Crystal Filter Design and Construction

1 Crystal Filter Design

A wide variety of crystals are produced for use with microprocessors and other digital integrated circuits. They are offered in several case styles, but the most common are HC-49/U and HC-49/US. Crystal resonators in the larger HC-49/U style case are fabricated on 8 mm diameter quartz discs, whereas those in the squat HC-49/US cases are fabricated on 8 mm by 2 mm strips of quartz. At any given frequency, C_m will be lower for HC-49/US crystals because the active area is smaller than it is in the larger HC-49/U crystals. Both types are cheap and have relatively small frequency spreads, making them ideal for use in the LSB ladder conFigureuration suggested by Dishal (Ref 1) — see **Figure 1**. This arrangement requires the motional inductances of all the crystals to be identical, and each loop in isolation (crystal and coupling capacitors either side) to be resonant at the same frequency. Series capacitors to trim individual crystals are needed to achieve this in some of the more advanced designs, where production frequency spreads are not sufficient to satisfy the latter requirement. Refs 2, 3, 4, 5, 6, 7, and 8 contain design information on Dishal LSB crystal ladder filters. Design software associated with Ref 8 (**11x09_Steder-Hardcastle.zip**) can also be downloaded from **www.arrl.org/qexfiles**.

The *min-loss* form of Cohn ladder filter, where $C_{12} = C_{23} = C_{34}$, has become very popular in recent years because it's so simple to design and build. However, it suffers from the drawback that the ripple in its passband response increases dramatically with increasing order, and ringing can be a real problem at bandwidths below 500Hz for Cohn *min-loss* filters of 6th-order, or more. The ripple may not be a problem in most narrow filters because it's smoothed out almost completely by loss, but the ringing can be tiring. For wider bandwidths, where the ratio of Q_u to f_o/BW is much greater, the ripple is not smoothed out, and is very evident. One way round this problem, without sacrificing simplicity, is to use the arrangement shown in **Figure 2**, which was originally designed for variable bandwidth applications. It was

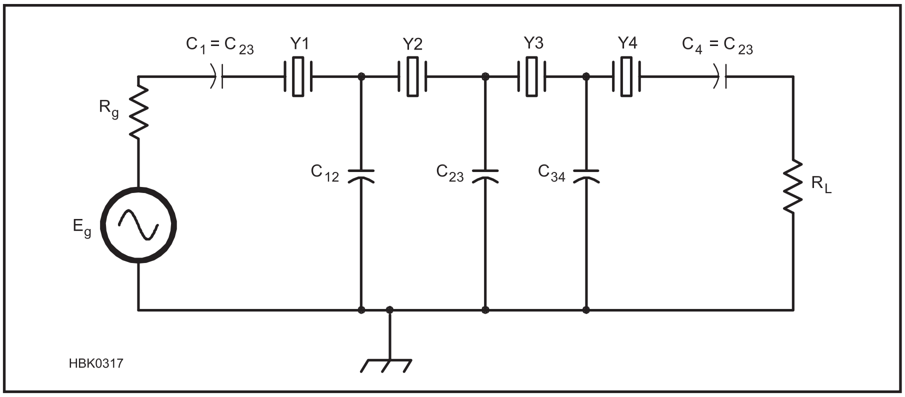
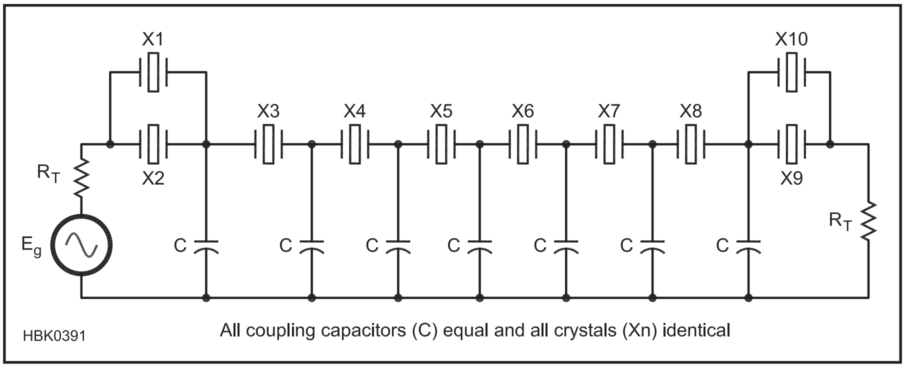


Figure 1 — Dishal LSB crystal-ladder filter conFigureuration. Crystals must have identical motional inductances, and the coupling capacitors and termination resistors are selected according to the bandwidth and type of passband response required.



All coupling capacitors (C) equal and all crystals (Xn) identical

Figure 2 — ConFigureuration of improved crystal ladder filter using identical crystals and equal coupling capacitor values. The parallel resonator end-sections (PRES) can provide excellent passband responses, giving either quasi-equiripple (QER) or minimum-loss (PRESML) responses with just a change in termination resistance.

