VHF Open Sources

Design of Low Power High-Stability Low Phase Noise Single Frequency VHF Sources with High Spectral Purity

Rick Campbell November 2008

This paper describes in exhaustive detail the design, measurement and testing of a family of high stability low phase noise VHF signal sources with high spectral purity. The three examples are for 50 MHz, 144 MHz, and 222 MHz, but enough information is presented that a designer can modify the component values to achieve similar performance on any frequency through the VHF range from 30 to 300 MHz.

There may be nothing new in these designs, but the optimized circuits, their detailed behavior and the component by component design considerations are not in the current textbooks. These details have been recovered from lore freely shared among retired radio designers and rediscovered by the author through hours of experimentation and analysis.

The sources described here are not the only approach: phase locked loops and direct digital synthesizers are more modern, and therefore have appeared more frequently in recent literature. The sources presented here were designed and built because they are useful, and offer advantages for applications that don't require extensive frequency agility. They have exceptional frequency stability and close-in phase noise, modest power requirements, and the ability to be built in any quantity (including one) using commonly available components. The name "VHF Open Source" refers to the free disemination of all design, construction and measurement details, to facilitate understanding, duplication, redesign, and part substitution. The only request is acknowledgement of this document when ideas, schemetics, photos or circuit board artwork are directly lifted from these pages.

Block Diagram The block diagram of the VHF open source is nearly 100 years old. The diagram includes an oscillator followed by a frequency multiplier. An amplifier often follows the frequency multiplier, as shown in the figure below.

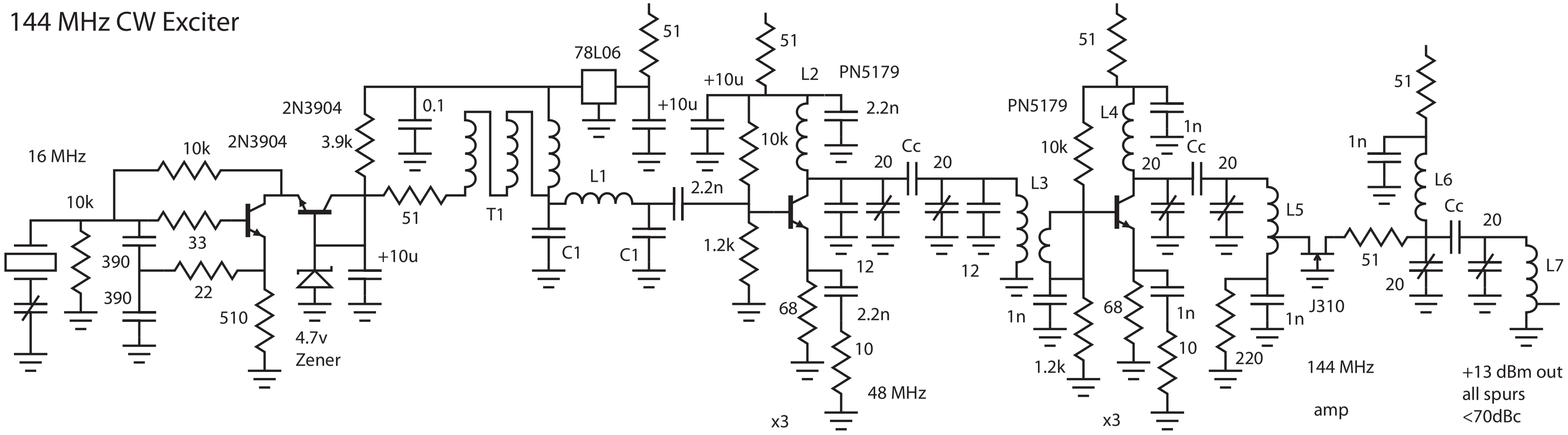
Many texts state that the frequency multiplier is needed because the oscillator frequency is limited. As best this is an oversimplification. A more important function of the frequency multiplier is to isolate the oscillator from the outside world. Frequency doublers are particularly useful, as 2nd harmonic leakage into an oscillator will not modify the phase within the loop, with an attendant frequency shift. Frequency sources with only a DC input and an RF output on a frequency other than the basic oscillator are well behaved.

