Simplified Tools and Methods for Measuring Crystals

By
Jim Kortge, K8IQY

Summary
This paper describes an approach for measuring crystal parameters using relatively simple test apparatus and test setups. Some of the required test instruments are easily built, using Manhattan-style construction methods. Others can be obtained on the surplus market at low cost. With careful use, the resulting crystal parameter values are comparable in accuracy to those measured with instruments costing thousands of dollars. The same instruments and setup can also be used for measuring crystals for use in multi-pole filters.

Background

One of the common elements in all modern superheterodyne receivers is at least one crystal filter. A contest grade receiver may employ more than one filter for improved performance. One can obtain a crystal filter essentially two ways; either purchase a commercial unit on the required IF frequency or build the filter from easily obtained components.

Purchasing the filter requires little effort, but the cost is high, on the order of $150.00, and may be much more than this amount for a high performance filter. On the other hand, the components to build a filter will probably cost one-tenth of the commercial unit, but effort is required to build the filter. Most of that effort is embodied in determining the characteristics of the crystals that will be used. The remainder is in assembling and testing the constructed filter.

What are the benefits of building a filter? First, one can tailor the filter's characteristics to exactly those desired. For example, the filter could be built for CW use with a pass band of 350 Hz. Obtaining a commercial filter with that bandwidth is prohibitively expensive, since it is not a standard. Another reason for building our own filter is the ability to choose the number of elements needed to achieve the performance desired. If a 4-pole filter is needed, that's what is built. On the other hand, if a 7-pole filter is desired for enhanced performance, it too can be built with little additional effort. We can even build a filter with an adjustable pass band; try to find one of those commercially. Finally, by building our own filters, we have many more options available in deciding the RF mixing schemes used. With commercial filters, most of those decisions are dictated by the offerings of the various manufacturers, which are limited unless a custom filters is ordered.

Crystal Parameters

Before we can build a crystal filter, we have to know the properties of the crystals that will go into it. If the filter is built without that knowledge, two important deficiencies will occur. First, the filter will probably be far from optimum in performance. There will most likely be artifacts in the pass band amplitude and phase characteristics, and the insertion loss will not be minimized. Second, our ability to reproduce the filter, regardless of its performance, or lack of, will be compromised. A second unit built from the same kind of parts will most likely be markedly different in performance. Notice that I used the term "most likely" since by chance, one may end up with a good filter, with reproducible characteristics, without knowing anything about the crystal elements used. However, the probability of that actually happening is very, very small. The remainder of this paper will concentrate on the equipment and test setups required to ascertain this vital information

Crystals are characterized by the following parameters:

Fs = this is the series resonant frequency of the crystal, and represents the point where the ***series*** inductive and capacitive reactance terms cancel.

Rs = this term is the equivalent series resistance of the crystal at resonance (Fs), and represents the energy loss in the quartz element.

Lm = this term is the motional inductance of the crystal, and represents the vibrating mass of the quartz element.

Cm = this term is the motional capacitance of the crystal, and represents the elasticity of the quartz element

Co = this term is the holder capacitance of the crystal, and is the capacitance of the plated contact areas on the quartz element, the connecting lead wires, and the parasitic capacitance to the surrounding case.

Q = this term represents the overall energy loss in the crystal when it is being driven by an external source. It is equivalent to the Q of a capacitor or inductor.

Figure 1 shows a typical electrical schematic for a crystal, with the various parameters identified.

As can be seen, the basic structure is a series RLC circuit comprised of Rs, Lm, and Cm, with Co in parallel with the RLC elements. This might suggest that the crystal will behave differently depending on the frequency exciting it, and that's exactly what happens. Figure 2 is a frequency response, or Bode plot for a 4.9152 MHz crystal, typical of the crystal element used in the 2N2/40+ IF filter, or the IF filter in a K1 or K2.

As suggested, we see a very sharp response peak from the series RLC part of the circuit at nominally the frequency marked on the case. However, there is also a very deep null about 10 KHz higher in frequency, at the parallel resonance point. This is where the "series" motional capacitance is absorbed into the motional inductance, and the "parallel" holder capacitance term, Co now prevails. Notice that the difference in amplitude between the series resonant peak and the parallel resonant null is about 100 dB. This very large dynamic range makes it difficult to see or measure the parallel resonance of a crystal unless one has access to an instrument with a corresponding very wide dynamic range. A spectrum analyzer, or similar instrument is typically required to make this measurement.

Here are the parameters for this crystal:

Fs = 4.9152 MHz

Rs = 13.0 Ohms

Lm = 0.070 Henry

Cm = 1.50E-14 Farad

Co = 3.64E-12 Farad

Q = 167,500

Crystal Parameter Measurements - Overview

Figure 3 is a block diagram of the basic setup used to measure the crystal parameters.

This arrangement employs a signal generator with good short-term stability and precision, a counter to measure the signal generator frequency if the generator does not have its own readout, a fixture to hold the crystal under test, and a suitable RF detector.