Table 1
3 dB-down k & q Values for Quasi-Equiripple (QER) Ladder Filters

Order	*q*	k_{12}	k_{23}	*Shape Factor*	*Max Ripple (dB)*
4	0.9942	0.7660	0.5417	4.56	0.002
5	1.0316	0.7625	0.5391	3.02	0.018
6	1.0808	0.7560	0.5346	2.31	0.09
7	1.1876	0.7459	0.5275	1.90	0.16
8	1.2532	0.7394	0.5228	1.66	0.31
9	1.3439	0.7335	0.5187	1.50	0.42
10	1.4115	0.7294	0.5158	1.40	0.60
11	1.4955	0.7261	0.5134	1.33	0.72
12	1.5506	0.7235	0.5116	1.28	0.90

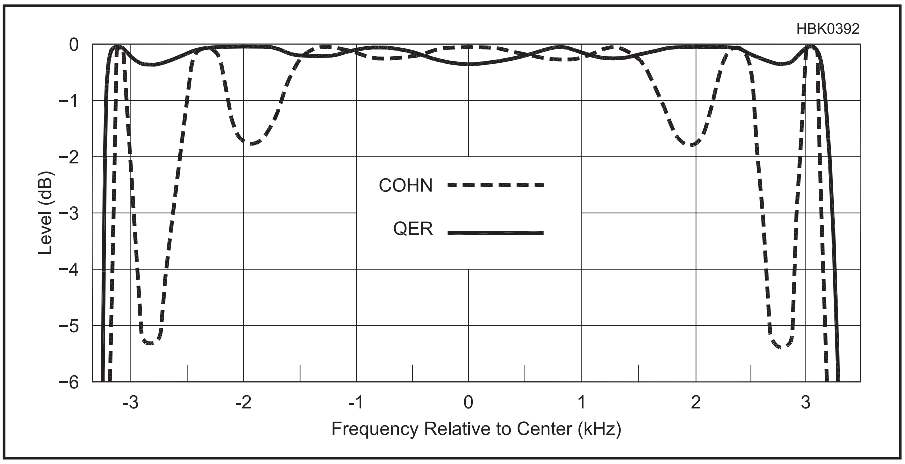


Figure 3 — Comparison of 8-pole Cohn min-loss passband response with that of the quasi-equiripple (QER) type. Note the almost equal ripple in the passband of the QER response.

devised to make the mesh frequencies track together as variable coupling changed the bandwidth. However, it has the great advantage that it can be optimized for almost equal ripple at maximum bandwidth, making it an ideal alternative for fixed bandwidth speech applications where the Cohn *min-loss* pass band is poor. Two crystals are used in parallel to halve the motional inductance and double the motional capacitance of the resonators in the end sections**,** and although the two additional crystals do not increase the order of the filter by two, they do reduce the passband ripple substantially while maintaining the simplicity of design and construction offered by the Cohn *min-loss* filter. In addition, the group delay of the parallel-resonator-end-section (PRES) conFigureuration is less than that of the Cohn *min-loss*. All the coupling capacitors are equal and the filter can be terminated to achieve a quasi-equiripple response (QER), so that its pass band resembles that of a Chebyshev design, or minimum loss (PRESML) with a response like that of the Cohn *min-loss*. **Figure 3** shows the Cohn *min-loss* and QER passband responses with infinite crystal Q_u for comparison. Values of k and q for QER filters from 4 to 12 poles are given in **Table 1,** along with the maximum ripple and shape factor for each order. The coupling capacitor value for any bandwidth can be determined from k_{23} using Eq 1 below. The end-section resonators formed by the two parallel crystals have twice the effective motional capacitance of the inner resonators, and since k_{12} is always 1.414 times k_{23} for the QER design the value of C_{12} will be the same as that calculated for C_{23} and all the other coupling capacitors, C, in the design.

$$C = f_o C_m/(BW\ k_{23}) \qquad (1)$$

The termination resistance, R_T, must be calculated using half the motional inductance of a single crystal, as illustrated in Eq 2, where L_m is the motional inductance of one of the parallel crystals used in the end-sections.

$$R_T = 2 \pi\ BW\ L_m/2q = \pi\ BW\ L_m/q \qquad (2)$$

An alternative way of producing a QER filter, which has the added benefit of improving the symmetry of the ladder filter response, is to add transformers with bifilar windings to each end of the filter so that the end sections are effectively like crystal gate filters with C_1 approximately equal to $2C_o$. Normally, Dishal LSB ladder filters have an asymmetrical response because each crystal produces a transmission zero at f_p, on the high side of the filter pass band This asymmetry can be counteracted to a certain extent if the value of C_1 in each end section is adjusted to over-compensate for C_o and produce nulls on the low side of the pass band to even up the overall response. Whereas the presence of C_o causes the motional inductance of crystals to increase and their motional capacitance to decrease throughout the pass band, over compensating the end crystals to produce nulls on the low side has the opposite effect and the end-section crystals appear as if their motional capacitance is higher and their motional inductance lower, like two crystals in parallel. Therefore, they can be made to produce the QER type of response with suitable coupling and terminations. Ref 9 provides more information on this topic.

