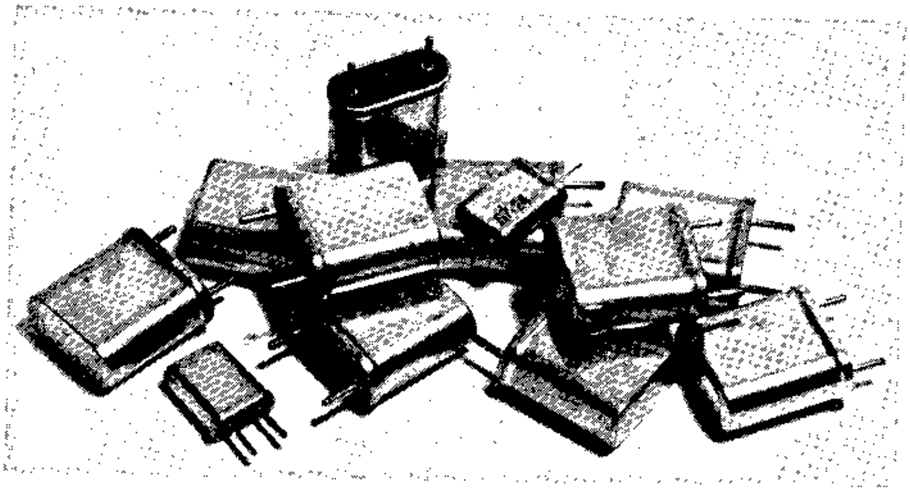
A Unified Approach to the Design of Crystal Ladder Filters



Have you turned away from a construction project because of high-cost crystal filters? Why not build your own?

By Wes Hayward,* W7ZOI

The design of crystal ladder filters has been treated in the professional literature[1] and amateur journals.[2] However, the design methods are specific — they treat crystal filters as a special field with isolated methods. Actually, the same design methods for L-C bandpass filters may be applied directly to crystal filters. Such a unified design method should be more pleasing to the designer, and will allow more flexibility in the resulting filters.

The amateur's interest is primarily one of economics. Crystal ladder filters are easily designed and built with readily available components, yielding great savings for the builder. Television color-burst crystals are attractive for ladder filters. These are at 3.579 MHz in the U.S., while European crystals are at 4.433 MHz. The latter are popular with the many builders in the G-QRP-Club.

This paper addresses a number of goals. Simple methods are presented for the crystal evaluation and measurements needed for the design of filters. The accuracy is adequate for most amateur filter designs. Also, a simple set of design equations is given, which allows the measured data to be used in the design of filters. Tables are presented for Butterworth and 0.1-dB ripple Chebyshev filters.

Finally, some design subtleties are presented to aid in the construction and tuning of rather precise filters. These details may be ignored for many simple amateur-built filters, but should be of interest to the exacting designer. The results of the more exact methods are compared with the simplified ones.

All of the design may be done with a hand-held scientific calculator. Detailed analysis of filter frequency response may be done with sophisticated programmable calculators, such as those offered by Hewlett-Packard or Texas Instruments. All of the analysis reported by the writer was done with an HP-41CV calculator.

Some Filter Fundamentals

Fig. 1A shows a traditional LC-coupled resonator filter. This circuit uses two coupled, parallel-tuned circuits. Many more resonators (tuned circuits) may be used to obtain a steeper skirt response. Filter bandwidth and response shape are determined by the loading caused by the end terminations (the source and load resistances) and by the coupling between resonators.

There is no reason to restrict the filters to those using parallel resonators. Series-tuned circuits are just as viable. This type of L-C filter is shown in Fig. 1B, the exact duplicate of that using parallel resonators. Design of multielement filters of both types is covered in the literature.[3]

A detail that is not generally appreciated is the relative freedom available to the filter designer. For example, a 5-MHz L-C filter with a 100-kHz bandwidth could be designed with inductors of less than 1 μH, with inductors greater than 10 μH, or with anything in-between. Some values might be more practical, but this is not a fundamental restriction. Once an inductor is chosen, the rest of the filter components are determined. This applies to both filters of Fig. 1.

Another overlooked detail can be the termination of the filters. Any filter *must* be terminated at both ends in the resistance for which it was designed. The filters of Fig. 1 are doubly terminated with equal resistances at each end. This is common, but not mandatory. It is not proper, however, to design a filter for a given load at each end, such as 50 ohms, and then to expect the same response from that filter with other terminations.

Fig. 2A shows the equivalent circuit for a quartz crystal. This is a model — a circuit that shows the same response as a real crystal. The components of the model may not be practical, but this is of no significance for design work. For example, a 5-MHz crystal used in some filters built by the writer had a motional inductance of L_m = 0.098 and a motional capacitance of C_m = 0.0103 pF. The loss resistance was R_s = 13.4 ohms, and the parallel capacitance was C_p = 5 pF.