Some details on each of the blocks in this diagram are appropriate. The signal generator can vary widely in terms of its capability. It can be a highly accurate, digitally synthesized, low phase noise, mega-dollar unit from Agilent or Rhode & Schwartz. It could be a lower cost, older unit from Racal, Fluke, or HP, such as an 8640B. Or it could be a very low cost, rather simple but highly stable, VXO based generator, built Manhattan-style that utilizes one of the crystals that will eventually be incorporated into a filter. We'll see details of this generator type later on.

The counter may or may not be needed, depending on the design of the generator. Which-ever way it is implemented, it must be capable of resolving 1 Hz at the crystal's resonant frequency, and have both good short term and long term stability. Almost any crystal base counter will suffice if the resolution requirement is met. The Arizona QRP Club's "Stinger Singer" would be suitable as a low cost choice.

A special crystal test fixture is required as part of this system. It must mechanically hold the crystal, and more importantly, provide appropriately conditioned signals to the crystal under test, and to the downstream detector. This element is also rather simple in design, and can be constructed Manhattan-style, using readily available parts. We'll see details of this test fixture later on too.

The final element in the system is some kind of RF detector. This could be something as simple as an RF probe, used with a digital voltmeter, or analog VOM. It could also take the form of a low bandwidth oscilloscope, with or without the RF probe used as a demodulator. My favorite is a HP 400EL AC voltmeter. These are available on the used equipment market, typically for under $50, and provide detection and an analog display in dB up to 10 MHz. A suitable alternative is a used HP 3400A. It has the same basic capabilities as the 400EL, but its primary scale is linear.

Of those crystal parameters shown earlier, only Fs, Rs, and Co are directly measured. The remaining are obtained by way of additional measurements, and a set of equations to compute them. Here are those equations:

Lm = (25+Rs)/(2*PI*DeltaF) where DeltaF is the frequency difference between the –3 dB points on the response curve

Cm = 1/(4*PI^2*Fs^2*Lm)

Q = (2*PI*Fs*Lm)/Rs

The actual crystal characterization is done a piece at a time, with the next parameter being derived from previous information in most cases. After we look at the details of the signal generator and crystal test fixture, we'll come back to these equations and see in detail how they are used.

Signal Generator Details – A Precision VXO

As was suggested earlier, one of the options for generating a stable signal for crystal testing is to use a VXO. The one that I am presenting fills the need for a precision, stable source, capable of providing measurement results comparable to those obtained with a high end, commercial signal generator. Over the past several years, I have suggested this approach to several experimenters, but am not aware that any actually tried it. I wasn't sure the idea was sound until a prototype was built, and several sets of crystals had been tested. The results using this generator were comparable to those obtained using my Racal-Dana 9087.

The schematic for this Precision VXO design is shown in figure 4.

This generator consists of a Colpitts oscillator, Q1 using a 2N5484 junction FET. The crystal employed is one from the set, which will be used for building a filter or for LO service. Controlling the frequency of oscillation is accomplished with a varicap diode, a MV209, and a set of 5 molded inductors configured as a binary weighted set. Inductance needed to force the crystal to oscillate at its marked case frequency is experimentally determined by selecting the desired total inductance using switches S1 through S5. When no inductors are selected, the minimum inductance is that of the leads going to S1 and S5 in the actual prototype. Maximum inductance is obtained when all of the inductors are selected and are connected in series. The minimum inductance change is 2.2 uH, provided by S1.

With most crystals, the tuning range of the varicap diode can provide the overlap needed to make the digitally controlled inductance work smoothly. It can also provide sufficient frequency span so that the resonant frequency of a crystal under test can be determined.
Frequency precision is obtained by using a 10-turn potentiometer, and stability is achieved through the use of a regulated supply, and by minimizing the RF levels in the oscillator circuit.

A second 2N5484, Q2, is used as a source follower to further isolate the oscillator from any changes reflected back from the output load. The stage is also set up, by way of a voltage divider (R8 and R9), to provide an output impedance of 50 ohms. This impedance properly drives the fixed input impedance of the Norton amplifier used in the output stage. Both Q1 and Q2 are supplied with 9 volts from a regulator. Using a regulated supply helps maintain frequency and amplitude stability.

The output stage, a PN2222 (Q3) provides a gain of +12 dB and amplifies the generated signal to a level of approximately –10 dBm, suitable for driving a crystal in the crystal test fixture. This stage is a noiseless Norton amplifier design. Downstream of this amplifier is a low pass filter, to reduce harmonic content above 20 MHz. A spectrum plot of the output is shown in figure 5.

Overall, this Precision VXO generator is designed to work with commonly available HC49, and HC49U style computer crystals used in IF filter service. It will operate with crystals in the frequency range of 3.5 through 13.5 MHz, but is optimized for crystals at 9 MHz and below.