2 Crystal Characterization

Simple crystal filters can be constructed using cut-and-try methods, but sometimes the results are very disappointing. The only sure way to guarantee good results is to fully characterize the crystals beforehand, so that only the most suitable ones are used in a design appropriate for the crystal motional parameters and the application. When crystal parameters are known, computer modeling can be used to assess the effect of Q_u and C_o on bandwidth, before proceeding to the construction phase. In addition to the *Elsie* design program available with the *ARRL Handbook* online supplemental content, AADE Filter Design and Analysis (**www.aade.com**) provides a free filter modeling program.

Crystal characterization can be done with very limited or very advanced test equipment, the main difference being the accuracy of the results. The *phase-zero* method for measuring C_m used in industry can be implemented by amateurs if a dual-beam oscilloscope is available to substitute as a phase detector — Ref 6 gives details of this method. However, many successful crystal filter constructors have achieved excellent results with a very limited amount of home-built test equipment. Ref 5 describes a simple switched-capacitor test oscillator for measuring C_m that was developed by G3UUR. His technique requires a frequency counter, a small 12 V power supply and very little construction effort. Using care and a more exact expression for C_m than the one given in Ref 5, this oscillator method can achieve results that are comparable with professional techniques. The circuit can also be modified to include relative Q or ESR measurement if a multimeter is available.

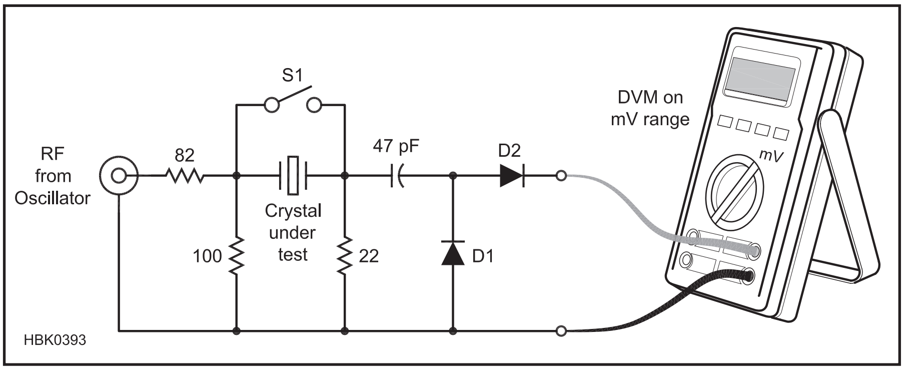


Figure 4 — A simple jig for measuring crystal ESR. The jig may be driven by a signal generator, or a modified crystal test oscillator, and the signal through the crystal detected on a DMM using the mV dc range. Resistors are ⅛ or ¼ W, 5%. D1 and D2 are small signal germanium or Schottky barrier diodes. S1 is a miniature pushbutton switch.

Values of Q_u for crystals can vary considerably, even within the same batch, and the ratio of the best to the worst, excluding dead ones, can be as high as 6 for cheap mass-produced crystals. This ratio can still be more than 2 for batches of high quality crystals. The relative activity of each crystal needs to be established to weed out the poor ones, and an estimate for Q_u is required to more accurately model the filter performance prior to construction. A modified version of the switched-capacitor crystal test oscillator is shown in **Figure 4**. The RF detector circuit at the output of the oscillator provides a means of assessing the relative activity of each crystal being tested. A DMM on a suitable dc voltage range attached across points M and G (ground) will give a digital readout roughly equal to the peak-to-peak RF voltage produced by each crystal. Crystals with higher Q values will produce higher output voltages, so each crystal can be ranked according to its output reading relative to others in the batch. For convenience, a socket should be used for the crystal under test. If crystals with wire leads are to be measured, this can be fashioned from a dual-in-line IC or transistor socket. There are also small PCB connectors that might make suitable sockets.

