

Crystal Ladder Filters for All

The authors share their comprehensive crystal filter design program.

Crystal ladder filters have been used in home construction projects for a very long time and radio amateurs have developed ever more sophisticated design strategies for their production. Almost any group of crystals, of the same nominal frequency, when connected into a ladder network will produce a band pass frequency response, but designing a really useful filter is more demanding. The purpose of this article is to show you how to produce filters with a more predictable performance using a new, freely available software package. The method is based on the equations of Milton Dishal, and is fully self-contained; there are no complicated calculations, approximations, or filter tables to look up.¹ The program takes over all the many complex procedures involved, and so enables the constructor to concentrate fully on the selection of the filter components and its construction. A ZIP file with the program, help files and a brief explanation is available for download from the ARRL *QEX* Web site.² After downloading the ZIP file, extract the files to a separate directory on your hard drive. Do not create that directory in the “Program Files” or “Documents and Settings” directories on your hard drive.

First Steps

Before starting any design process you need to know the properties of the materials you are going to use, and crystals are no exception. In fact, they are much more complicated than more familiar components such as capacitors or inductors, or indeed than *L/C* tuned circuits.

Crystal Parameters

The equivalent circuit of a crystal, shown in Figure 1, consists of the motional inductance, L_m , and the motional capacitance,

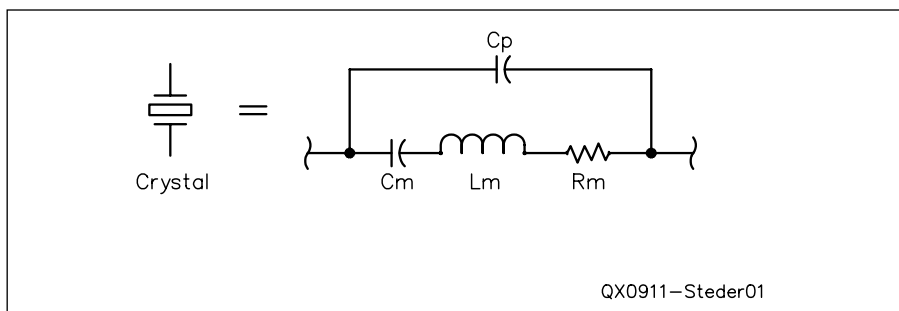


Figure 1 — The mechanical properties of a quartz crystal can be represented by the electrical equivalent components shown above.

C_m , in series with the loss resistance, R_m ; which all combine to produce a series resonance. Together with C_p they produce a parallel resonance as well. Because of this double resonance, a crystal connected in the series circuit of Figure 2 will produce a sharply peaked response that is followed at a slightly higher frequency, by a very sharp dip.

Therefore, a ladder filter with crystals as the series elements will always show a steeper slope on the high frequency side. This makes it ideal for making lower-sideband SSB filters. By assembling a filter with a sufficient number of crystals, however, the slope on the low frequency side can be made steep enough to use the filter for upper-sideband operation as well. This can be seen in Figure 3. The Dishal program is also a very convenient tool for determining the necessary number of crystals for a desired specification.

Measuring C_p

This is the capacitance of the crystal's electrodes, together with the unavoidable associated circuit strays. It can easily be measured at low frequency by using a bridge or a component test set. It has a very low value, of the order of 3 to 6 pF, so it is necessary to arrange to make this measurement when the

crystal is mounted in a similar position to its final assembly in the filter, in order to produce a realistic value for use by the program.

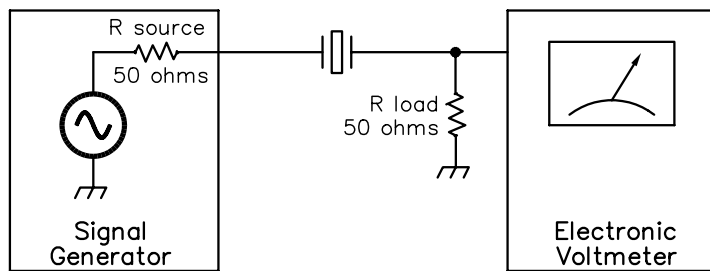
Determining L_m and C_m

L_m and C_m cannot be measured directly, so they have to be obtained by alternative means. For people with limited test facilities the classical method of doing this, which requires precise measurements of phase shift (see Note 6), may be replaced by one of the alternatives listed in the Notes.

