the voltage amplitude of a 145 MHz signal should be fairly accurate. **Wrong.** I keep saying, "question authority" and don't make assumptions." I should follow my own advice.

Surely every oscilloscope owner has noticed the little switch on the probe handle. The switch has two settings, "1-X" - a direct connection to the signal - and "10-X." The 10-X attenuates the signal by a factor of ten so you can observe much larger signals. So, in theory, if you switch from 10-X to 1-X, the signal should increase in size ten times on the screen. I have often noticed that the multiplier on HF looked more like 4-X or 6-X, not 10-X. When I bought the new 3 pF VHF scope probes and looked at 145 MHz signals, I noticed that the switch made hardly any difference - 1-X looked pretty much like 10-X. Because VHF makes crazy readings on a nearby disconnected multi-meter, it finally dawned on me that, if the oscilloscope can't display the difference between 1-X and 10-X, my power measurements must be wildly inaccurate.

I measured the probe capacitance in the 10-X mode and found it lower than in the 1-X mode. Therefore, the capacitance of the probe in 10-X interferes the least with tuned circuits. Also, because the display should be calibrated as 10 times higher amplitude than the number on the screen, this means that **10-X gives the most accurate amplitudes**.

How to measure VHF power

I could spend hundreds of dollars on a modern VHF power meter. Then it occurred to me that the rate of temperature rise in the dummy load resistor should directly relate to the dissipated power. The dummy load I have been using on the final amplifier is a metal film 51 ohm resistor rated at 1/2 watt. I can measure DC current, DC voltage and resistance accurately. Therefore, I can measure the resistor temperature rise in one minute at different DC power levels and know how much power causes the heating at each level.

The thermometer consists of a thermocouple amplifier plugged into the multi-meter voltmeter. The thermocouple tip is jammed under the load resistor.



To calibrate the measurement I clipped the lab DC power supply across the 51 ohm resistor and measured the cold temperature of the resistor. Then I applied 5 volts DC across the resistor which gave me 1/2 watt of power dissipation. After one minute, I shut off the current and measured the final temperature. Next I repeated the test for 1 minute with 7.14 volts DC which delivered 1 watt.



Time	Voltage	e Power	Start Temp	., °C End Temp., °C	Temp Rise, °C
1 min.	5.0 volts	DC 0.5 watt	23.7 °C	32.3 °C	+8.6 ° C
1 min.	7.14 volt	es DC 1.0 watt	22.16 °C	43.3 °C	+21.14 °C
1 min	VHF a	about 3/4 watt	25.0 °C	42.3 °C	+17.3 °C
1 min	VHF 2	20 volt supply	21.0 °C	about 46.0 °C	about +25 °C

As expected, the meter goes bonkers with the VHF turned on. Consequently, the temperature must first be measured with the resistor cool and the VHF turned off. Then, the meter is turned off and the VHF is keyed ON for exactly one minute. The moment the VHF is turned OFF, the meter is switched back on before the resistor has chance to cool.

Typical data for DC and VHF heating are given above. Because the measurement is clumsy to perform, the results are imprecise. During several trials the temperature rise with VHF heating varied between 16 °C and 19 °C. This implies that the real output of the VHF transmitter output stage is roughly half way between 0.5 and 1.0 watt. Let's call it 3/4 watt. The input to the final amplifier stage was from yet another experimental final driver board which only put out about 700 millivolts RF peak measured by the oscilloscope. Some of the experimental driver boards have briefly generated as much as "3 volts peak." Reaching an official "one watt output" is obviously possible with my construction methods and components. I have had driver amplifiers briefly generate more than enough drive several times. The remaining challenge is how to make the amplifiers work two days in row.

I bought a new Fluke model 87 multimeter to replace my elderly multimeter. The Fluke 87 has a built-in thermometer mode and comes with a thermocouple. Best of all, it seems to be immune to RFI! That makes this measurement MUCH more practical.

