Comparing Quartz Crystal Measurement Methods

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Abstract: The motional parameters of a quartz crystal are determined with two test oscillators and a vector network analyzer. The results are compared, showing good correlation between methods. The simple oscillator measurements appear adequate for the design of crystal filters.

Introduction

Homebrew crystal filters were common in the early days of single sideband when the radio amateur was first beginning to experiment with the mode. The first filters were built at low frequencies (e.g., 455 kHz) where surplus crystals were available. An early paper was then published by Ben Vester, W3TLN, "Surplus-Crystal High-Frequency Filters," QST, Jan, 1959. This was one of those cornerstone QST papers for me, providing information to get me started with the construction of some functioning crystal filters. The filters that Vester presented were of the cascade half-lattice form that functioned in the HF spectrum of several MHz. Vester's paper was strictly an experimenter's guideline with no information on modeling or synthesis.

The scene changed in the late 1960s with the introduction of effective imported 9 MHz crystal filters from KVG in Germany. Other filter vendors also appeared on the scene at that time. Radio amateurs continued to build gear, but now with commercial filters. It was only when KVG discontinued their line of filters that hams became serious about building their own crystal filters. The dominant pioneer in this effort was Hardcastle from the UK. His first paper in RadCom, December 76, was adapted and reprinted in QST in December 78. He was the first (that I recall) to have presented the lower sideband ladder form of crystal filter to the amateur radio community.

My first serious efforts with crystal ladder filters (QST, 1982) were aimed at some simple methods for crystal characterization. I used these crystal models to generate some simple filters. A later paper (QST, 1987) presented a different simplification afforded by the so called minimum loss topology of Cohn, leading to filters that can be built with virtually no design effort.

All of the crystal filter efforts depend upon our knowledge of the crystals to be used in the filter. The crystal is modeled by the circuit of Fig 1.

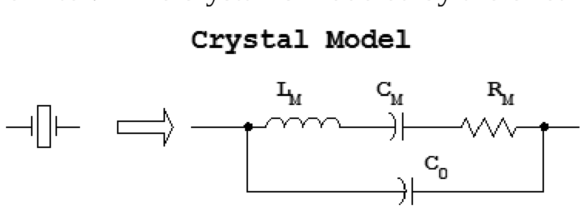

Fig 1.

The crystal is essentially a series tuned circuit consisting of a very large (compared to the discrete elements we usually associate with RF filters) motional inductor, L_M, that is resonated by a motional capacitor, C_M. A loss element is modeled as motional resistance R_M. Physically, the crystal consists of a wafer of quartz that is coated by a metal film on the two surfaces. The wafer thickness determines resonant frequency. But the structure is that of a parallel capacitance with a very low loss dielectric. This is C_0 within the model. To effectively design crystal filters, we need to know all model parameters.

Measurement Methods

There are several schemes that can be applied to determine the parameters in the model of Fig 1. The first one that I did was based upon an over simplified model for the crystal where the parallel capacitance, C_0, was ignored, shown in Fig 2.

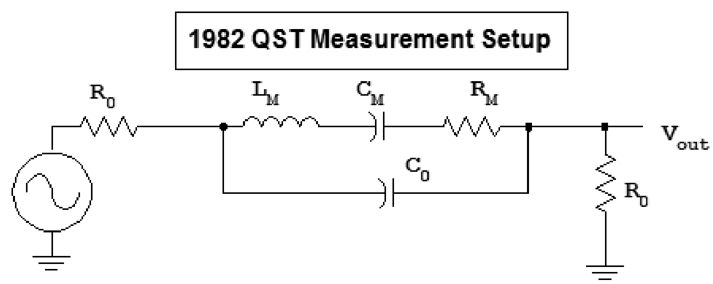

Fig 2. Scheme used for crystal measurements. C_0 was ignored during analysis after measurements.