The first of these methods, which was suggested by G3UUR, tests the crystal in a Colpitts oscillator.⁷ The result of that measurement is evaluated by the routine “Xtal/G3UUR,” located in the “Xtal” drop-down menu. This then provides values for L_m and C_m .

The second, and easiest of these alternative methods, was described by Wes Hayward W7ZOI (see Note 7) and also by K8IQY.¹³ Here, the crystal is treated as a very high-Q tuned circuit and by measuring the -3 dB bandwidth and the loss resistance, R_m , we can calculate the motional inductance. This method has the advantage of not needing accurately calibrated capacitors, but it does need an accurate 3 dB attenuator and a finely-tuned, stable signal generator. This

¹Notes appear on page 18.



QX0911–Steder02

Table 1
Measured Parameters for Crystals Purchased in Germany

$F_s = 4913.57$ kHz
 $L_m = 69.7$ mH
 $C_m = 15.053$ fF
 $C_p = 3.66$ pF

Note: For the benefit of anyone unfamiliar with the unit fF is the abbreviation for femtofarads and 1 fF is equal to one thousandth of a picofarad.

Table 2
Measured Parameters for Crystals Supplied with an Elecraft K2 Kit

$F_s = 4913.57$ kHz
 $L_m = 76$ mH
 $C_m = 13.805$ fF
 $C_p = 3.65$ pF

the frequency but also the motional inductance or capacitance of each crystal. As an example of this variation see Tables 1 and 2. Table 1 is a group of crystals purchased in Germany and Table 2 refers to the crystals supplied with an Elecraft K2 kit.

The Design Program

A very detailed description of the facilities provided within the program is given in the “Help” file so only the major features will be described here. This article gives sufficient information to get you going. The initial input display is illustrated in Figure 3.

The program assumes identical crystal parameters. Therefore the standard procedure is to select crystals from the list of measured items that show the best match for f_s , L_m (or C_m) and C_p , calculate their average values and insert them into the program.

The first parameter to be entered is C_m , the motional capacitance, in femtofarads (or L_m , the motional inductance in millihenrys). Then enter F_s and C_p , which were measured earlier. The 3 dB bandwidth is your own choice and depends on whether you are making an SSB or a CW filter. In our case the value used was 2.4 kHz. This allows for a little bandwidth “shrinkage” due to the finite crystal Q. Too large a figure here will result in the program giving an error message informing you of the maximum achievable bandwidth. We chose to design a 0.2 dB ripple Chebyshev filter using 8 crystals. The final entry is the frequency span to be displayed. In this example it is 10 kHz, but larger and smaller bandwidths can be handled. Then all you need to do is to press the “Calculate” button and all the component values required are presented on the left-hand panel, together