Complete 20 milliwatt 144 MHz CW Source

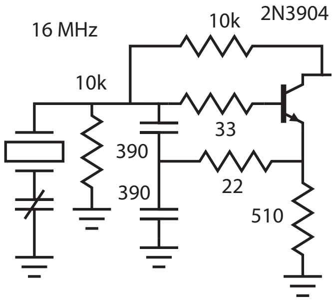
Rick Campbell KK7B November 2008

Spectral purity of output depends on electromagnetic shielding and isolation between stages not shown in the schematic

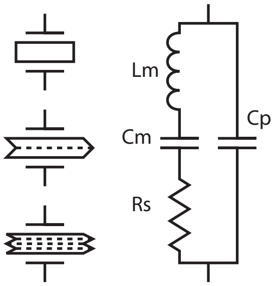
144 MHz CW Exciter



Oscillator The basic oscillator circuit is a familiar Colpitts circuit, with a tapped capacitor serving as an autotransformer between the emitter and base of a common collector amplifier circuit. The common-collector amplifer has a gain of less than 1, so the circuit will not oscillate without the voltage gain provided by the high-Q quartz resonator and tapped capacitor. When directly connected to the buffer amplifier circuit on the next page, the reflection coefficient at the juntion of the two 10 k resistors where the crystal connection is just slightly greater than 1 across most of the high frequency range from 3 to 30 MHz. To isolate the oscillator from variations in transistor performance over process and temperature, the transistor is embedded in a network of series and parallel resistors. The 2N3904 is a quiet general purpose NPN transistor with low noise at audio and an Ft above 300 MHz. 390pF capacitors work from 6 MHz through 18 MHz with active crystals. 220pF may be a better choice above 10 MHz, and 150pF above 16 MHz.



With gain just sufficient to maintain oscillation, multiple levels of voltage stabilization on the operating conditions of the active device, isolation between the oscillator and external circuitry, and resistors swamping out the semiconductor parasitics, the operating frequency is determined by the quartz crystal network. The primary source of drift is the temperature variations of the crystal, and a secondary source of drift is the thermal stability of the variable capacitor in series with the quartz crystal.



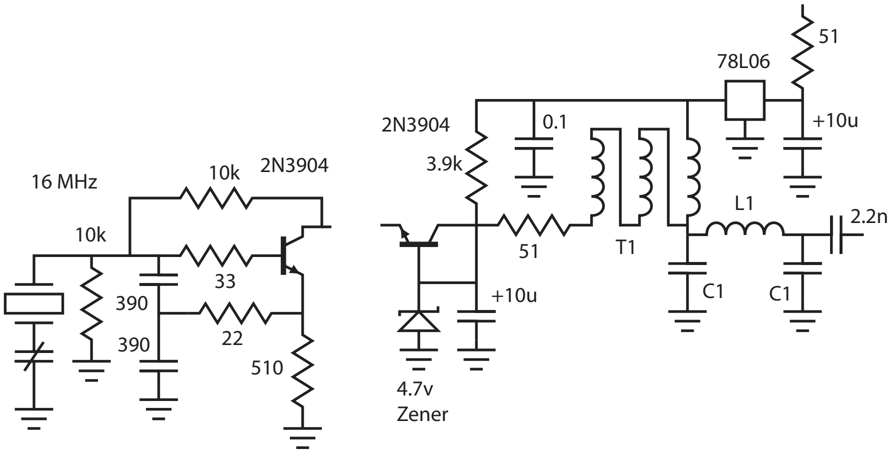
The schematic symbol of a quartz crystal is shown on the upper left. The drawings below the schematic symbol illustrate the shear vibrational modes of the piezoelectric slab of quartz. The upper drawins shows a fundamental mode, and the lower drawing illustrates a third order mode of the same piece of quartz. Note that the thickness determines the resonant frequency. The schematic model to the right has a motional inductance Lm, motional capacitance Cm, and series resistance Rs that model the mechanical-piezoelectric behavior of the quartz blank, and a parallel capacitance Cp that represents the actual capacitance between the metal plating on the surfaces of the crystal.