The formula for C_m presented in Ref 5 is much simplified and less accurate than the exact derivation for C_m. Better accuracy can be achieved with Eq 3, where F_1 is the frequency obtained with S1 closed and F_2 is the one with S1 open.

$$C_m = 2\ (F_2 - F_1)\ [C_S + C_O + C_R]/F_1 \qquad (3)$$

All capacitances in this equation are in pF and the frequencies in Hz. $C_R = 4C_S\ C_o/C_F$ and C_o is the total parallel capacitance of the crystal, including the contribution from the metal case — it's assumed that the metal case is floating during these measurements and is not grounded, or being held. The feedback capacitors, C_F, are 390 pF in **Figure 5** and the series capacitor, C_S, is 68 pF. C_o typically varies from 2.5 to 5.5 pF for HC49/U crystals in the 4 to 12 MHz range and about 1.5 to 3.5 pF for the smaller HC49/US crystals. LC meters that can measure down to 0.01 pF and 1 nH can be constructed using PIC technology. Commercial LC meters with amazingly good specifications are also available at moderate prices if a PIC LC meter seems too ambitious a project for home construction at this stage. Obviously, great care must be exercised to avoid stray capacitance and errors in setting

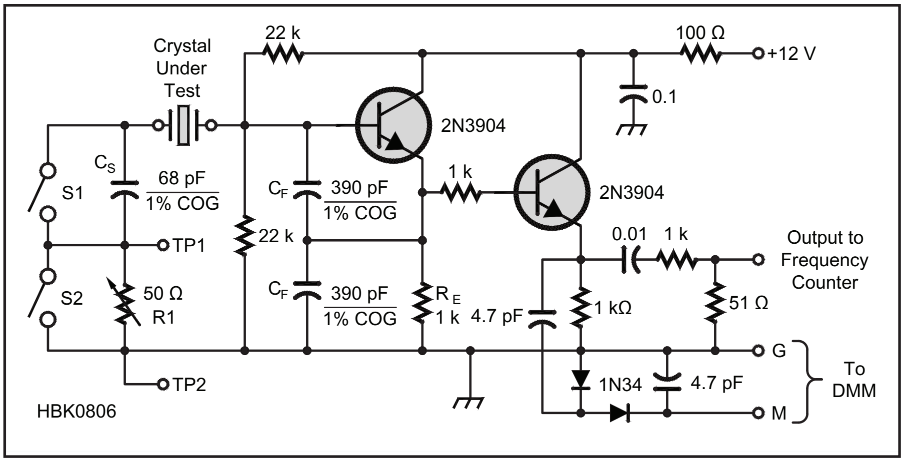


Figure 5 — Circuit of a modified switched-capacitor test oscillator which can be used to measure crystal motional parameters C_m and r_m.

zero when measuring such small values of capacitance.

When the value of C_o cannot be determined easily, or the utmost accuracy is not required, a simplified version of Eq 3 may be used. An average value for the type of crystals being tested can be assigned to C_o at the expense of a few percentage points loss in accuracy. For HC49/U crystals, a reasonable average for C_o is 3.75 pF and using the values for C_F and C_S shown in Figure 5, the more exact expression simplifies to Eq 4.

$$C_m = 148\ (F_2 - F_1)/F_1 \qquad (4)$$

Again, F_1 is the frequency registered on the counter when S1 is closed and F_2 when it's open. Both frequencies are in Hz and C_m comes out in pF. If more accuracy is required, the value of C_m obtained with Eq 4 can be used to estimate C_o from Eq 5 and that value used in Eq 5 to achieve a closer estimate for C_m.

$$C_o = 175\ C_m + 0.95 \qquad (5)$$

Also, the series-resonant frequency f_S for each crystal can be estimated by calculating the amount by which F_1 is higher than f_s and then subtracting that from F_1. This frequency difference, ΔF_1, is given by Eq 6 for the value of C_F used in Figure 5.

$$\Delta F_1 = C_m\ F_1/400 \qquad (6)$$

Ranking crystals according to their oscillator output is sufficient to be able to select the best (highest Q) crystals for a filter, but if you want to use computer modeling to correct for the influence of loss on bandwidth, then an estimate of ESR or Q_u is necessary. This can be done quite simply with the test oscillator shown in Figure 5, but requires just a little more time and effort than just ranking relative Q by RF output. There will be a spread of output levels corresponding to the range of Q values. Pair up two crystals from the low end of the spread with similar output Figures (within 5%) and reasonably closely matched frequencies (within 50 Hz). Pair up another couple of crystals from the high end. Connect each pair of similar crystals in parallel and place them in the test oscillator a pair at a time with S_1 and S_2 closed. The output level should be much higher using a parallel pair than for each crystal alone. Now open S_2 and adjust the variable resistor VR1 until an output level is reached that is equal to the average of the levels previously obtained with the two crystals individually. After removing each pair check the resistance of VR1 using your DMM. Test points TP1 and TP2 are provided for such measurements and should be feed-through types mounted on the front panel or side of the oscillator box. The ESR value of the two similar crystals in the pair is approximately twice the value of the resistance measured across the test points. This method may be very crude, but it will give you an ESR value that is certainly better than 20%, and probably within 10% of the value measured by more accurate means. Once ESR values for the crystals at the extremes of the spread are established, one can be done in the middle of the range for good measure and values roughly assigned to those in between. Then, an average of the motional parameters and Q values of the set of crystals chosen for a particular filter can be used for modeling purposes.