The method depended upon two measurements. First, the insertion loss of the crystal versus that when the crystal was replaced with a “through” path was evaluated. We assumed that C_0 was zero. Hence, the insertion loss at resonance, which is where the response is largest, allows one to calculate R_M. The second measurement was realized by tuning the signal source and noting the frequency where the response was 3 dB below the peak. Knowing these, a bandwidth could be calculate, allowing a loaded Q to be evaluated. This then allowed one to calculate the motional L and C at resonance and to extract the unloaded Q and, hence, R_M.

The scheme of Fig 2 works well enough, although it requires a stable source of RF for bandwidth measurement. It is, of course, invalid to assume that $C_0=0$. The assumption does not produce major errors, especially if a transformation is done to move to system characteristic resistance, R_0, that is well below the usual 50 Ohms. C0 can be measured with an independent bridge that operates well away from any crystal resonance. The now ubiquitous AADE L/C meter works great for this determination, although care is required during meter zeroing. More will be said about this.

The methods of Fig 2 were presented in QST for May of 1982. Shortly after that paper was published, I received letters from Dr. David Gordon-Smith, G3UUR. In that correspondence, he suggested that one could infer the motional L and C from observation of the crystal operating in an oscillator. The frequency would be shifted by inserting a known capacitance in series with the crystal. The basic scheme is presented in Fig 3.

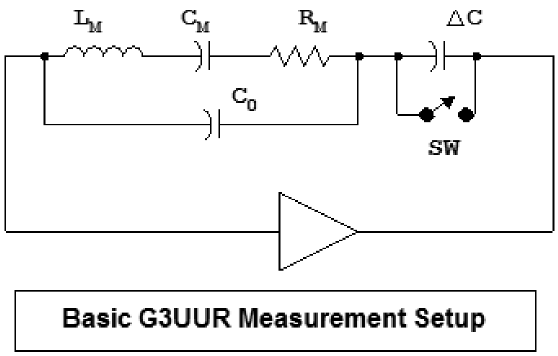

Fig 3. Oscillator scheme suggested by Gordon-Smith, G3UUR. The oscillation frequency is measured with the switch open and closed. The values for ΔC and C_0 are determined with independent measurements.

I didn't implement this suggestion for a long time, for I was able to get the data I needed from the method of Fig 2. But several years later the scheme was implemented. Two oscillator circuits were eventually used, shown in Fig 4. Biasing and grounding are omitted for clarity.

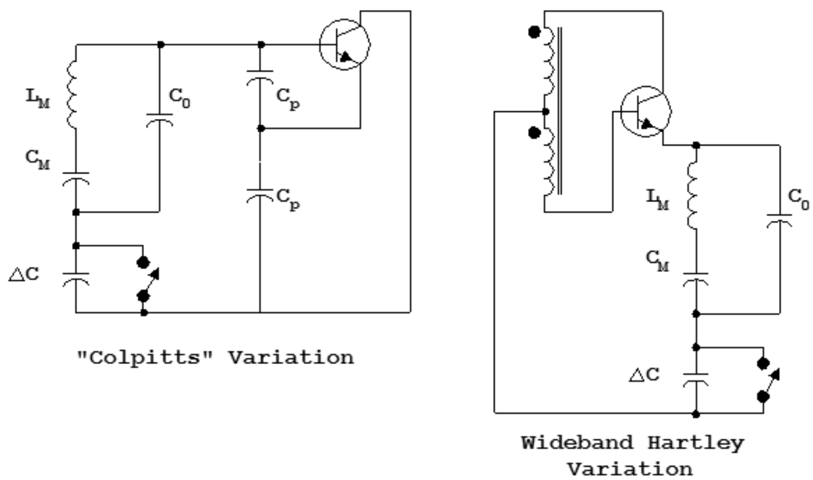

Fig 4. Two variations of the G3UUR measurement scheme. The left circuit uses a Colpitts-like oscillator. It is assumed that C_P, the Colpitts capacitors, are much larger than ΔC. The right hand variation uses a bifilar wound wideband transformer in a Hartley like circuit. It functions to lower frequencies, allowing many ceramic resonators to be evaluated. A practical variation is given in Fig X below.