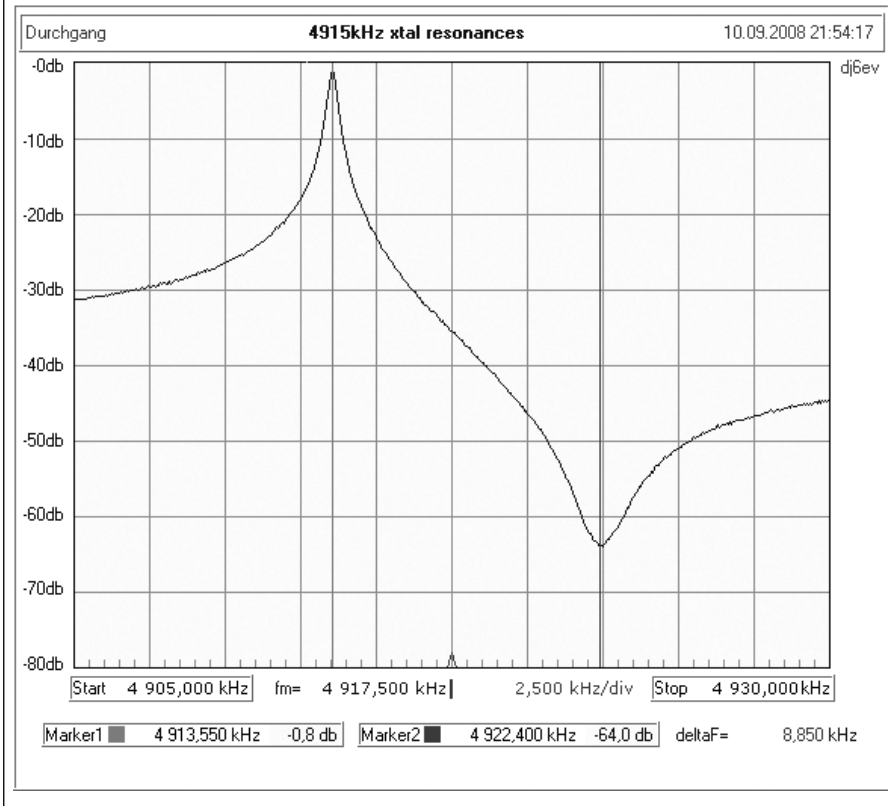


Figure 2 — Part A shows the 50 Ω test circuit to show the properties of a crystal. Part B shows the frequency response of crystals, showing series and parallel resonance.

may easily be home-brewed by using one crystal from your batch of crystals in a variable crystal oscillator circuit (see Note 13). Again, the calculation routine is located in the “Xtal” menu as “3 dB-Method.”

Whichever measurement method you decide to use, you need to check the complete batch, making a note of F_s , C_m and R_m for each crystal, as well as C_p . All of these will be needed later as input to the computer program. It is particularly important to take notice of R_m , because it will allow you to weed out any low-Q (high R_m) samples. Also, at this stage it is worth selecting the highest and lowest frequency crystals for use as LSB and USB carrier crystals.

A Typical Filter

For an SSB filter, we suggest that you use crystals within the range 4 to 11 MHz for a first attempt. These are cheap and readily available because they are produced in large quantities for computer and communications applications.

It goes without saying that care needs to be taken in the selection of crystals. One cannot assume that crystals with equal frequencies and the same case style will show the same motional inductance. This can vary significantly from manufacturer to manufacturer and can even vary from batch to batch. It is therefore mandatory not only to measure

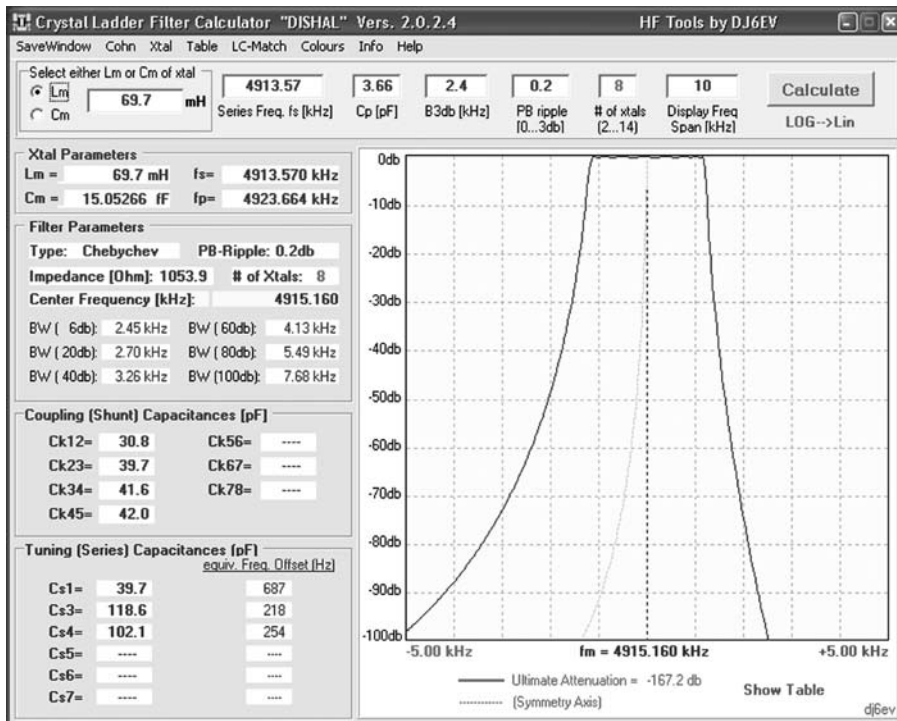


Figure 3 — Filter design program user interface.

with a graph of the frequency response on the right.

The top tool bar has a drop-down menu “Table,” which allows this graph to be replaced by a table of insertion loss. This enables you to make an easy comparison between the theoretical response and your subsequent measurement of your own filter.