Should a more accurate means of measuring crystal ESR be required, the phase-zero method or a VNA should be considered. Whatever the means of crystals characterization, a spreadsheet to record the data should be prepared beforehand and some means of marking the crystals with a number or letter organized. Sticky white dot labels are probably the most convenient way to identify each crystal. They adhere well to metal surfaces and can be written on with a ball-point pen. Alternatively, a permanent marker pen directly on the metal case could be tried, but is sometimes not all that permanent.

Measuring Crystal Parameters

The following sidebar is an overview of the Jan/Feb 2016 *QEX* article "Crystal Parameter Measurements Simplified" by Chuck Adams, K7QO. The complete article is available as a PDF file with the ARRL Handbook Supplemental online content.

This section describes a simple workbench technique developed by K7QO to characterize the electrical parameters of individual crystals. The parameters are discussed elsewhere in this section. (See also the section "Crystal Oscillators" in the Oscillators and Synthesizers chapter.) In addition to the test fixture, the procedure requires a digital RF signal generator, a frequency counter, an accurate L/C meter, and an RF voltmeter or RF probe used with a voltmeter.

The electrical equivalent circuit for a quartz crystal is shown in **Figure A**. A test capacitor with a known value, C_X, is added in series with the crystal to shift the crystal's resonant frequency. By measuring the crystal with and without the effects of C_X, values for L_m, R_m, C_m, and C_0 can be determined.

In order to make the measurements reliably and to minimize the effects of stray capacitance and inductance a simple test fixture is used. The schematic of the test fixture is shown in **Figure B**. The input and output impedance of the fixture is close to 50 Ω, but is not critical. R2 and R3 are small to reduce the loaded Q of the crystal. The resonant frequency of the crystal is not affected by the resistor values. Small values for R2 and R3 narrow the resonant peak and minimize the effects of stray capacitance. **Figure C** is a photo of the test fixture being used.

The crystal is installed in the test fixture and measurements (described completely in the PDF article) are made with C_X both in-circuit and shorted by the jumper, JMP. From the shift in resonant frequency and amplitude described in the full article, all four primary crystal parameters can be obtained. In the PDF article, K7QO also describes a simple method of using a Colpitts crystal oscillator to find closely matched crystals in a batch.

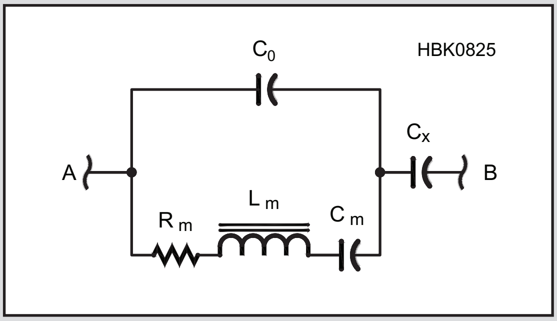


Figure A — This schematic shows the equivalent circuit for a crystal in series with the test capacitor,

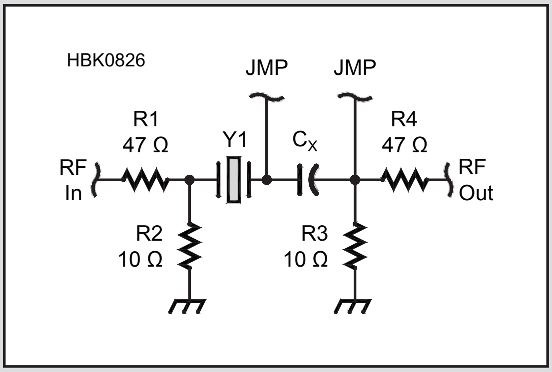


Figure B — The schematic diagram for the K7QO test fixture. Note that R1 = R4 and R2 = R3. Y1 is the crystal being tested and C_X is the test capacitance added to shift the crystal's resonant frequency. K7QO uses a 47 pF capacitor for C_X. JMP represents a jumper to short-circuit C_X.

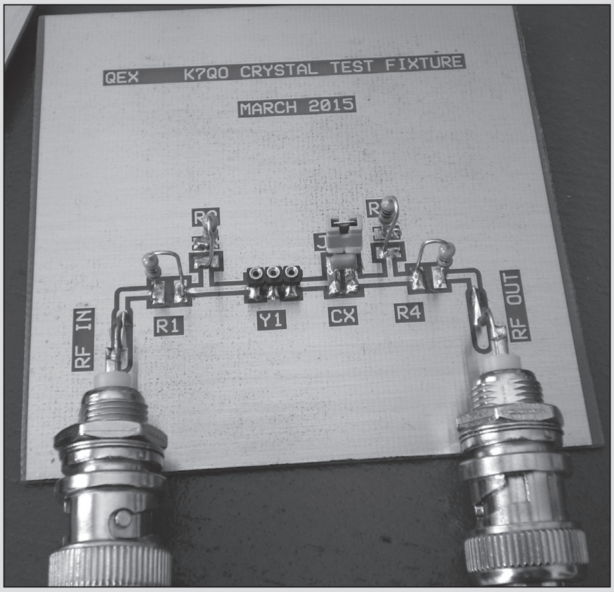


Figure C — The finished crystal test fixture. The center pin of the crystal socket is grounded to reduce the effects of the parasitic capacitance of the socket which is in parallel with the crystal's C_0.