The method presented in Fig 4 has been used extensively in my lab, although I always wondered just how accurate it was. Which oscillator topology is better and how do the results compare with measurements performed with a proper vector network analyzer, which is the method used for virtually all non-amateur applications? A VNA measurement is shown in Fig 5.

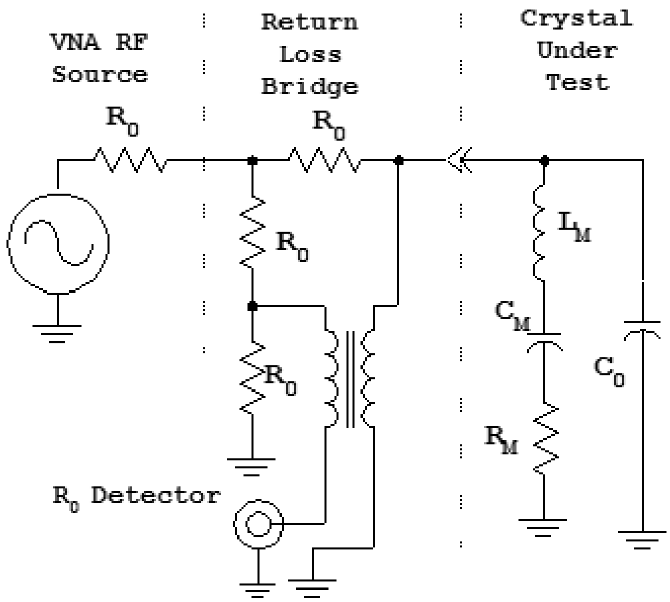

Fig 5. The ideal method for crystal characterization uses a vector network analyzer with a suitable bridge. Measurement at four known frequencies near the crystal resonances will allow the four unknown parameters to be calculated.

A Series of Experiments

VNA Measurements:

A couple of years ago I finally procured a vector network analyzer. The VNA I got is designed by Paul Kiciak, N2PK. One of the software programs with the analyzer is XTAL2.EXE. This program starts with user supplied frequencies that bracket the series and parallel resonant frequencies. The program then searches for the resonances. Once found, it does detailed measurements near the series resonance, which is the frequency where the reactance of L_M is cancelled by that of C_M. The program then supplies all four model values as well as the unloaded Q as output values.

It was time to perform this important comparison experiment. So I fired up the VNA and searched the box where I kept my calibration *standards*. A crystal was in the box with some other goodies, all left from earlier experiments. The crystal was made by FOX and was in an HC-49 can (full sized!) and was marked with a frequency of 11.0592 MHz. This rock was from a batch of 100 from a local surplus source.

The N2PK VNA is a fundamental instrument that has a RF output port with a power of about 0 dBm available and a detector port. A computer controls the instrument, saves measurement data, and performs calculations as needed. A measurement is almost always preceded by a calibration. In this case, an OSL (open, short, load) calibration is used with the return loss bridge. The bridge is a homebrew unit in need of further characterization.   I ask that the program do 10 measurements for each one indicated, which allows some averaging of data.

VNA Results:

F-series = 11.0594411 MHz
F-par = 11.0826015 MHz
C_0=4.53 pF
L_M = 0.01089184 H
C_M = 19.016041 fF
R_M = 7.43 Ohms
Q_u = 101850