As a guide to what you may expect to measure, the parameters of the crystals used in the Figure 3 filter were as listed in Table 1. We suggest you try out the program by entering these values into the program yourself and press “Calculate.”

Amateur Radio Designer

In order to confirm the validity of the program and its underlying algorithms, a number of filters have been constructed. Also, they have been simulated using the *ARRL Radio Designer* software formerly marketed by ARRL. A typical simulation response is shown in Figure 4 and of particular note is the ability of *ARD* to simulate the effect of losses within the filter caused by the finite *Q* of the crystals. Note how the edges of the passband become more rounded and the ripple is no longer of equal amplitude across the passband.

Some Design Refinements

Ideally, the crystals used in this type of filter should all be absolutely identical but unless you have a large batch from which to select, you will have to use the closest you can to this ideal. An acceptable tolerance would be approximately $\pm 2\%$ of the design bandwidth. For an SSB filter, this is around ± 50 Hz but only ± 10 Hz for a CW filter. Don't despair, however, there is a special feature in the program to help you to compensate for these deviations from the ideal. This is in the bottom left-hand corner of the results panel, and displays the frequency shift produced by placing the calculated value of capacitance in series with each crystal. If you look at the initial measurements you made on the crystals, you may be fortunate enough to find crystals that already deviate from the ideal by a similar amount. If so, they can be used in the filter without any additional series capacitor at all. Otherwise you need to calculate the size of the capacitor required to pull it onto the target frequency. There is a facility for “Xtal tuning” included under the “Xtal” drop-down menu, which calculates the size of this capacitor for you. A very detailed description of the use of this facility is given in the “Help” file.

Because the filter components are dependent upon your choice of such details as bandwidth and passband ripple you will find that making small changes to these can result in capacitor values that are sufficiently close to standard preferred values not to need fur-

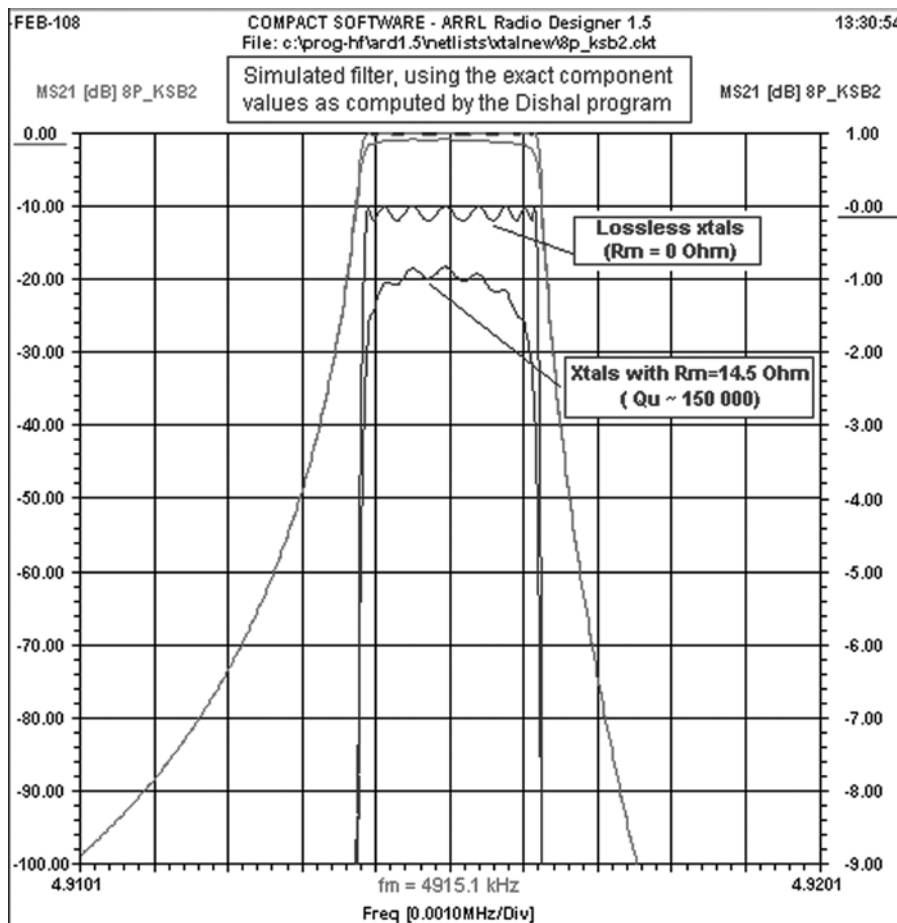


Figure 4 — ARD simulated filter response compared with theoretical response.

ther trimming. Even if you are not that fortunate, you should usually be able to make the required capacitor using no more than two capacitors in parallel.