3 Building a Crystal Ladder Filter for SSB Use

One of the great advantages of building your own crystal filter is the wide choice of crystal frequencies currently available. This allows the filter's center frequency to be chosen to fit more conveniently between adjacent amateur bands than those commercially available on 9 and 10.7 MHz do.

The 8.5 MHz series crystals used in this project were chosen in preference to ones on 9 MHz to balance the post-mixer filtering requirements on the 30 and 40 meter bands, and reduce the spurious emission caused by the second harmonic of the IF when operating on the 17 meter band. The crystals have the equivalent circuit shown in **Figure 6** and were obtained from Digi-Key (part number X418-ND).

The crystal-to-case capacitance becomes part of the coupling capacitance when the case is grounded, as it should be for best ultimate attenuation. The motional capacitance and inductance can vary by as much as ±5% from crystal to crystal, although the resonant frequency only varies by ±30 ppm. The ESR (equivalent series resistance) exhibits the most variation with mass-produced crystals, and in the case of these 8.5 MHz crystals can be anything from under 25 Ω to over 125 Ω.

Since the frequency variation has a spread of more than twice what can be tolerated in a 2.4 kHz SSB filter design, and the ESR is so variable, individual crystals need to be checked and selected for frequency matching and ESR. In order to allow plenty for selection, 30 crystals were purchased for the prototype. A frequency counter capable of making measurements with 10 Hz resolution, a DMM with a dc mV range and two simple self-constructed test circuits are required for crystal selection.

The project filter shown in **Figure 7** is based on a 7-pole QER (quasi-equiripple) design that has a shape factor of 1.96 and offers simplicity, flexibility, and a great passband. The 39 pF coupling capacitors can be silver mica or low-k disc ceramic types with a tolerance of ±2%. The termination resistance shown in the diagram has been reduced to allow for the loss in the end crystals (roughly 36 Ω for each parallel pair). The total termination resistance should be 335 Ω, theoretically, and the actual value used should be adjusted to reflect the effective ESR of your end pairs.

If more than nine suitable crystals are available from the batch tested, the order of the filter can be increased without changing the value of the coupling capacitors. The bandwidth will change very little — by less than +1% per unit increment in order. The termination resistance will need to be reduced as the order is increased, however, by the ratio of the q1 values given in Table 1. Increasing the order will improve the shape factor and further reduce adjacent channel interference, but also increase the passband ripple.

Effectively, each crystal in the middle section of the filter has a load of around 20.25 pF because of the 39 pF capacitors and 1.5 pF crystal-to-case capacitance on either side. The end crystal pairs are also shifted up in frequency as if they have the same load. Therefore, for best matching, all crystals should be checked in an oscillator with this load capacitance. The oscillator for this test is shown in **Figure 8**, and it will be seen that it shares many common parts with the VXO circuit used for ESR measurements shown in Figure 5. The 22 pF input capacitor and two 470 pF feedback capacitors in series present about 20 pF to the crystal under test. A transistor socket can be used as a quick means of connecting the crystals in circuit, rather than soldering and de-soldering each one in turn. If test crystals are soldered, adequate time should be allowed for them to cool so that their frequency stabilizes before a reading is taken.

The crystals need to be numbered in sequence with a permanent marker to identify them, and their 20 pF load frequencies recorded in a table or spreadsheet as they are measured. When this is complete, the oscillator can then be converted to a VXO, as shown in Figure 5, and using this and the jig in Figure 4 the ESR of each crystal can be assessed by comparison with metal or carbon film resistors that give the same output readings on the DMM.

The variable capacitor used in the VXO to check the crystals for the prototype filter was

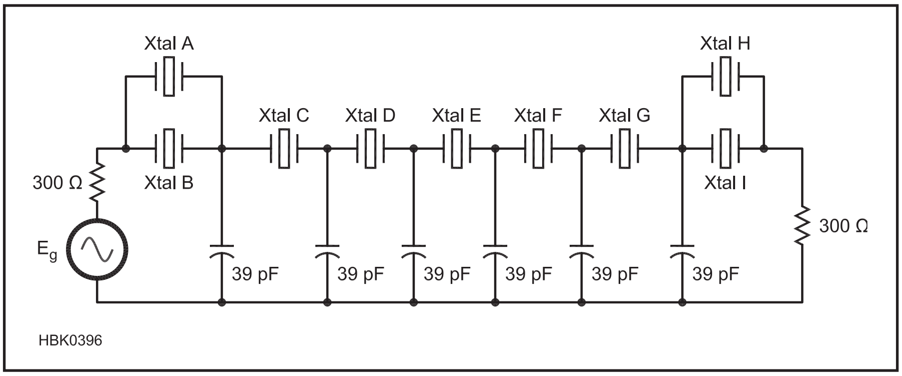


Figure 7 — 7-Pole 2.4 kHz QER ladder filter using ECS 8.5 MHz crystals (ECS-85-S-4) from Digi-Key (X418-ND).