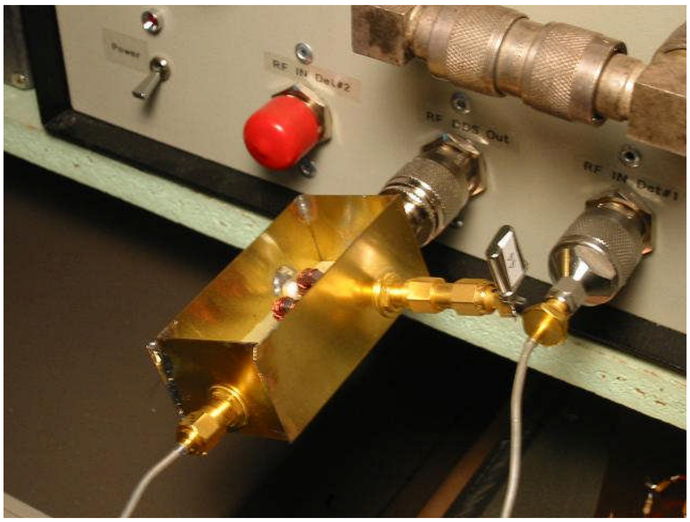

Fig 6. Crystal being measured with the VNA.   The crystal leads are soldered to a SMA connector.

Parallel Capacitance Measurements

The next crystal measurements will use oscillators.   These require independent determination of the parallel capacitance, which is nicely done with an AADE L/C meter. Also, the oscillator measurements will require that the crystal leads be exposed to fit in my oscillators.   Hence, I wanted to measure C_0 before the SMA connector would be removed from the crystal.   This turned out to be interesting and I thought it was worthy of further comment.

I started by turning on the AADE meter, switching to C and pushing the zero button. This eliminated the residual reading of almost 3 pF, producing 0 on the scale.   I then attached the small clips to the wires on the crystal.   This produced an inflated value of 5.6 pF.   The alligator clips on the wire ends were much closer than they had been during calibration.   I rearranged the wires so the clips had a lower C overlap during the zero process with closer spacing.   This is shown in Fig 7.

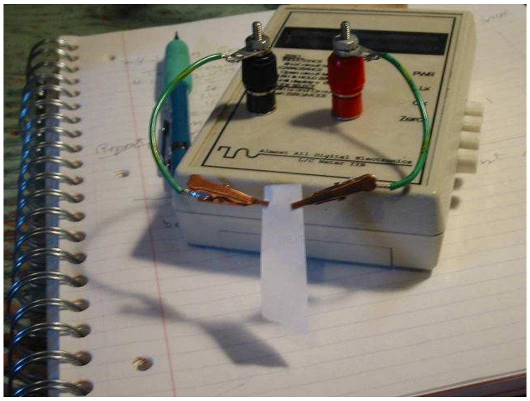

Fig 7. Test clip leads arranged "end to end" and clipped to a strip of paper for zeroing.

The clip leads were then attached to the crystal for a measurement result of 5.17 pF, shown in Fig 8 below. This is still higher than the VNA measurement, but the clips are closer to each other than they were with the zero operation.   Clearly, this is a place where exacting, indeed *retentive* measurement practices could be useful

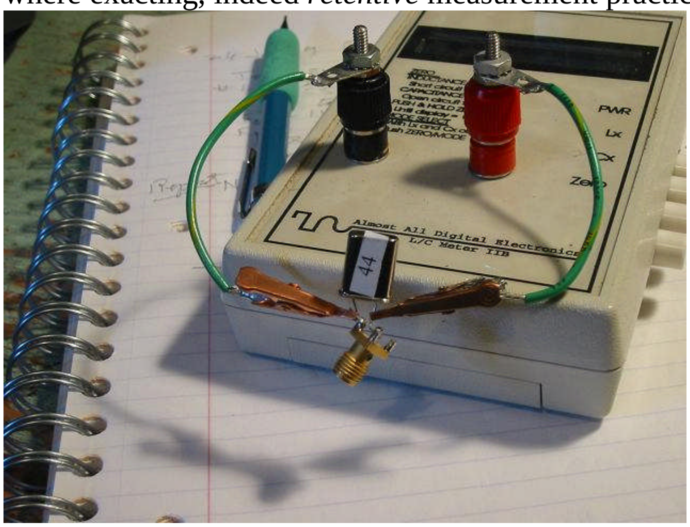

Fig 8.   Measurement of C_0 with the AADE L/C meter.

Following the measurement shown in Fig 8, the crystal was unsoldered from the SMA connector and measured, producing a result of 4.11 pF.   This is the value we will use for later calculations, although this is probably low owing to strays.   Our VNA calibration standards are all on SMA connectors.