A prototype was built using Manhattan-style construction for the basic frequency generator portion. Figures 6 through 8 show some of the construction details. After finding out how well the generator worked, an Arizona ScQRPion Stinger Singer frequency readout was added.

Besides having a clean output spectrum, this low cost generator also has excellent frequency stability. Its warm-up drift is a few Hz, and the stability over a 24-hour period is within 20 Hz. Short-term stability is not measurable with the equipment in my laboratory.

The tuning range with a 4.9152 MHz crystal is approximately plus and minus 250 Hz, more than adequate for covering the series resonant frequency of crystals being characterized, or matched. More importantly, with the wide range of inductance available, the oscillating frequency of the VXO crystal can be moved over a considerably wider range, assuring that one can find the series resonant frequency of a crystal under test.

Its overall size will allow it to fit nicely into a Ten Tec TP-17 case. That case is 1.75 X 4.25 X 3.5 inches in size.

Crystal Test Fixture – A Crystal Drive Circuit

Figure 9 show the schematic for a Crystal Test Fixture.

The driving signal from the generator is first attenuated by 3 dB before being applied to the crystal. Some attenuation is desirable to reduce the load variations the generator sees as the crystal is driven at various frequencies. As the attenuation is increased, the variations decrease. As in all designs, there are tradeoffs. If more attenuation is used, more generator power must be provided to achieve a drive level sufficiently large that we can accurately measure the crystal. The 3 dB value is a reasonable choice, but 6 dB would also work, and provide a bit more isolation.

After the first attenuator, the drive is applied to a 4:1 step down transformer, T1. This transformer uses bifilar construction, and is wound with 10 turns. While wire size isn't critical,

#28 or #30 are the preferred sizes for ease in winding. The output impedance of T1 is 12.5 ohms, which is a reasonable approximation to the Rs values for the crystals being tested.

The drive signal next passes through the crystal being tested, and on to another transformer, T2. This transformer is identical to T1, and is connected to provide an impedance step up back to 50 ohms. Another 3 dB attenuator follows T2, again, to help keep the 50-ohm impedance constant into the output amplifier, as the crystal impedance varies during testing.

The output amplifier, Q1, is a Norton configuration, identical to the output amplifier used in the Precision VXO. It uses a PN2222 transistor, provides 12 dB of gain, and has an output impedance of 50 ohms. The output signal is then routed to the output connector either directly, or through a built-in RF detector. With either output configuration, a 50-ohm load is provided to the output amplifier.

When the test crystal is replaced with a short circuit, the net gain of the test fixture itself is 6 dB. The test fixture, as designed, should be driven with a signal generator having an output impedance of 50 ohms. In like manner, the output should be connected to a detector with an input impedance of 50 ohms. When using the RF detector setting, an internal 50-ohm load is provided to the output amplifier.

Figures 10 and 11 show how this fixture was constructed.

Measuring Crystal Parameter - Details

Now that we have seen the details of the measuring system, let's go back and walk through the measurement of a crystal, and see how each of the parameters is obtained.
Once that is done, we'll also take a look at using the system for measuring a group of crystals for use in a crystal filter.

We start with perhaps the most important aspect of the process, getting the equipment ready to do the measuring. First, connect everything together, and make sure it follows the setup diagram. Next, and this is the important part, turn everything on, and let it warm up for at least 4 hours, longer if at all possible, and overnight if you can plan your measurement session that far ahead. The reason is that we are going to be making measurements down to one Hz out of several million, and temperature drift is our worst enemy.

Next, decide how many crystals will be tested, and get them out on the bench so they can warm up to ambient temperature also. You'll quickly find out how sensitive crystals are to temperature changes when you start doing these measurements. You can see the temperature drift induced by picking up a crystal and plugging it into the test fixture. Once plugged in, you can see it change again due to heating caused by the drive signal. And finally, you'll discover that crystals measured in one session will not be the same if measured again several hours later, the next day, or the next week. This caveat is especially important if you are only finding the resonant frequency of each unit for matching purposes. Do them all in one batch, or you will end up with confusing, inaccurate, and inconclusive results. I'd also suggest that at least 5 crystals be measured and that an average of each parameter be used as the characteristics for the batch.

OK, let's measure a crystal. We'll assume that all of the equipment is warmed up and stable.

Step 1
Put a crystal into the Precision VXO socket, if you are using that kind of signal generator. If not, skip this step. Adjust the Precision VXO tuning pot to the center of its range, that is, at 5 turns from one end. Remove all of the inductance by setting S1 through S5 to the bypass position. Measure the frequency of the VXO crystal. If it is above its case marked frequency, start adding inductance. Keep adding inductance until the measured frequency is below that marked on the case. Reconfigure the inductance switches a final time to make sure you are as close as you can get to the frequency marked on the crystal case. Above or below is acceptable, but below is preferred.