The filter impedance also depends upon your choice of input parameters, but this can be matched over a wide range by adding an extra inductance and capacitance at both ends of the filter. Again, this calculation is incorporated into the program, maintaining our aim of providing you with a complete design package. To this extent it is very educational to make changes to the input values, just to see what effect they have on the calculated components. The program will tell you when you exceed the limits of practical designs.

The measured insertion loss will always be higher than is shown in the design response, which assumes perfectly lossless components. This is mainly due to the R_m of the crystals, but the capacitors also add a small contribution. Similarly, additional insertion loss is incurred if impedance matching networks or transformers are introduced. Binocular transformers like the BN2402-43 or similar cores usually introduce less loss than toroidal cores because of their much better coupling coefficients.

It is very important that the inductive reactance of these transformers is at least ten times higher than the required filter impedance, otherwise the filter will show distortion of the passband and increased ripple because of its sensitivity to reactive loads. Similarly, the termination impedances should not differ from the calculated value by more than -5 to $+10\%$. Otherwise, this will cause the passband shape and ripple to deviate significantly from the desired format. It has been noted that narrow band CW filters are more tolerant of these departures from the ideal than are wider bandwidth filters.

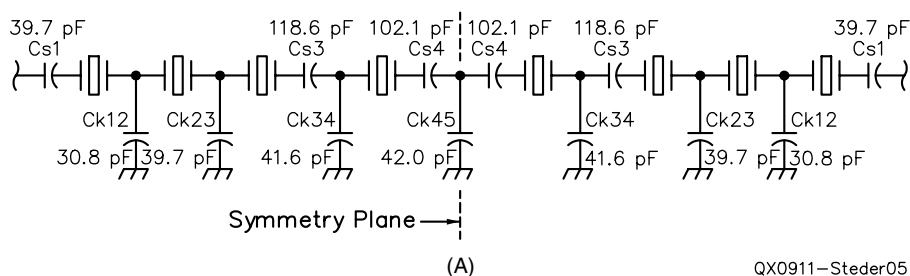
Further Refinements

If you insert a value of zero as the crystal's shunt capacitance in the program, it will calculate component values for the type of filter described in Note 7, where the crystals have been shunted by inductors that resonate with C_p . This type of filter has a frequency response that is inherently symmetrical in both stop bands, and for some applications such as spectrum analyzers, it may justify the additional complexity. It is educational to observe the effect that this neutralization of C_p has on the value of the coupling capacitors.

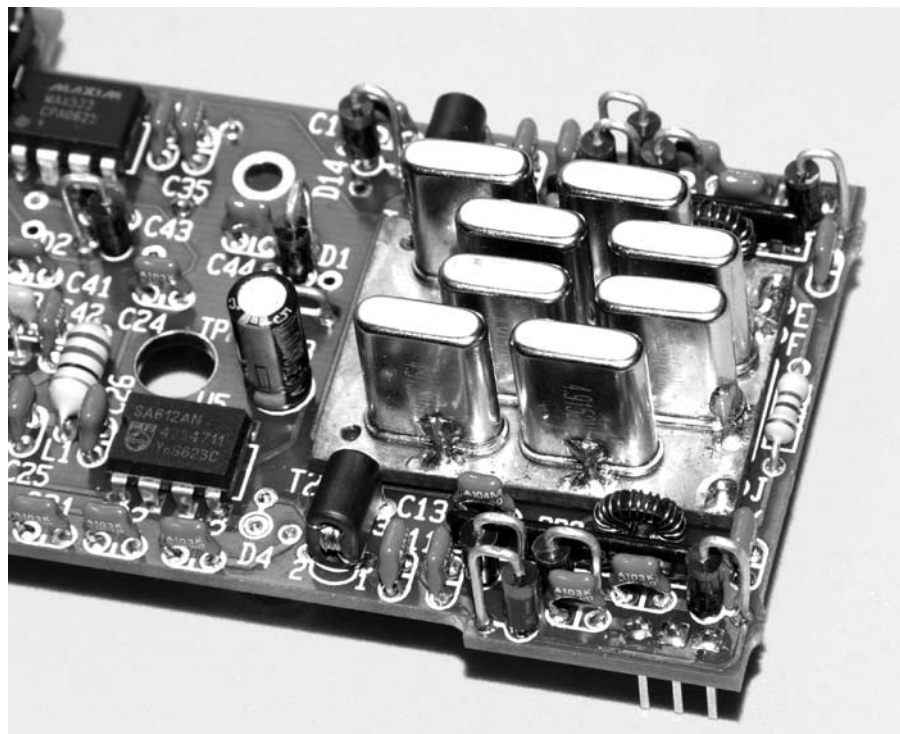
Filter Design and Choice of Filter Frequencies