Measurements with the Wideband Hartley Oscillator.

The next step in the process was to measure the motional parameters with the oscillators. My test oscillator was initially configured with the Wideband Hartley circuit.   The two circuits are show in Fig 9 below.

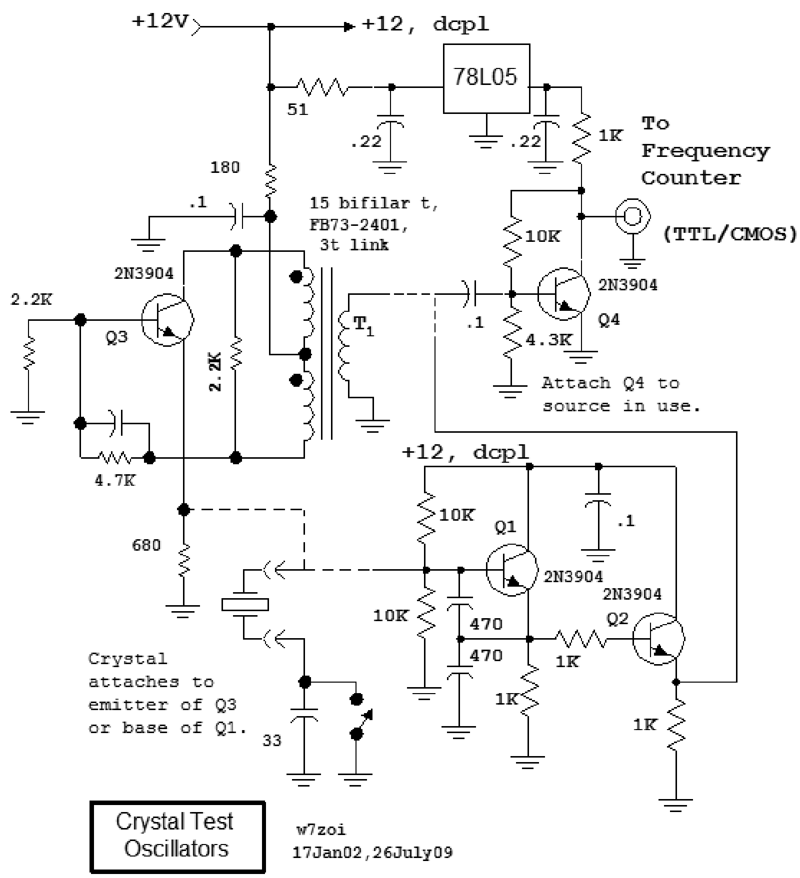

Fig 9. Two forms of the test oscillator are built into one box. Only one is functional at a time. The unused oscillator is disconnected from the crystal socket and the output is disconnected from Q3, which is an analog to TTL converter needed for my Radio Shack frequency counter in the highest resolution mode. ΔC = 36.9 pF, which results from a 33 pF capacitor and the capacitance of the open switch.

The lower frequency was11.057796 MHz while the upper value was 11.060615 MHz. Note that the lower value is below the series resonance measured with the VNA. (Corrections have been applied to account for slight frequency offsets between instrument clocks.) The frequency difference is 2819 Hz. From this we calculate that the motional inductance is 0.0099089 H. This is below the VNA result by 9%.

Measurements with the Colpitts Oscillator.

The Hartley variation was disconnected and the Colpitts circuit was connected to the crystal socket and switch and counter buffer. The circuit was built with C_P=470 pF. The two oscillation frequencies were 11.059474 and 11.062005 MHz. The lower is now above the series resonance measured with the VNA. The frequency difference is 2531 Hz, resulting in L_M=11.0385 mH, which is above the VNA result by 1.3 %.

The expression used to calculate motional capacitance for both of the above oscillator measurements is

$$C_m = 2 \cdot (C_s + C_0) \cdot \frac{\Delta F}{F}$$

This is the corrected expression presented on line. (w7zoi.net and click on EMRFD errata.) C_S is the switched capacitance in pF. C_M and C_0 are also in pF. L_M is then calculated from resonance. L_M and C_M are not independent, but are linked to each other through resonance.