Step 2
Insert a crystal into the Crystal Test Fixture. Let it stabilize for at least a minute, maybe two. Start increasing the frequency of the generator being used, looking for a change in the detector signal level. If none is noted, increase the detector sensitivity until an increase or decrease is noted. If the signal is increasing with increasing frequency, keep going in that direction until a peak is found. If the signal is decreasing with increasing frequency, reverse the frequency direction, and find a peak. Vary the frequency back and forth through the peak several times until you are sure you've found the best peak you can get. Measure the frequency of the generator and write it down. Also, write down the reading shown on the detector, as we'll need this value later. The frequency we noted where the peak occurred is our first parameter, **Fs**, the resonant frequency of the crystal.

Step 3
Remove the crystal, and replace it with a 25-ohm, cermet, or other non-inductive trim potentiometer, and don't change the generator frequency setting. Adjust the trim potentiometer to the same reading that was recorded when the crystal was in the test fixture. Remove the trim potentiometer, and replace it with the crystal being characterized. Measure the trim potentiometer with a DMM, set on its lowest ohm scale. Be sure to compensate the reading for lead length errors if a non-zero reading occurs when the test leads are shorted together. Record this resistance value. This is our second parameter, **Rs**, the equivalent series resistance of the crystal.

Step 4
Readjust the signal generator to assure it is still set on the resonance peak of the crystal under test. Record the detector setting. Adjust the signal generator higher in frequency until the detector setting decreases by 3 dB, or 0.707 times its peak reading. Record the generator frequency of this point. In a like manner, retune the signal generator lower in frequency until the resonance peak is passed, and the detector is again lower by 3 dB, or 0.707 times the peak reading. Record this generator frequency. Subtract the lower reading from the higher, and record the difference. This is the DeltaF term in the Lm equation. For those who are curious about the Lm equation, the "25" constant in the numerator is the sum of the impedances driving the crystal, in our example test fixture, 2 times 12.5 ohms, or 25 ohms total. Plug the Rs and DeltaF values into the Lm equation and do the math. The numerical result is our third parameter, **Lm**, the motional inductance of the crystal.

Step 5
We're done with the measurements on this first crystal, so replace it with another crystal in the test fixture, and return the signal generator frequency control to the 5-turn position.
This will allow the next crystal to stabilize while we complete the remaining calculations.
Continuing on, plug in the Fs and just computed Lm values into the Cm equation, and turn the crank. The resulting value is our fourth parameter, **Cm**, the motional capacitance of the crystal.

Step 6
After removing the crystal from the test fixture, plug it in to whatever apparatus you have for measuring low capacitance values. My preferred instrument is an AADE L/C Meter. However, companies such as B & K Instruments also make an L/C meter. There are other choices too, including using an MFJ 274B Antenna Analyzer or the RF-1 antenna analyzer made by Autek Research. If an instrument is not available, use a value of 3.5 pF as the estimated Co for HC-49 style crystals in the 3.5 to 9 MHz range. This measurement or estimate yields the fifth parameter, **Co**, the holder capacitance.

Step 7
Almost done, plug in the Fs, Rs, and Lm values into the equation for Q, and do the math. The result is our sixth, and last parameter, **Q**, the Q of the crystal. The higher the Q value, the better the crystal will be for use as a filter. The higher the Q, the lower the insertion loss. Values above 150,000 are really good, those above 100,000 are more than adequate, and those above 50,000 are useable, but the filters will be about as lossy as can be tolerated.

Step 8
Measure at least another 4 more crystals using the previous steps. Compute the average value for each of the parameters and record these in your logbook along with other relevant information, such as manufacturer, measurement date, etc. As you accumulate crystals, and measurement information, these records become very important in deciding who makes good crystals for filters, and who does not. There is much variation among manufacturers.

Matching Crystals for Filter Elements

Now that we know the characteristics of a batch of crystals from the previous steps, using the test setup for matching crystals for filter use is a natural extension. It's really quite simple. The basic process is this: Insert a crystal in the test fixture. Let it "soak" for a fixed time period. A minute is suggested as the minimum. Adjust the signal generator for a peak reading on the output detector. Write the last 4 digits of the frequency readout on the crystal with an indelible marker. Put another crystal in the test fixture, and repeat the process until all of them are done. As you are measuring your batch, look for crystals that show excessive drift, or which result in very low readings on the output detector. Mark these with an "X", and don't use them in your filter. Those that tend to drift will result in a less than optimal filter, and those producing low detector outputs have abnormally high equivalent series resistance values. Using those in a filter will raise its insertion loss, sometimes by a significant amount. All of these rejects will work fine as Local Oscillator crystals, so don't throw them away, just don't use them in a filter.

Once all of the crystals are measured, select the set that has the tightest frequency grouping for use in your filter. With a group of 20 or more crystals, sets of 4 or more are often within a range of 20-25 Hz. The “rule of thumb” is to have the crystals matched within 10% of the filters bandwidth. So for a 500 Hz filter, the crystals should all be within a span of 50 Hz, quite easy to do with crystals from a known source.