We recommend that the design value for the passband ripple be kept fairly low, on the order of 0.1 to 0.5 dB. This is because, as detailed earlier, the real filter will show an

The Calculated 8-Pole Filter
with a 3 dB Bandwidth = 2.4 kHz
and Ripple = 0.2 dB



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(B)

Figure 5—An 8-pole Chebyshev filter circuit is shown at A. Part B shows the filter installed in an Elecraft K2 transceiver.

increased ripple due to the inevitable component tolerances and losses. Filters with higher ripple do, however, provide better shape factors, so it may be a price worth paying, particularly if you are not prepared to select more accurate components.

Generally the choice of intermediate frequency is decided by other factors in the overall system design, but the limitations of crystal filter design must also be taken into account at that stage. Some of these considerations are summarized below.

For SSB filters in particular, lower frequencies such as 4915 kHz used in the popular K2 transceiver have the advantage that the crystal Q_u (unloaded Q) is normally greater than that of higher frequency crystals. Also, the filter band edges are much closer to the

calculated values because the relative bandwidth $b3/f_m$ is higher for lower frequency IF values. Furthermore, higher frequency filters show more rounding of the passband edges and have a higher insertion loss, all due to the lower Q and the lower relative bandwidth, $b3/f_m$. Unfortunately, lower frequency filters have a more asymmetrical stopband response and you need to use a higher-order filter to obtain the required selectivity. Life is never easy for the filter designer! All these conflicting factors are easily demonstrated by the program, and it is worth experimenting just for its educational value, even if you never intend to make a filter.

It is perhaps an obvious point, but it is worth stressing that the choice of an IF that is within or near to a broadcast band will make

it almost impossible to avoid breakthrough of the powerful broadcast signals.

Construction Hints

One of the most important requirements is the careful and accurate measurement of *all* components, not only the crystals themselves. The capacitors should not only be measured accurately for their value but should also be tested for their HF quality, especially when using small ceramic capacitors. Painstaking care pays off by producing very good filters.

If SMD (surface mount) capacitors are used in the filter, they will exhibit an additional capacitance to ground unless the ground-plane is removed from below them. These values can only be estimated, and will reduce the effective bandwidth of the filter if they are not deducted from the calculated values. This is less critical when the coupling capacitances exceed values of 100 pF (for instance in CW filters).

Ladder filters are friendly, and if the passband curve down to around -10 dB fits the design expectations, the stopband response will also follow the computed values. The stopband rejection is heavily influenced by the degree of input-to-output isolation, and careful physical layout and screening of the filter components is mandatory if the potential full performance is to be realized.

Based on experience, the crystal cases should be grounded using the shortest possible connections to minimize stray inductance. Double-sided circuit boards are best, with as many through connections as possible for the ground planes. All leads in the layout should be as short and wide as possible to keep stray inductance and resistance very low. Similarly, all the shunt components should be grounded directly. Failure to do so results in additional coupling, which the program is not designed to take into account, and will produce unpredictable passband distortion.

It should be noted that typical crystal cases, such as HC49-U, often have small "bumps" where the leads enter the can. To ensure rigid installation, the crystals should sit comfortably on the ground plane of the circuit board, and this will be facilitated if appropriate holes (about 0.5 mm deep) are carefully drilled into the surface of the board. Otherwise vibration will eventually cause the leads to fatigue and fracture at this point.

Figure 5A shows the circuit diagram of the filter designed in Figure 3. Figure 5B shows it installed in an Elecraft K2 transceiver.