A custom crystal with selected temperature curve and an air or glass dielectric piston trimmer capacitor will provide remarkable frequency stability, typically 1 part in 10^8 in the author's examples. For crystals designed to be operated at room temperature, a foam packing bead slipped over the crystal will significantly reduce short-term drift by increasing the thermal time constant of the crystal package. For low battery drain operation in harsh thermal environments such as winter mountaineering, the crystal oscillator has been packaged in a separate small enclosure worn inside clothing. The operator may then carry an extra candy bar to help maintain a constant crystal temperature instead of a lead acid battery to run a crystal oven. The crystal frequency may be tweaked over a narrow range--10 kHz or less--at the fundamental by adjusting the series capacitance between about 2pF and 50pF.

The basic Colpitts oscillator circuit is designed to operate with the buffer circuit shown below.

This circuit may be analyzed using Linear Technology Switcher Cad III or other Spice simulator to select values for the capacitors. Remove the crystal and drive the network at the junction of the 10k resistors using a reflection coefficient simulator. An example file is at the link on the Portland State University RF Design Web Page.

Oscillator - Buffer The Colpitts oscillator-common base buffer circuit below has been widely published and duplicated in various forms since the late 1970s. The earliest example in the author’s references is a 1979 Ham Radio article by Joe Reisert describing a high performance battery powered frequency standard for amateur microwave weak-signal communication.



Several subtle and important circuit and physics details contribute to the performance of this circuit. Examining the DC operation first, note that the 6 volt regulator sets up a current through the 4.7 zolt zener diode determined by the 3.9k resistor. That sets the base voltage on the common base buffer stage at approximately 4.7 volts, and an emitter voltage of about 4.0 volts. The voltage divider from the emitter of Q2 consisting of a pair of 10k resistors sets the base voltage on the oscillator transistor at about 2.0 volts, and an emitter voltage of about 1.3 volts. the 1.3 volt drop across the 510 ohm emitter resistor sets a current through the transistor pair of about 2.6 mA. When the circuit oscillates, the current increases slightly. The total current drain for the complete circuit during operation is about 4 mA.

The 4.7 volt zener operates in the sweet spot between zener and avalanche modes. Avalanche breakdown has a positive temperature coefficient, and dominates above about 6 volts. Zener breakdown dominates at lower voltages, and has a negative temperature coefficient. Voltage regulating diodes operating near 5 volts exhibit both breakdown mechanisms, and have nearly zero temperature coefficient. The junction capacitance of a zener diode is relatively high, on the order of 100 pF, which acts as an internal bypass capacitor for high frequencies, but the breakdown mechanism is noisy, and the 10 uF electrolytic capacitor across the zener diode bypasses low frequency noise at the transistor base.

The oscillator-buffer output power is determined by the drive into the emitter of the common base stage, the collector voltage, and the impedance presented to the collector. With the values shown, the impedance at the collector is about 500 ohms, and the output power is about +4 dBm. Replacing the 78L06 with a 78L09 results in an output power of about +8 dBm.

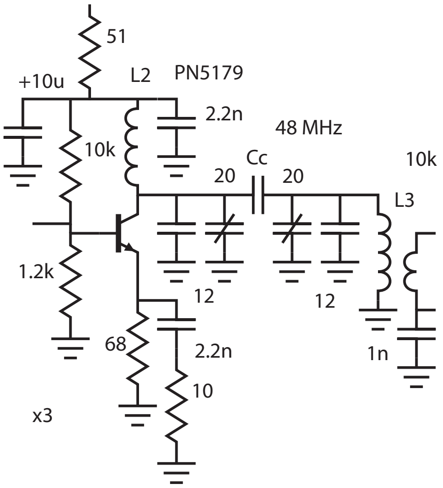
+7 dBm is 5 milliwatts, or 0.71 volts peak across a 50 ohm load. The trifilar wound ferrite transformer T1 has a 3:1 step-down from the collector to the 50 ohm load and additional resistance in series with the collector, so the voltage swing at the collector is a little more than 3 times the peak voltage at the load. The voltage swing at the collector for +8 dBm output is thus about 6 volts pea-to-peak, and the voltage swing at +4 dBm is about 4 volts peak-to-peak. The pi-network CLC on the output is a low-pass filter to provide an output that is closer to a sine wave. These values may be adjusted to optimize drive to the following multipleir stage to improve harmonic output and DC eficiency.