Because 700 mVolts peak indicated voltage produced about 3/4 watt, I can calculate a crude conversion factor for my oscilloscope indicated voltages. From this I learned that the real amplitudes are roughly 10 or more times greater than seen on the scope.

$$P = I^2R = I^2$$
 (51 ohms), 0.75 watts/51 = I^2 ,

Therefore, Irms = 0.12 amps rms, Vrms = 6.18 volts rms

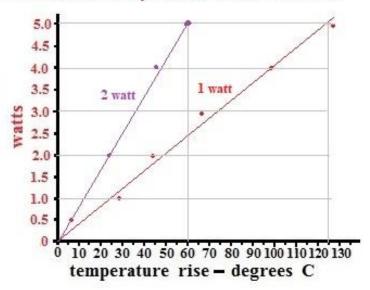
Vpeak = 6.18 volts rms (1.414) = 8.7 volts peak 12 times greater than 700 millivolts peak!

(The square root of 2 = 1.414, Vpeak = 1.414 times Vrms,)

Notice that, if I observed 3 volts peak on the scope open circuit, it implies an oscillation in the L-C circuit of 30 or more volts peak. That's not impossible, just hard to believe. Remember that when we had our 5 watt 40 meter QRPs working well on a 12 volt power supply, they would deliver 22 volts peak to a 50 ohm load.

I first used a 1/2 watt metal film resistor but at two watts DC the resistor began to discolor and smell. Similarly, at 5 watts DC the 51 ohm, one watt, composition resistor plotted below began to smell and smoke. If you overheat a resistor, check it later with an ohm-meter to be certain it still has the correct resistance. As a rule, overheated resistors increase their resistance.

Power measurement - temperature rise on a 1 and 2 watt carbon composition resistor dummy loads after 1 minute



When I bought the VHF oscilloscope, a GW Instek (model# GDS-1152A-U), it didn't arrive with low capacitance probes. This is why I bought the "300 MHz VHF probes" separately. The probes enclosed with the instrument had 15 pF capacitance which was sure to kill most VHF signals. The probe with my new frequency counter was just a short length of RG-58 coax with little alligator clips on the ground and center conductor. I thought perhaps the simple coax probe might be accurate - it wasn't. It just indicated amplitudes twice as high as my VHF probe. In other words, the RF displayed voltages were about 1/6 of the real value.

Even though the displayed voltage amplitudes are much too small, I am still assuming that *relative* amplitudes of input voltage to output voltage indicate gain or loss of voltage. Also the shape of the waveform displays stability and harmonics. The scope is still important, but it isn't a complete description of the output waveform. Whenever possible, measure the output power with a more direct method, such as temperature rise.

VHF transistor mysteries solved

And now we know why VHF transistors turn on with drive that appears less than the base to emitter voltage. *The true base RF voltage was 10 or 12 times higher than I observed on the scope!* Also, forward bias didn't help for most transistors. The collector voltage was already operating well above the base to emitter voltage. I was trying to bias the transistors for class A operation when the drive voltage was already more than enough for class C operation. Class C doesn't need forward bias.

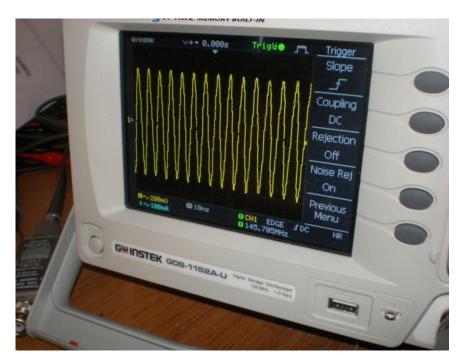
I was frequently frustrated by the inability to put 2 amplifiers in series and get twice the gain. And now we know why. *I was already operating in class C and generating big voltages*. When I put identical amplifiers in series, it was physically impossible for the second amplifier to generate more RF collector voltage. I would have had to use ever higher supply voltages for each successive stage. Notice that *I could only reach more than one watt by raising the supply voltage to 20 volts DC* or higher.

Real VHF power meters

All the commercial VHF power meters I have seen are Standing Wave Ratio (SWR) bridges. These devices are placed in series with a coaxial cable and the load. The load is usually an antenna or a dummy load. HF power meters consist of a transformer that taps and rectifies a sample of the RF load current. The DC sample is displayed with a sensitive ampere meter. There are usually two taps and rectifiers to measure power going in both directions forward power to the load and reflected power back to the transmitter. For reasons I haven't yet grasped, the tiny DC current represents RF current times RF voltage. I've never built a successful HF power meter. Mine always act like voltmeters instead of power meters.