Final Comments

I hope you have found the information within to be enlightening and more importantly, useful. Measuring crystal parameters can be done accurately, with relatively simple equipment if you don’t mind building some of it. Matching crystals is also easy to accomplish when using the equipment and methods shown. Your efforts can result in home-built filters that are remarkably good and very inexpensive compared to commercial units.

Drawings and Photos

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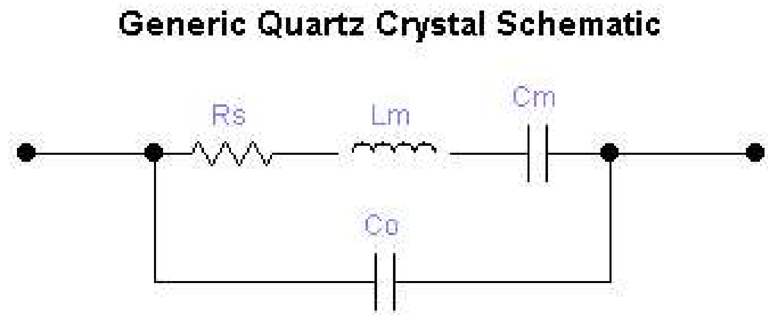

Figure 1

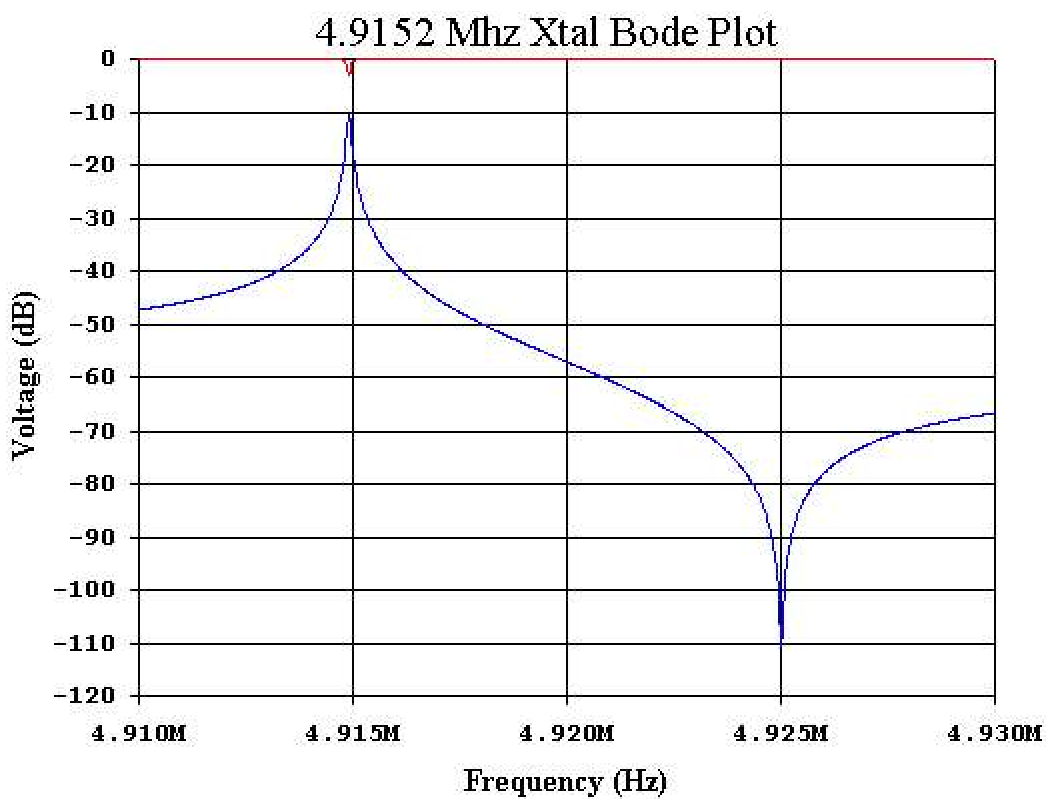

Figure 2

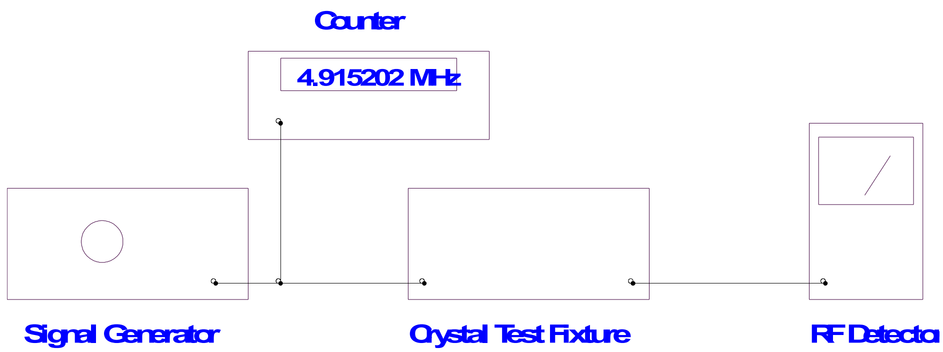

Figure 3

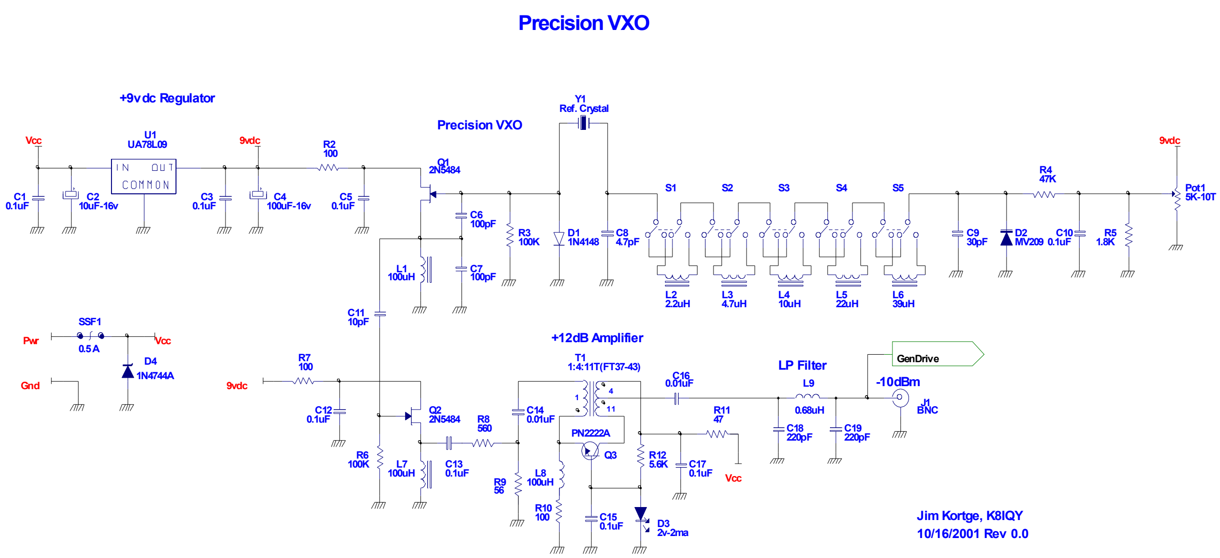

Figure 4

Precision VXO Output Spectrum

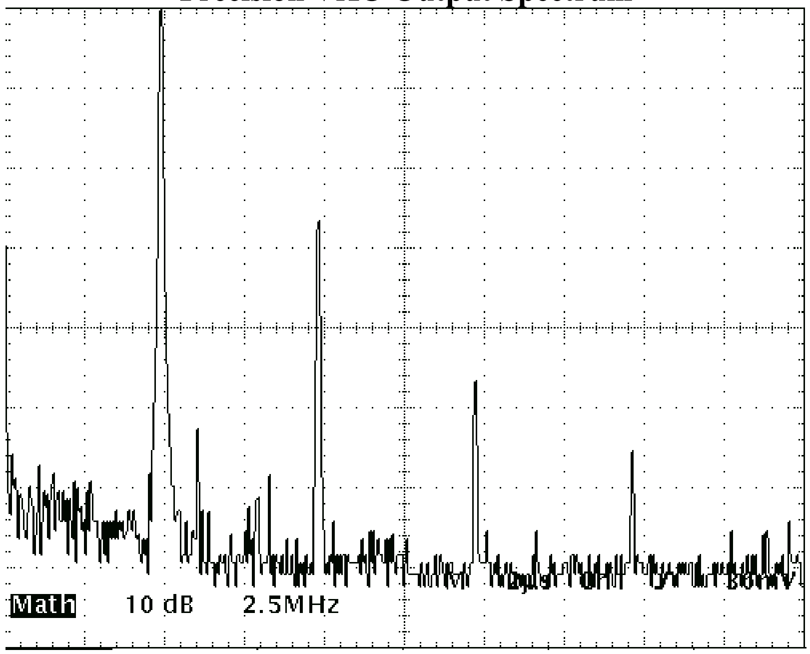

Figure 5