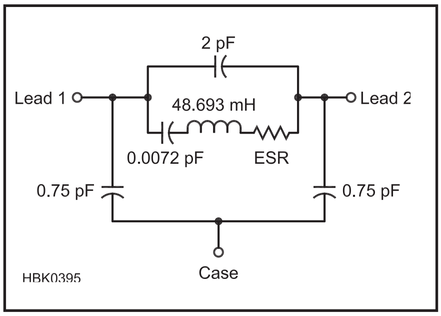


Figure 6 — Real electrical equivalent circuit of an ECS 8.5 MHz crystal with its metal case grounded.

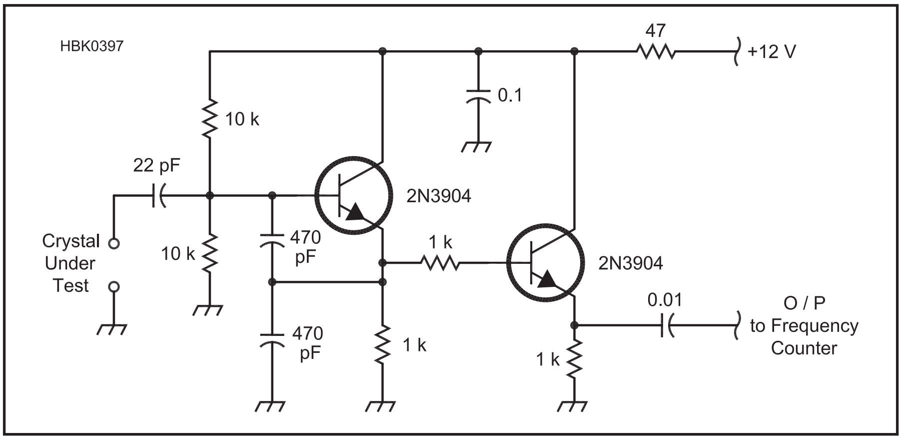


Figure 8 — Test oscillator with 20 pF capacitive load for matching crystal frequencies.

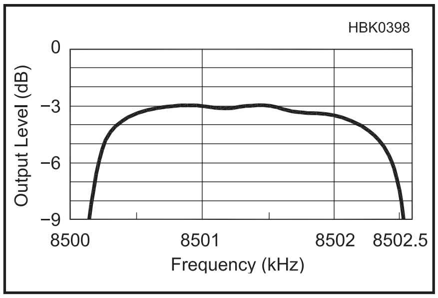


Figure 9 — Passband response of prototype 8.5 MHz QER crystal ladder filter with 3 dB insertion loss.

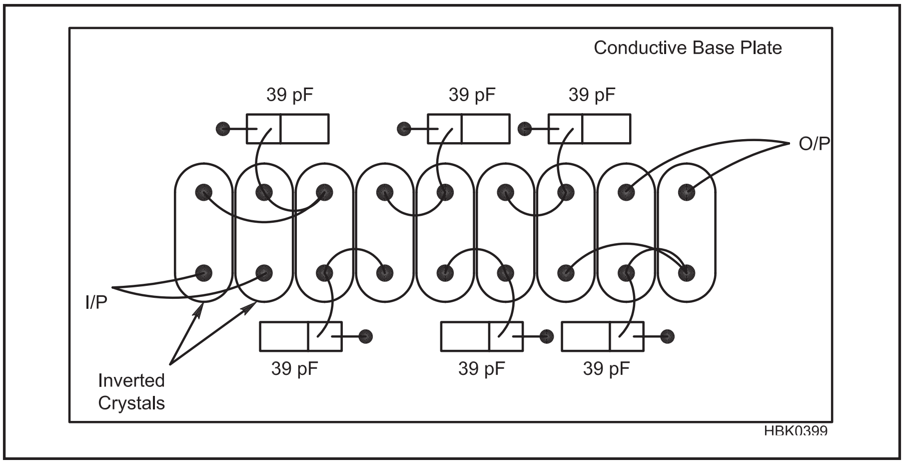


Figure 10 — Suggested construction arrangement using inverted crystals with their cases soldered to a conductive base plate and direct point-to-point wiring using only component leads.

a polyvaricon type with maximum capacitance of 262 pF and the inductor was a 10 µH miniature RF choke. If smaller values of variable capacitor are used the inductor value will need to be increased in order to ensure the frequency swing is great enough to tune thru the peak of the lowest frequency crystal in the batch.