VHF and microwave power meters are usually machined metal coax-like devices called "directional couplers." The solid metal coax has an opening in one side to admit a small probe with short piece of wire that parallels the coax center conductor. One end of the probe wire has a tiny load resistor. The detector diode is located at the opposite end of the tiny length of wire. The diode end determines the direction of the indicated power. The probe is the equivalent of a secondary winding on an HF transformer winding.

Long ago at my job I had the machine shop copy the directional coupler of a commercial VHF meter. Amazingly, it worked well at 450 MHz and, with modification, it also worked well at 2.45 GHz. The Bird Company has been making VHF/ microwave meters like this for many decades. Various models are \$350 and higher when new, but I saw some on E-Bay.com for much lower prices. Used, small modern power meters sell for \$35 to \$50.



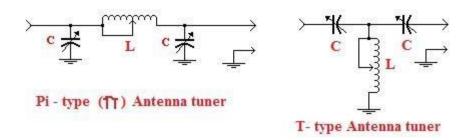
Getting serious about amplifier design - impedance matching

I happen to own a copy of "**RF Circuit Design**" by **Chris Bowick**. It is an old book published by Howard W. Sams & Co., Inc., Indianapolis, In, 1982. It's still available from Amazon.com. The book is almost entirely about designing VHF circuits. It covers filters, components and calculation methods including vector math and Smith Charts. It seems to cover everything we need to design our two meter transmitter except construction techniques. For me,

some of the calculations that the author says are easy and obvious, weren't. However, I did have success applying the book's lessons and I believe they're useful:

How to design VHF amplifiers the way the professors do it

One way of looking at impedance matching between amplifier stages is that the coupling circuits are very much like the Pi-type and T-type antenna tuners described in Chapter 9.



A major barrier to designing a transistor amplifier is that you need all internal resistance and capacitive specifications for your exact transistor type. In other words, you need to have an exact equivalent circuit for your transistor. These internal "components" are extremely significant, especially for VHF. Even worse, the equivalent impedances vary with frequency, voltage and other variables. To find the equivalent Rs and Cs, you must interpret them from graphs. Next, the design of the Pi-type or T-type tuner linkage must incorporate these frequency dependant components and make them part of the interstage tuner.

Curiously, very few transistor specification sheets show these signal parameter graphs and they never teach you how to use them. Bowick's book explains the process. He does mention that many data sheets don't give the parameters and we must measure them for ourselves. When he says "we," he probably means Kenwood, Yaesu and Icom. Few hams, including me, have the instruments or know-how to measure VHF transistor parameters. When you can find them, these parameters are presented by a dozen or more curves. The values you need vary with frequency, collector voltage, class A or C, input power and output power.

There are two kinds of transistor internal parameters - small signal "S-parameters" and large signal parameters. S-parameters, are sometimes presented as "y" or "Z-parameters." They are the same data just given in different ways. S-parameters are sets of 4 complex impedance variables used for designing the most sensitive, low noise receiver amplifiers. A complete set of graphs for a transistor that includes S-parameters can be 6 or 8 pages. Large signal parameters are simply the transistor input and output series resistances and capacitances. Fortunately, the simpler large signal parameters are what we need for transmitters and are easier to understand. The graphs for power amplifiers "only" require one page displaying 4 families of curves.