Figure 6

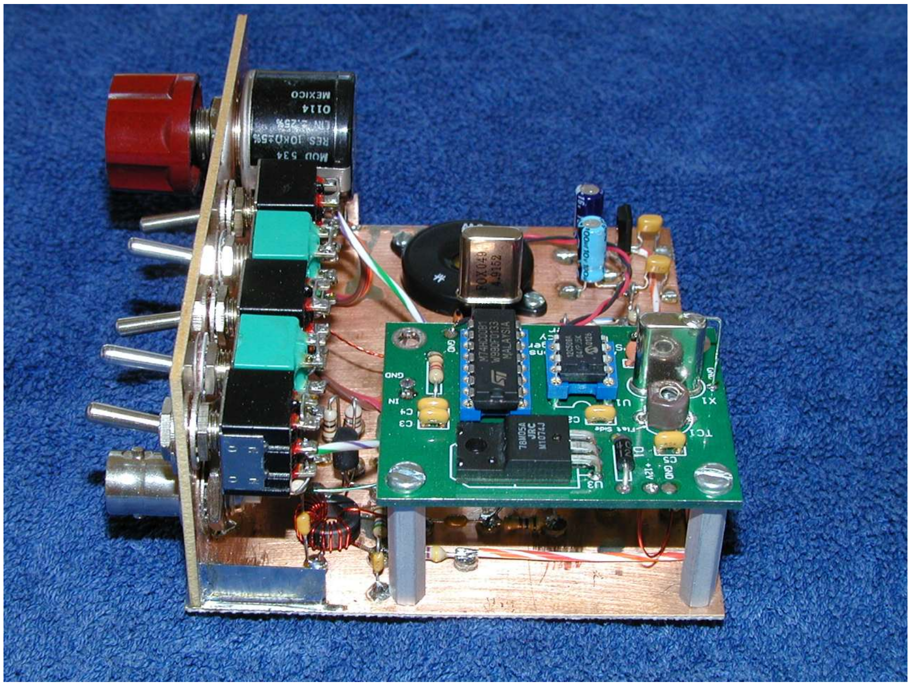

Figure 7

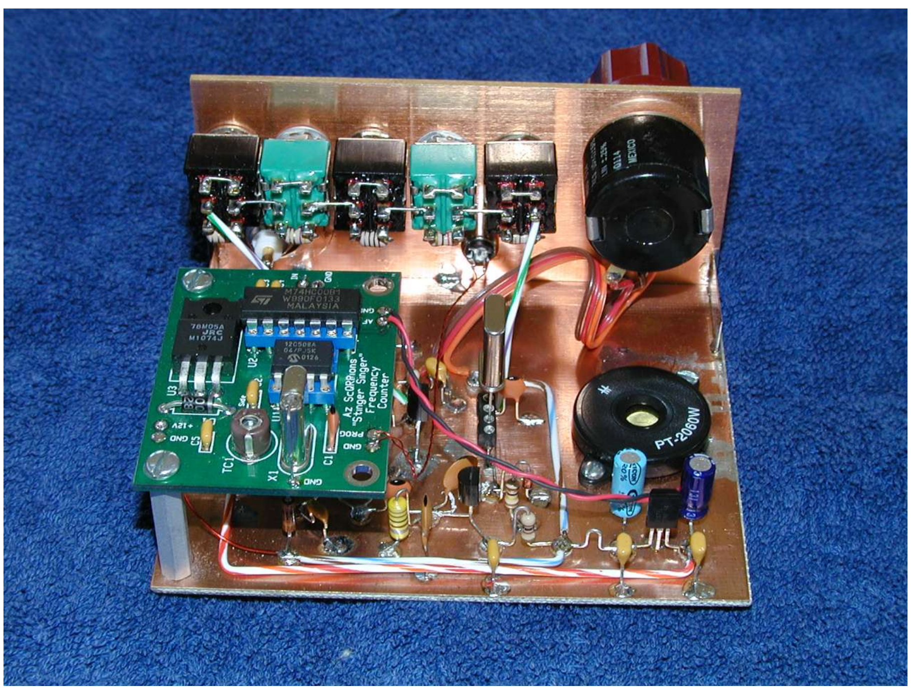

Figure 8

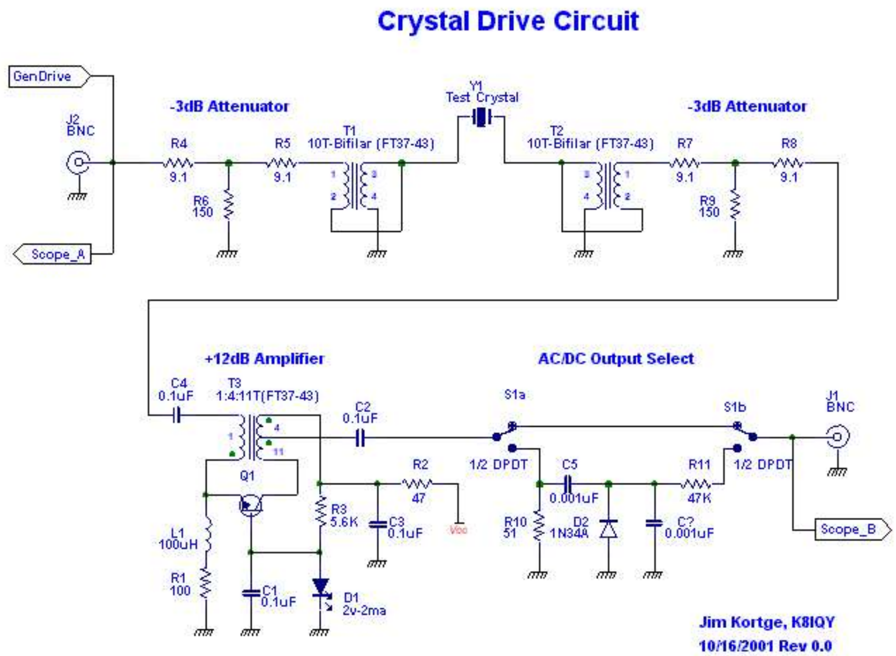

Figure 9

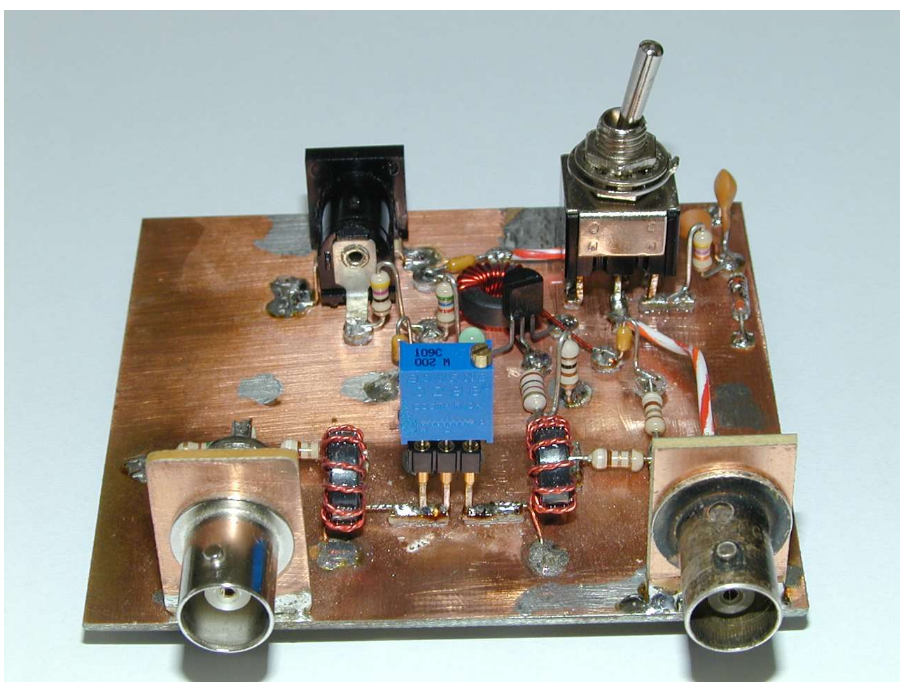

Figure 10

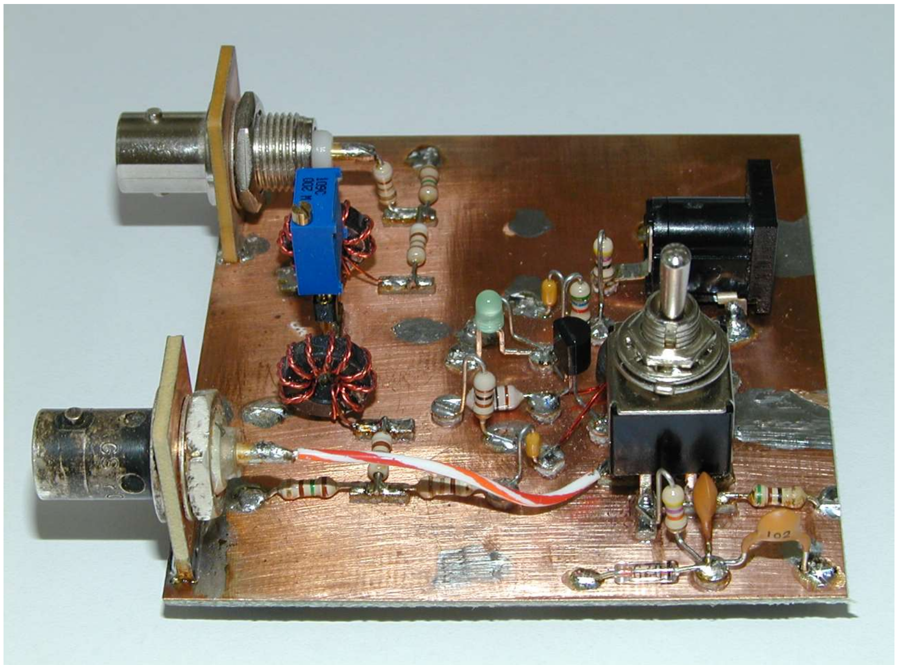

Figure 11