Measurement of Q

An independent measurement is required to determine Q. The scheme that I used is that from EMRFD, Chapter 7. The crystal is attached as a shunt element in a 50 Ohm system, shown in Figures 10 and 11 below. At resonance, the attenuation was 13.5 dB for this crystal. The result was Q_u=114490 using Eq. 7.6 from EMRFD.

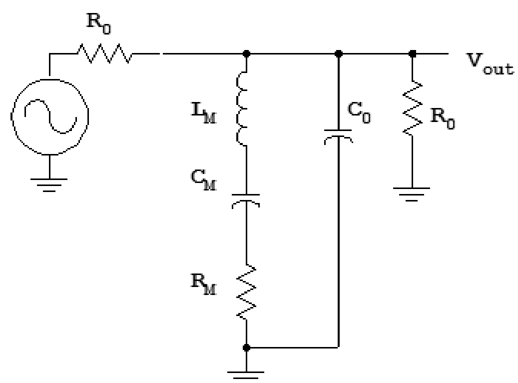

Fig 10. Method used for Q measurement.

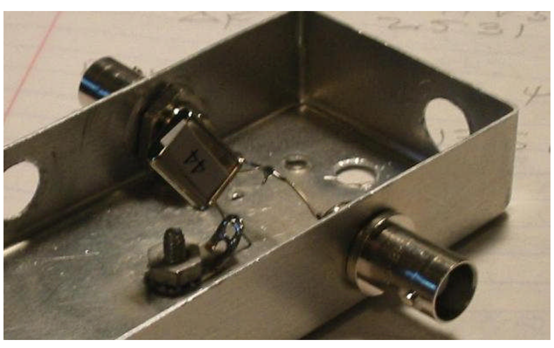

Fig 11. Test fixture used to measure crystal Q.

An extremely interesting, but subtle detail emerged with the later measurements. The Q of some crystals was compromised by as much as a factor of two by excessive power. Better results were obtained with a power applied to the bridge of -14 dBm or less. I encountered this phenomenon in the past in connection with crystal filters used in commercial spectrum analyzers.

Some More Data

Having measured just one crystal in detail left questions. What would the Colpitts oscillator do at other frequencies? Three additional crystals were resurrected from the junk box and were measured with the VNA and with the Colpitts characterization oscillator. The following results were obtained:

Freq.	xtal #	L_M (VNA)	L_M(osc wrt VNA)	Q(VNA)
4.000 MHz,	7	0.13834 H	+1.0 %	180K
5.000	624	0.09936	+10.3%	116K
10.00	393	0.01901	-1.3%	223K
5.000	446	0.098467	+8.2%	147K
5.000	107	0.102118	+2.7%	139K
6.002	1	.065648	+1%	247K

Conclusions and Extensions

The vector network analyzer is the preferred instrument for crystal characterization. However, it is slow and missing from the measurement arsenal for most amateur experimenters. The correlation between the VNA and the oscillator is very encouraging, suggesting that oscillator measurements are good enough.

Chris Trask has built a crystal characterization oscillator based upon the Butler topology. His circuit isolates the crystal from reactive circuit elements and should be ideal for L_M determination. This design is found on his web site, http://www.home.earthlink.net/~christrask/Crystal%20Test%20Set.pdf.

The May 1982 QST paper put a lot of emphasis on measuring crystal Q. I now feel that this is less important, at least for crystal filter applications. It is useful to sample a small fraction of the crystals within a batch (10% is usually enough) to be sure that the typical Q_u exceeds a reasonable minimum. If the desired filter is a very narrow one and is to be built with poor quality crystals, it may be necessary to test all units before use. It is not as critical with wider filters. As an example, I built an 8^{th} order SSB filter at 11 MHz with a bandwidth of 2 kHz. Crystals from the same batch used for this study were used. Simulation (with GPLA) suggested an insertion loss of about 3.3 dB with Qu=100K for the crystals. The filter was built and measured, yielding a bandwidth within a few percent of the design value and an insertion loss under 4 dB. An 8 crystal CW filter would, however, be stressed with these parts. Simulations with a typical value for Qu usually provides enough information. The 8^{th} order SSB crystal filter is shown in Fig 12 with a schematic in Fig 13 and measured response in Fig 14.