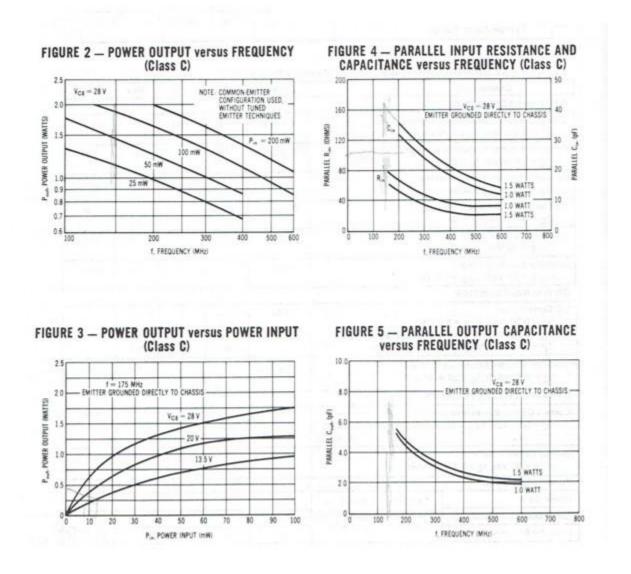
Available power transistor types

In the following analyses I am using the 2N3866 because I own some and because I also have the complex data curves needed to design matched input and output circuits. This is an obsolete part and normally only available at ridiculously high prices. I saw several ads for 2N3866s on E-Bay.com for 2 to 3 dollars each. If you look up equivalent transistors on-line, the **2N4427** is mentioned as a similar part and is found in several on-line 2 meter transmitter schematics. The rated collector-to-emitter voltage is only 20 volts, so that's a disadvantage. I bought some 2N4427s from Mouser.com at a low price, but they are also on the verge of being

obsolete. One of several manufacturers of the 2N4427 list the characteristics alongside the 2N3866 curves. My guess is that 2N4427s are actually 2N3866s that flunked the 30 volt breakdown test and were down-rated to 20 volts. My attempts to substitute it for 2N3866s seem to work the same.

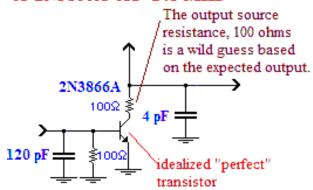
There are several modern transistors that are listed as 2N3866 substitutes. Modern transistors don't use the old "2N" prefixes and have other type number names. All the specifications I have checked out so far were *not* equivalent - too low voltage, too low frequency, etc. If they are affordable and if you can find their power amplifier data curves, buy some. If they really are similar, they should work in circuits much like mine.

Here are the large signal parameter graphs for the 2N3866 or 2N3866A transistors:



Using these curves I was able to come up with the following equivalent circuit for a 2N3866 and 2N3866A transistor at about 145 MHz. As you can see, the transistor has internal resistors and capacitors that must be part of your amplifier design. The base side of the transistor is the difficult part. The output side is much simpler.

EQUIVALENT CIRCUIT OF A 2N3866A AT 145 MHz



These parameters vary widely with frequency and, as shown in the diagram above, are only valid for 2 meters and 12 volt operation. At 145 MHz the 2N3866 has an input capacitance of about 120 pF and an internal input resistance of roughly 100 ohms. These are huge loads and the variation with frequency explains why I couldn't just plug in any VHF transistor and expect it to work in the same circuit. The 2N3866 output R and C are more reasonable. I soon learned that the 4 pF output capacitance is easily absorbed by tuning the LC collector tank circuit.

To estimate the output source resistance, I had to know the "expected" power output to find the resistance on a graph. 1/2 watt gives 100 ohms which was a convenient number. At 100 ohms, it matches the input resistance of the next stage 2N3866 amplifier, so all I needed for the design were the input and output capacitances. Obviously, "100 ohms" may have to be changed if reality dictates. In retrospect, I'm amazed that my "3 watt amplifier" with the MRF652 worked so well without using the original 2N3553. Dumb luck!

Matching the output to a dummy load is easy

Compared to most of the academic VHF design procedure, load matching *can be* delightfully simple. As explained above, the internal output resistance depends on what power output you expect. In the example below, I connected a resistor and capacitor directly to the collector with no variable Ls and Cs.

$$R_L = (Vcc - Vsat)^2 / 2($$
 expected power output)

For example,
$$50 \Omega = (12 - 2)^2 / 2 x$$
 one watt

For example, if you are hoping for one watt output, subtract the saturation voltage from the supply voltage, square the result, then divide by twice the desired power.