When the buffer amplifier is operated within it's linear range--with output level determined primarily by signal level at the emitter rather than by power supply voltage--the common base amplifier has high reverse isolation S12. This is useful when driving a non-linear circuit such as a frequency multiplier, as it isolates the quartz crystal oscillator from the non-linear load.

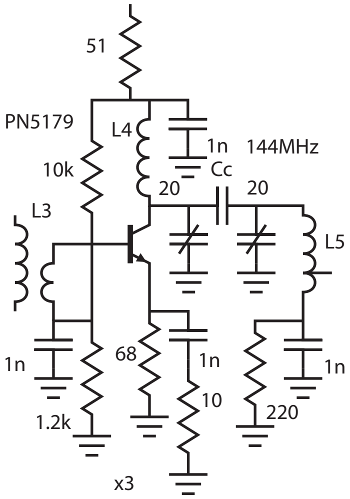
Frequency Multipliers Folloing the oscillator-buffer is the first of several frequency multiplier stages. Each frequency multiplier is designed to be driven by approximately +4 dBm and to provide a clean sine wave output at about +4 dBm at the second or third harmonic to the next stage. The primary frequency multiplication mechanism is current limiting in an over-driven class A amplifier stage. The frequency multiplier stages are biased for a quiescent current of about 1mA. Current increases to about 4 mA with drive. The voltage at the emitter resistor is a convenient test point for tuning previous stages, since it increases linearly with operating current. This is a classic technique well known to mobile radio technicians.

The bypass capacitor is degenerated by a series resistor to provide a non-zero AC emitter resistance. This raises the impedance at the base, which reduces the drive power requirement from the previous stage. Since it also reduces distortion and gain, there is a complex trade-off between efficient frequency multiplier operation, drive power needed from the previous stage, operating current, and operating voltage. It is highly instructive to observe frequency multiplier operation at the bench and in a transient simulator to explore the relationship between all of various parameters.

A narrow double-tuned circuit provides enough spectral purity for X2 and X3 frequency multiplers that that drive to the following stage looks like a sine wave. The double-tuned circuit also performs an impedance transformation between roughly 1k presented to the collector and 50 ohm drive to the next stage. The number of turns on the output link on L3 is adjusted for optimum drive to the next stage. The undesired fundamental and harmonic outputs from a X3 multiplier will be suppressed more than 40 dB relative to the desired output. This is expressed compactly as "-40 dBc undesired outputs." While this is sufficient spectral purity for proper operation of the next stage, it is not good enough for many applications. The tuned output amplifier after the last X3 stage provides added suppression of undesired harmonic outputs.

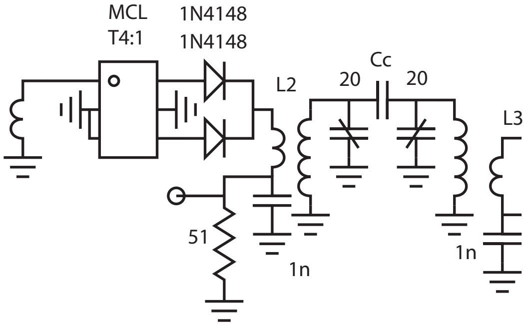


A second frequency multiplier stage is shown at the right. The primary difference between the two stages is the practical implementation of the selective elements in the double tuned circuit on the output. Below 100 MHz, toroidal inductors wound on powdered iron cores are used, tuned either by squeezing and spreading turns, or with poly trimmer capacitors as shown. The self-shielding properties of toroid cores help keep the magnetic fields in the vicinity of the appropriate areas of the circuit board, but do litle to prevent electric field coupling. At frequencies above 60 MHz air-core solenoids become compact and useful. Tuning may be achieved by squeezing and spreading turns, or with poly trimmer capacitors as shown. Coupling capacitor Cc are typically 1 pF or less, and may be either chip capcitors or gimmick capacitors made from short lengths of insulated twisted pair.