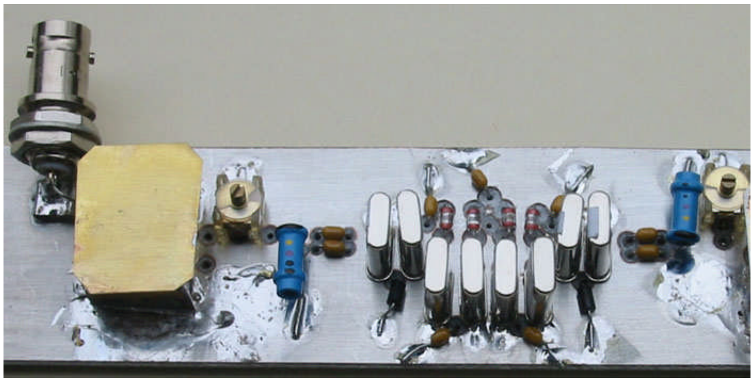

Fig 12, 8th order filter. Shielding of terminating transformers improved stopband attenuation.

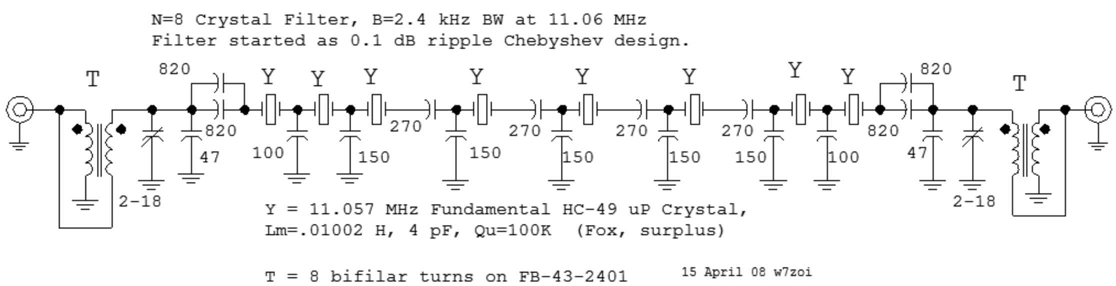

Fig 13. Schematic for crystal filter of Fig 12.

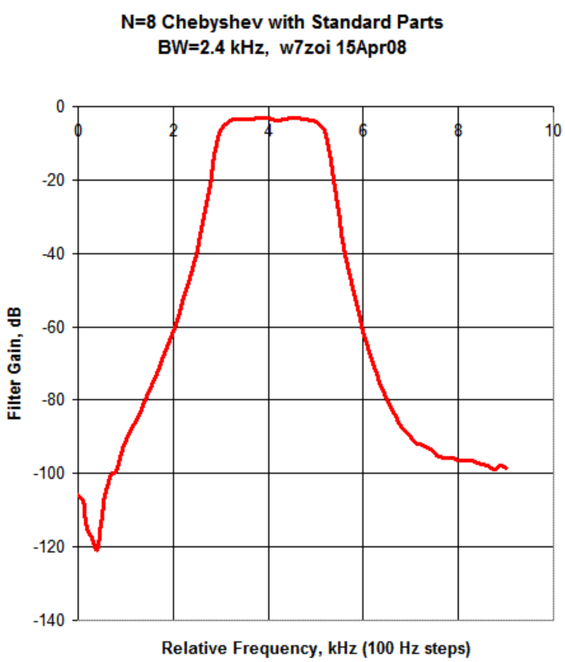

Fig 14. Measured frequency response for the 11.06 MHz crystal filter of Fig 12.