Measuring saturation voltage

You can measure the saturation voltage yourself. First, turn off the DC supply and the RF driver. Then put a 100 ohm resister in series with the transistor collector and isolate the supply from the other loads on the supply. Next, put 12 volts on the 100 ohm collector load and slowly introduce a small, milliampere DC current into the transistor base using a 10K pot. Put a DC voltmeter on the collector and observe when it reaches minimum, the saturation voltage, Vsat. I measured just 0.10 volts DC on the 2N3866 collector. From reading the book, I gather that 2 volts is more typical with larger transistors. Besides, 2 volts makes 12 volts come out at 50 ohms, which is a much more convenient number for show and tell. For a one watt output with a 12 volt supply and 2 volts saturation, 10 squared divided by 2 x 1 watt = a 50 ohm load.

I tried a 50 ohm load directly on a 2N3866 which was putting out roughly 3/4 watt of RF. I connected a 0.01 μ F disk capacitor (a short circuit for VHF) to the collector and a 50 ohm resistor connected to ground. Sure enough, there was a big VHF voltage across the hot 1/2 watt resistor, presumably about 3/4 watt. Before this experiment, I had assumed I would need a complex Pi or T coupler to achieve this. In this instance, just for breadboard development, a simple 0.01 μ F cap and 50 ohm resistor can make a good dummy load. Unfortunately, real antennas need compensation for their inductance and capacitive components. During your early experimenting you only have to worry about the more complex base side of the interstage matching circuitry.

Resonate away the internal, mismatched components

The first strategy to matching transistor parameters to the next stage or an antenna is to resonate any inductive or capacitive components that are reducing the RF voltage across the resistive portion of the load. As you know, series L-Cs look like zero ohms - a short circuit. Parallel L-Cs look like an infinite resistance. These tricks are applied to make the unwanted reactances invisible to the source.

When the transistor output resistance - source impedance - is different from the load resistance, we need to add capacitors or inductors to make the load *look like* the same resistance as the source. When resonating the reactive Cs with Ls isn't enough, we can add Ls or Cs to make the load look as though it has the same impedance as the source transistor.

Transformers are the intuitively obvious way to do this and that's what we usually did for HF interstage coupling circuits. There are big voltages across a multi-turn winding and there are small voltages across a winding with few turns. Unfortunately, low impedance VHF transformer secondaries are awkward to build because there may be only one or two turns in the entire primary winding. So the usual method is to construct a "Pi," "T" or "L" network between the source and load. "L" networks are just a combination of two elements - capacitors, inductors or one of each. "Pi" and "T" networks have 3 elements.

Calculating the inductance of air core coils

For VHF calculations to be useful, we need a way to wind coils with the desired inductance. Toroids at 2 meters aren't practical, at least not the sizes and types I've used. When homebrewing HF projects, the ability to predict and calculate inductance was vital. All my coils above 72 MHz have been small air core coils consisting of a few turns of 22 gauge wire in coils about 6 mm in diameter. So far, I have fumbled along guessing turns and dimensions, but if I want to know what I'm doing, I need to predict inductances. Assuming the bare wire diameter is about 20 or 22 gauge, below is a formula for this calculation that seems to work. I wind them on a 1/8" Philips screw driver shaft. I hope you remember your high school algebra:

Calculating air core coil inductance

 $L = \underbrace{0.394 \, r^2 \, N^2}_{9r \, + \, 10\ell}$ L = inductance in microHenries $\ell = \text{length in cm}$

r = radius in cm

N = number of turns of wire

resonating the shunt capacitance to make it go away

In the 2N3866 transistor equivalent base input, there is a huge, 120 pF shunt capacitor to ground. (At 145 MHz 120 pF is really big.) The effects of this huge input shunt capacitance can be eliminated by resonating it with a parallel inductor. As you know, a parallel L-C circuit has infinite impedance when tuned to resonance. So, if we can add an inductor in parallel that resonates, it will act as though the internal capacitance doesn't exist. An advantage of a shunt inductor on the base is that it locks the DC base voltage to zero. This is supposed to give the transistor a slight amount of negative bias which keeps the transistor in class C mode. If you study examples of VHF class C amplifiers, they often have an RFC shunt to ground which insures zero base DC voltage.

The remaining problem will be to match the 100 ohm internal resistance of the transistor input with the source resistance of the transistor driving it.