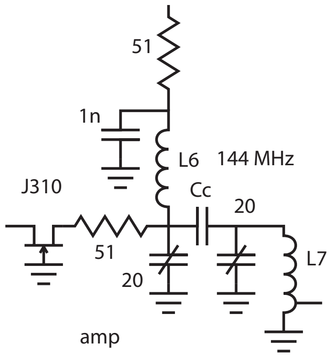
The frequency multiplier shown above is driven from a link wound on the toroid, to illustrate just one way to couple signals between stages. Often the choice of interstage coupling is made for convenience of the layout. The electric and magnetic fields around inductors, tuning capacitors, and all the interconnecting traces are significant, and changes to the layout often have more impact than changes in component values or circuit topology. It is important to optimize stage-by-stage at the bench while observing the effects of component placement and circuit topology. There are no 3D electromagnetic-electronic simulators capable of handling all the circuit board and component parasitics, dielectric and magnetic properties of different component materials, and the myriad devices in common use at VHF. There is no substitute for a designer with depth of understanding and experience participating in all aspects of the design, from sketches of the block diagram to analysis and simulation of candidate circuit schematics through prototyping and optimizing at the bench. Until you build and measure it, you don't know what you don't know.

Balanced diode frequency doublers are attractive alternatives to active frequency multipliers when stage gains and power levels may be adjusted to compensate for the expected 6 to 8 dB conversion loss. They require clean sine wave drive, and the output waveform is rich in even harmonics. They are well-behaved, with a nearly linear relationship between drive and output levels over a significant range from about +3 to +16 dBm drive for the version shown at the right.



At higher frequencies, and for higher multiples such as 4 5 6 and 7, passive diode multipliers in conjunction with narrow filters and 50 ohm gain block ICs are attractive. Linear gain block ICs draw more current than optimized cascaded frequency multiplier stages, which may be significant for battery operated applications.

Balanced diode frequency doublers are particularly useful as the last stage of a frequency multipler chain when a modest output level is needed. As previously mentioned in conjunction with oscillators, low level x2 and /2 signals may be added to a fundamental without altering the phase of the fundamental. This has significant benefits for balanced mixers, direct conversion receivers and free running oscillators. An additional benefit to using a diode doubler as the final stage in a local oscillator is that there are no power supply currents flowing at the output frequency. This improves shielding and bypassing performance.



Isolating Output Amplifier Unlike balanced diode multipliers, transistor frequency multipliers are non-linear circuits optimized for operation with particular drive and load levels and impedances. Microwave frequency multipliers are often operated with an isolator on the output to prevent load impedance variations from affecting multiplier operation. Using an isolating amplifier on the output of a VHF frequency multiplier chain achieves the same function, and offers a convenient place for additional selectivity to reduce close-in harmonics of the fundamental oscillator. The common gate J301 amplifier shown at the right serves both functions well. S11 is well-behavied and determined by gm of the device. S12 is approximately -40 dB for excellent isolation between drive and load, and S21 is modest at VHF.

Electromagnetic Shielding Practical VHF circuits need electromagnetic shields to confine signals to particular regions in space. The amount of shielding is a compromise between cost, performance, and weight. Reducing undesired signals to undetectable levels requires that individual stages be constructed in individual modules with fully shielded interconnecting cables, as is common in space electronics and spectrum analyzers. It is instructive to design circuit modules and circuit boards with the option for additional shielding, and then observe the performance on a spectrum analyzer as shielding is added. The 144 MHz oscillator-multiplier amplifier chain shown in the earlier schematic has spurious outputs suppressed roughly 60 dBc with no shields, and more than 70 dBc with small tinned steel shields between stages. Separating the last X3 multiplier and common gate amplifier into individual diecast boxes with interconnecting semi-rigid SMA cables reduces all undesired outputs below -90 dBc, with no changes to the circuit diagram. Obtaining the desired output level and suppression of unwanted outputs to about 40 dBc may be achieved with little shielding, but suppression of unwanted responses below 50 dBc requires electromagnetic design and measurements.