Once all the crystals have been checked and their 20 pF frequencies and ESR values recorded, the best selection strategy is to look over the Figureures for a group of nine crystals that have a spread of frequencies of less than 10% of the 2.4 kHz bandwidth. They can then be considered for position in the filter on the basis of their ESR values. The ones with the lowest values should be selected for the middle positions, with the lowest of all as the central crystal.

The crystals with the highest ESR values should be paired up for use as the end parallel crystals because their loss can be absorbed in the terminations. Try to use a pair of crystals with similar values of overall ESR if you want the two terminating resistors to have the same value after subtracting the effective loss resistance of each pair of end crystals from the required theoretical termination resistance of 335 Ω. **Table 2** shows how the nine crystals chosen from the batch of 30 obtained for the prototype were selected for position to obtain the passband curve shown in **Figure 9**. It can be seen that the spread of frequencies for a load of 20 pF in this case was 215 Hz, and the values of ESR varied from 27 Ω (best) to 108 Ω (worst). The prototype bandwidth (–6 dB) came out at 2.373 kHz with 39 pF coupling capacitors that were all approximately 1% high of their nominal value. A random selection of ±2% capacitors should produce a bandwidth of between 2.35 and 2.45 kHz. If a wider bandwidth is required, 33 pF coupling can be used instead of 39 pF, with the theoretical termination resistance increased to 393 Ω. This should provide a bandwidth of around 2.8 kHz.

Table 2
Measured Parameters for the 9 Crystals Selected for Use in the Prototype 7-pole 2.4 kHz SSB Filter.

Xtal	*Freq (20pF)*	*ESR (Ω)*	*Q*
A	8501.342 kHz	87	30k
B	8501.441 kHz	60	43k
C	8501.482 kHz	33	78k
D	8501.557 kHz	32	81k
E	8501.530 kHz	27	97k
F	8501.372 kHz	28	93k
G	8501.411 kHz	52	50k
H	8501.477 kHz	108	24k
I	8501.400 kHz	54	48k

The motional capacitance of the ECS 9 MHz series crystals available from Digi-Key (part number X419-ND) should be only slightly higher than that of the 8.5 MHz crystals, so they could be used in this design with a corresponding increase in bandwidth — probably around 300 Hz, making the overall filter bandwidth at 9 MHz about 2.7 kHz (±60 Hz with 2% tolerance, 39 pF capacitors).

Construction can be a matter of availability and ingenuity. Reclaimed filter cans from unwanted wide-bandwidth commercial crystal filters could be utilized if they can be picked up cheaply enough. Otherwise, inverted crystals can be soldered side by side, and in line, to a base plate made of a piece of PCB material, copper, or brass sheet as shown in **Figure 10**. The coupling capacitors can then be soldered between the crystal leads and the base plate, or crystal cases, depending on which is more convenient. Excellent ultimate attenuation (>120 dB) can be achieved using direct wiring and good grounding like this, particularly if lead lengths are kept as short as possible and if additional shielding is added at each end of the filter to prevent active circuitry at either end of the filter from coupling to and leaking signal around it. A case made from pieces of the same material can be soldered around the base plate to form a fully shielded filter unit with feed-thru insulators for the input and output connections.

REFERENCES

1. M. Dishal, "Modern Network Theory Design of Single Sideband Crystal Ladder Filters," *Proc IEEE*, Vol 53, No 9, Sep 1965.
2. J. A. Hardcastle, G3JIR, "Ladder Crystal Filter Design," *QST*, Nov 1980, p 20.
3. W. Hayward, W7ZOI, "A Unified Approach to the Design of Ladder Crystal Filters," *QST*, May 1982, p 21.
4. J. Makhinson, N6NWP, "Designing and Building High-Performance Crystal Ladder Filters," *QEX*, Jan 1995, pp 3-17.
5. W. Hayward, W7ZOI, "Refinements in Crystal Ladder Filter Design," *QEX*, June 1995, pp 16-21.
6. J.A. Hardcastle, G3JIR, "Computer-Aided Ladder Crystal Filter Design," *Radio Communication*, May 1983.
7. John Pivnichny, N2DCH, "Ladder Crystal Filters," MFJ Publishing Co, Inc.
8. H. Steder, DJ6EV, and J. Hardcastle, G3JIR, "Crystal Ladder Filters for All," *QEX*, Nov-Dec 2009, pp 14-18.
9. D. Gordon-Smith, G3UUR, "Extended Bandwidth Crystal Ladder Filters With Almost Symmetrical Responses," *QEX*, Jul/Aug 2011, pp 36-44.