First, resonate the capacitance:

$$1/(2\pi f)^2 = LC,$$

Where $\pi = \text{Pi}$, 3.1416; $\mathbf{f} = \text{frequency}$; $\mathbf{L} = \text{inductance}$; and $\mathbf{C} = \text{capacitance}$.

At VHF frequencies the capacitances are still in pF while the inductances are usually in nanoHenries, nH. nH means 1/1000 of a microHenry. Expect numbers like tens or hundreds of nanoHenries.

$$1/(2\pi f)^2 = LC = 1/\{2(6.28)(145MHz)\}^2 = L (120 pF)$$

Solving for L, $L = about 10 \text{ nHenries} = 0.01 \text{ microHenry} - A very small inductance.}$

$$L = 0.394r^2N^2 / \{9r + 10\ell\}$$

To make the number of coil turns calculation work, 10 nH = 0.01 microHenries. Let radius = 0.33 cm, nominal length of coil = 0.66 cm

Coil Q is supposed to be optimum when the length of the coil is twice the coil diameter. That's why I listed .66 cm as the length. Of course, I can't know the true length until I know the inductance, but that doesn't seem to be too critical. The coil I calculated seems to work better than larger coils or no coil.

$$L = 0.394r^2N^2 / \{9r + 10\ell\}$$

 $L = 0.01 \ \mu H = \{0.394(0.33 \ cm)^2 N^2 \} / \{9(0.33 \ cm) + 10 \ (0.66 \ cm)\}$

Solving for N, N = 0.52 turns

This tiny "coil" is just a little 1/4 inch "U" shaped loop of wire soldered to the PC board between the transistor base and ground. Believe it or not, a full one turn loop didn't work as well.

Calculating the collector capacitance compensation

The 2N3866 collector capacitance is just 4 pF or less, depending on the supply voltage. This is a tiny capacitance, so for it to resonate at 145 MHz we'll need a much larger inductance.

$$1/(2\pi f)^2 = LC = 1/\{2(6.28)(145MHz)\}2 = L (4 pF)$$

120 pF is 30 times larger than 4 pF, so the inductance will be 30 times

larger L = 0.3 microHenries

$$L = 0.394r^2N^2 / \{9r + 10\ell\}$$

$$L = 0.3 \,\mu\text{H} = 0.394 \,\text{r}^2\text{N}^2 / [9(.33 \,\text{cm}) + 10 \,(.66 \,\text{cm})]$$

Solving for N, N = 8.3 turns

These calculations imply that we are going to connect a 8.3 turn coil from the collector to ground. This is a direct DC short across the power supply. We can't have DC-zero-ohm coils connecting the supply voltage to ground. However, putting a huge (for VHF) 0.01 μF capacitor in series with the 300 nH coil prevents it from shorting out the power supply. From the point of view of VHF currents, the .01 μF cap is a short circuit. During a VHF sinewave cycle it doesn't charge to a significant degree. Yes, theoretically it can resonate with any value of L, but in practice, it doesn't interfere with the tiny Ls and tiny Cs.

At this point in the design I now have the collector directly connected to the base of the next 2N3866 transistor. Huge D-C currents would flow, destroying the transistor. To prevent the flow of DC, I used my usual 10 pF capacitor, but now this is a new reactance that needs to be eliminated. Also, the 10 pF capacitor will effect the collector L-C circuit so it can't be too large. To cancel this reactance I put it in series with another inductor. L-C series circuits look like zero impedance at the resonant frequency. To make the 10 pF capacitor resonate at 145 MHz:

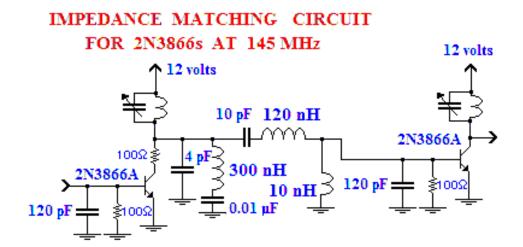
$$1/(2\pi~f~)^2$$
 = LC = $1/\{2(6.28)(145MHz)\}2$ = $L~(10~pF)$, solve for L L = $0.12~\mu H$

$$L = 0.394r^2N^2 / \{9r + 10\ell\}$$

$$L = 0.12 \ \mu H = 0.394 r^2 N^2 \ / \ [9 (.33 \ cm) + 10 \ (.66 \ cm)]$$

Solving for N, N = 5.2 turns.