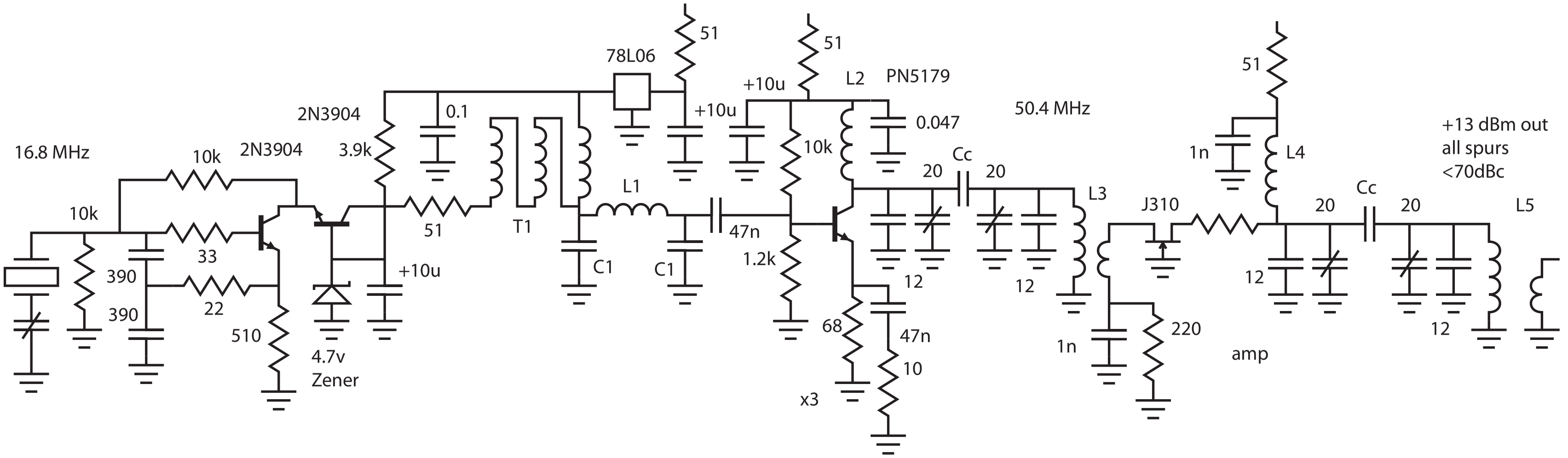
Simulation Versus Measurement There is little in a circuit simulator to indicate the inportance of electromagnetic coupling between VHF components. Disappointing performance on an open circuit board may lead the designer down the path of adding additional tuned interstage components. Such additions add complexity and tune up time without solving the problem if unwanted outputs are radiated across the board or coupled on power supply lines. A simulator is a valuable tool to obtain a 1 dB improvement in the gain of an amplifier, but seldom useful if an additional 10 dB suppression of a -90 dBm spurious output signal is needed. A careful designer will simulate nearly everything, measure everything possible, and ponder every detail of the design, from the models used in the simulator to E-field coupling in high impedance portions of the circuit and H-field coupling in low impedance circuit areas.