And Finally

The computer program that has been described here provides a design tool suitable for use by designers with little or no

prior experience in filter design. By making this program freely available we hope more people will be tempted into the highly enjoyable home-brew facet of amateur radio. You can find the latest program version and any updates on the Warrington Amateur Radio Club (WARC) Web site.¹⁴

Jim Koehler presented an automated method of measuring crystal parameters in a Jul/Aug 2008 *QEX* article.¹⁵ A much greater number of excellent articles have been published in *QST* and *QEX*, and their exclusion is not to be regarded as a value judgment. It is just that we have chosen those which complement our article by describing some features in greater detail than we could fit in here. In fact, a much extended list of crystal filter references is included on the Warrington Amateur Radio Club (WARC) Web site (see Note 14).

Notes

¹Milton Dishal, "Modern Network Theory Design of Single-Sideband Crystal Ladder Filters," *Proceedings of the IEEE*, Sep 1965.

²The crystal ladder filter design program is available for download from the ARRL QEX Web site. Go to www.arrl.org/qexfiles and look for the file **11x09_Steder-Hardcastle.zip**.

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³J. A. Hardcastle, G3JIR, "Some Experiments with High-Frequency Ladder Crystal Filters," *Radio Communication*, RSGB, Dec 1976, pp 896-898, Jan 1977, pp 28-29, Feb 1977, pp 122-124, Sept 1977, 687-688. A summary of this material was published by ARRL in the Dec 1978 issue of *QST*, pp 22-24.

⁴J. A. Hardcastle, G3JIR, "Ladder Crystal Filter Design," *Radio Communication*, RSGB, Feb 1979, pp 116-120. This article was reprinted by ARRL in the Nov 1980 issue of *QST*, pp 20-23.

⁵J. A. Hardcastle, G3JIR, "Computer-Aided Ladder Crystal Filter Design," *Radio Communication*, RSGB, May 1983, pp 414-420.

⁶J. A. Hardcastle, G3JIR, "Quartz Crystal Parameter Measurement," *QEX*, Jan/Feb 2002, pp 7-11.

⁷Wes Hayward, W7ZOI, "Refinements in Crystal Ladder Filter Design," *QEX*, June 1995, pp 16-21. This article was reprinted in *QRP Power*, ARRL Publication No. 210.

⁸Doug DeMaw, W1FB, "A Tester for Crystal F, Q and R," *QST*, Jan 1990, pp 21-23 (with Feedback in Mar 1990 *QST*).

⁹Wes Hayward, W7ZOI, "Designing and Building Simple Crystal Filters," *QST*, July 1987, pp 24-29.

¹⁰Wes Hayward, W7ZOI, "A Unified Approach to the Design of Crystal Ladder Filters," *QST*, May 1982, 21-27 (with Feedback in July 1987 *QST*).

^{10A}Also see "An Oscillator Scheme for Quartz Crystal Characterization," www.w7zoa.com.

¹¹Randy Evans, KJ6PO, "Crystal Parameter Measurement and Ladder Crystal-Filter Design," *QEX*, Sept/Oct 2003, pp 38-43.

¹²Jack Smith, K8ZOA, "Designing the Z90's Gaussian Crystal Filter," *QEX*, May/June 2007, pp16-26.

^{12B}Also refer to www.cliftonlaboratories.com.

¹³Crystal filter test equipment: www.k8iqy.com.

¹⁴Warrington Amateur Radio Club: www.warc.org.uk.

¹⁵Jim Koehler, VE5FP, "Some Thoughts on Crystal Parameter Measurement," *QEX*, July/Aug 2008, pp 36-41.

Note: The articles from Notes 4, 5 and 6 are available on the Warrington Amateur Radio Club Web site at www.warc.org.uk. The articles from Notes 8, 9 and 10 were reprinted in *W1FB's Design Notebook*, ARRL publication No. 126, ISBN:0-87259-

QEX+

Next Issue in QEX

Thomas Dean, KB1JJJ, describes "A Digital FHSS Transmitter" that he designed as a project for a digital logic class at the United States Military Academy. Using an Altera DE2 Development and Education Board with a Cyclone II field programmable gate array (FPGA), Cadet Dean created a software defined frequency hopping spread spectrum (FHSS) transmitter. The article presents a demonstration of the kind of system that can be contained on a single IC, and describes how it was created.