The full impedance matching circuit, *including internal transistor parameters*, is shown below:



This circuit coupling scheme as shown above produced a voltage gain of over 3 times - better than usual! Gee, maybe I should have paid more attention in engineering school! Changing the 120 nH coil from 5 turns to 6 turns, produced a tiny improvement. 7 turns was slightly worse.

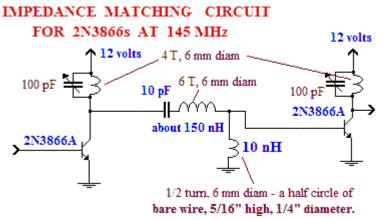
I said earlier that I picked 100 ohms transistor source resistance because it was convenient - 100 ohms was already matched to 100 ohms. I originally assumed 1,000 ohms because I thought the output would be tiny. Using the chart, this value produced a larger series inductor, 8.2 turns, which didn't work nearly as well as the 6 turn coil.

The half turn coil is extremely sensitive

The surprise for me in the calculated design was the miniscule base-to-ground inductor. It's hard for us HF guys to appreciate the significance of a half inch of bare wire. It will pay to experiment with different lengths of wire and exact dimensions.

The 300 nH inductor isn't needed

300 nH is so large that it approaches being a radio frequency choke, an RFC. As you might have guessed, taking it out of the circuit had no obvious effect on the gain. To say it another way, 4 pF is not very significant and was easily compensated or "absorbed" by tuning the LC circuit on the first transistor collector. Recall that ground and the 12 volt supply buss look identical to VHF RF currents. The real circuit of course doesn't show the transistor internal resistances and capacitances. An inductor grounds the base for DC current, so no base resistor is needed. The actual coupling circuit is below:



Because of the way this analysis was done, I never had to deal with more than 2

variables at a time. According to Mr. Bowick, so long as there aren't 3 or more variables, it is not more efficient to set up a Smith chart. For example, in theory, analyzing three element antenna couplers would be easiest using a Smith chart. In practice, if the 3rd element is a capacitor coupling to the antenna, the capacitor is nearly always large. It is like a short circuit at that frequency and this level of precision isn't needed.

In contrast, if we were designing a complex HF preselector filter like the ones needed for the receiver in Chapter 13, there might be 6 or more elements that must work together to produce a simple resistive output. The Smith chart has a central, vertical line that plots total resistance. The capacitive and inductance elements are on radial lines to the left and right of the resistance line. To handle multiple elements, the user mechanically selects capacitance and inductive element points that cancel and always return to the resistance plot. This eliminates the complicated algebra that would otherwise be needed.

Two more answers to the intermittent VHF amplifier mystery

While working on this circuit, I had the opportunity to directly observe improved gain suddenly vanish, then reappear, for no obvious reason. The best answer is simply that VHF circuits are often quite hard to adjust. Tiny adjustments of tuning caps can produce **huge** differences. A bit of vibration or other change and the perfect resonance vanishes. When I finally installed the two RF boards in a metal box, the output L-C stage and the input stage L-C both had to be retuned. I assume subtle changes in local capacitance, caused the signal to disappear. Sometimes just touching the stage heat sink with a finger could restore the signal. However, only retuning the L-Cs restored the signal without holding a finger on some magic location.

A less likely answer is that the transistor stage might have begun to oscillate spontaneously - it became a regenerative amplifier? For example, I could connect the supply and get a big output. Then I could disconnect the 12 volts, reconnect the supply and only have a small fraction of the gain. In the amplifier board I deliberately used transistors that had formerly appeared to lose gain permanently. Obviously these transistors were not damaged as I had earlier assumed.

The exploration described in this chapter, Chapter 16A, made it possible to make VHF amplifiers that work. Successful transmitter modules are described in Chapter 16B. Receiver modules are in Chapter 16C.