Complete 20 milliwatt 50 MHz CW Source

Rick Campbell KK7B November 2008

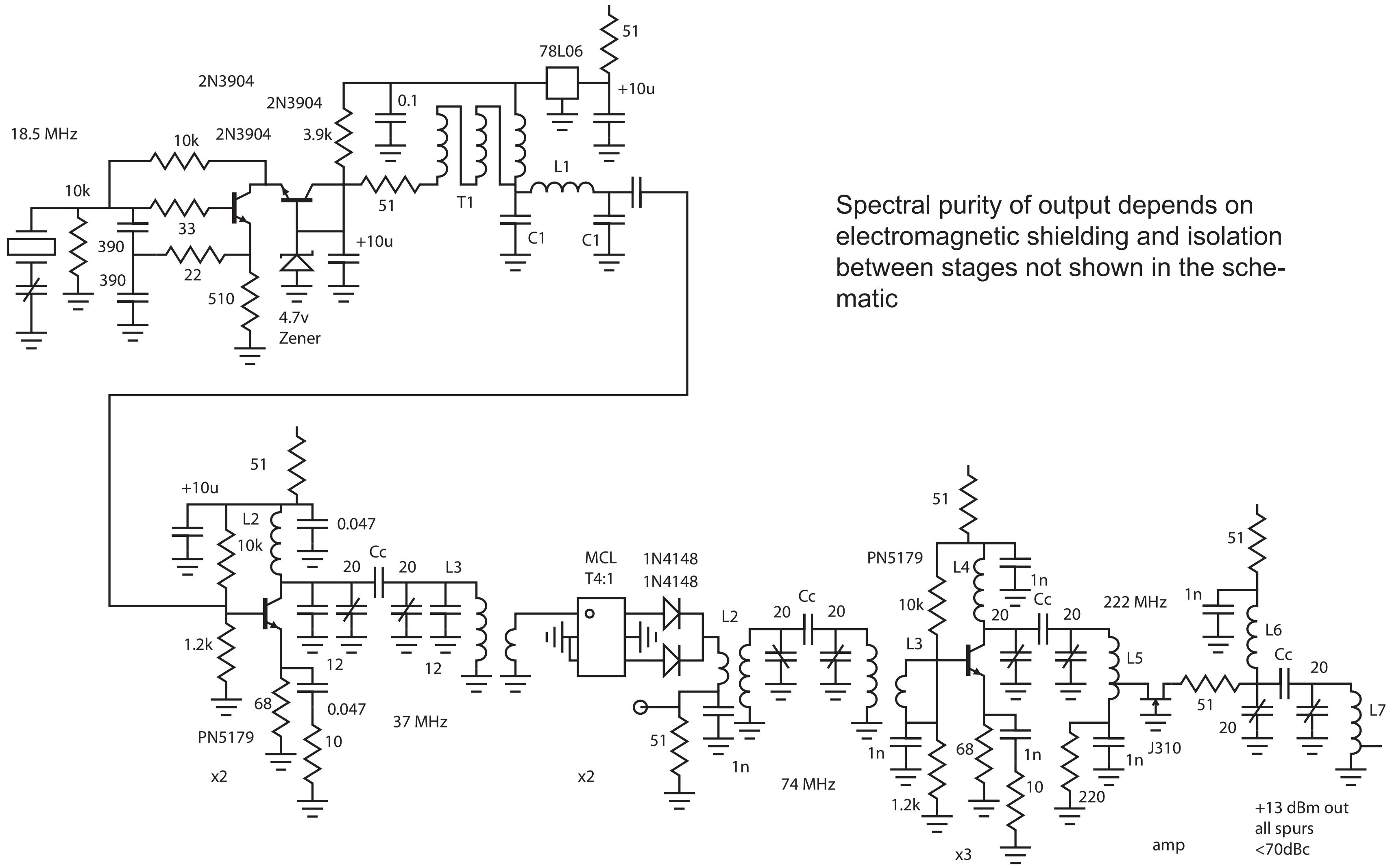
Spectral purity of output depends on electromagnetic shielding and isolation between stages not shown in the schematic

50 MHz CW Exciter



Complete 20 milliwatt 222 MHz CW Source

Rick Campbell KK7B November 2008

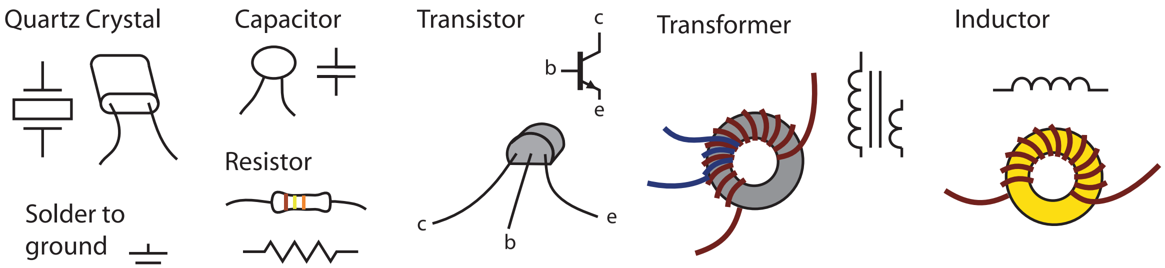


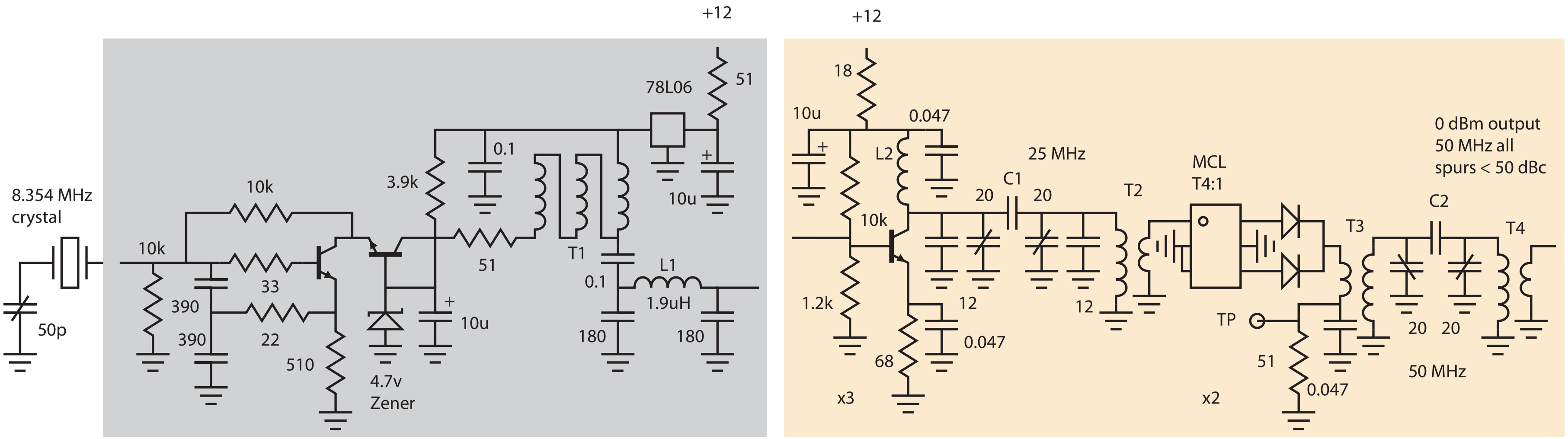
Spectral purity of output depends on electromagnetic shielding and isolation between stages not shown in the schematic

1 milliwatt 50 MHz CW Source

Rick Campbell KK7September 2007

50.125 MHz VXO for microT2 exciter





All 3 transistors 2N3904 or equivalent

T1 4t trifilar on FT25-43

L1 and associated 180pF capacitors
X=100 ohms at crystal freq.

gray circuitry is part of microT2

L2 18t T25-2 resonant at 3x crystal freq.

T2 18t:3t T25-2 resonant at 3x crystal freq.

x3 and x2 built on unetched copper clad

T3,T4 16t:2t T25-6 resonant at 6x crystal freq.

MCL T4:1 may be replaced by trifilar transformer like T1

TP reads ~0.4 volts when properly tuned

0 dBm output drives microT2 buffer amp

C1 3/4" long twisted #28 gimmick

C2 3/8" long twisted #28 gimmick

41 and 58 MHz spurs -45 dBc