The parallel capacitance, C_p of Fig. 2A,

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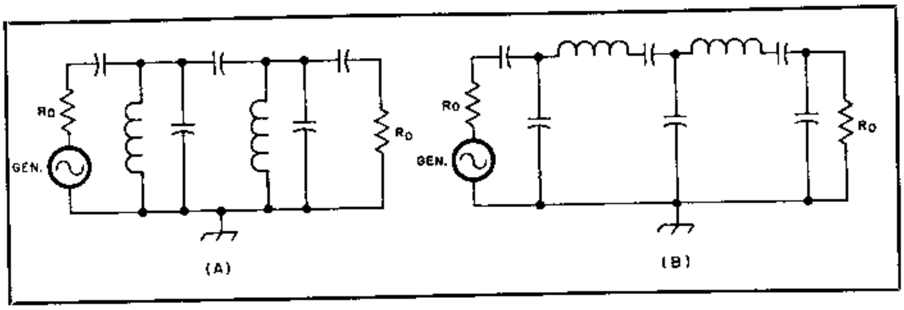


Fig. 1 — Double-tuned circuits with equal termination at each end. Parallel resonators are used at A; series-tuned circuits are used at B.

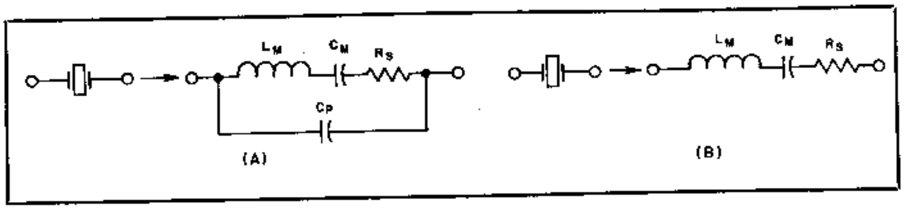


Fig. 2 — Equivalent circuit for a quartz crystal. L_m and C_m are "motional" components. Parallel capacitance, C_p, is included at A while it is ignored at B.

is rarely more than a few picofarads and may often be ignored for a design. This leaves the equivalent circuit of Fig. 2B. This is nothing more than the series-tuned circuit, exactly like that used in the L-C filter of Fig. 1B. Realizing this, the same methods may be used for the design of an L-C or crystal filter — one is no more complicated than the other.

Crystal Measurements

If the methods of LC-filter design are transferred to the design of crystal filters, it is mandatory that the vital inductance and capacitance values in the crystal, L_m and C_m, be known. It is not reasonable to substitute an arbitrary crystal of "proper" frequency into an existing design and expect it always to work. This will be illustrated later.

The crystal parameters are measured indirectly, but easily, with lab-quality instrumentation. A suitable measurement may also be done with equipment available to most amateur experimenters, and with a special test set constructed from ordinary components.

The nature of the measurements is understood with reference to the simplified crystal equivalent circuit of Fig. 2B. The crystal is placed between a source of known characteristic impedance and a detector, also of well-defined impedance. The generator is adjusted until a peak response is found. Then, the reactances of L_m and C_m cancel, leaving the result dominated by R_s. This is evaluated easily by replacing the crystal with a small-value variable resistor that is adjusted for the same response in the detector. The potentiometer is then measured with an ohmmeter, providing a value for R_s.

Next, the crystal is reinserted in the signal path and the generator is tuned to both sides of center frequency. The two frequencies where the response is down by 3 dB are noted. The difference is the loaded bandwidth in the test circuit. This is used to calculate a loaded-Q value. But, this is directly related to L_m. Using the condition for resonance, C_m is then calculated. C_p may be measured, but is not vital to the design of the filters described in this paper. Instead, we have assumed that C_p = 5 pF for all examples.

Fig. 3 shows the test set that is used to perform the measurements. The first element is a signal generator. It should have an adjustable output level (up to about −10 dBm or more) and should have excellent stability and good bandspread. Remember that we may be measuring frequency differences of only 100 Hz or so. A suitable generator is described in Chapter 7 of *Solid State Design.*[4] The output of the signal source is applied to a frequency counter and to the test set. The counter should have a 1-Hz resolution.

The generator output is attenuated with a 20-dB pad and then applied to the crystal. The high attenuation ensures that low power is delivered to the crystal and provides a 50-ohm termination for the crystal. Output from the crystal under test drives an amplifier with a 50-ohm input resistance. The signal is amplified by four gain stages and then applied to a diode detector, D1. The dc output drives a high-impedance voltmeter. The test set should be operated with output voltages of 2 or less to prevent overdrive of the amplifiers. Q4, the related components, and the detector may be eliminated, if desired. Then, the output from Q3 is routed to an oscilloscope with a 50-ohm terminator.

Amplifier gain is switchable with S1. With S1 open, the net gain is somewhere around 40 dB. Closing S1 changes the emitter degeneration in Q2, causing the net gain to increase by 3 dB.

A batch of crystals may be evaluated easily for filter applications with this test set. A crystal is inserted and the generator is tuned for a peak response in the voltmeter. That response is carefully noted. The crystal is then removed and replaced with the potentiometer. This is adjusted to obtain the same voltmeter response as was obtained with the crystal. The "pot" is then removed from the circuit and measured, providing a value for R_s.

The crystal is now reinserted in the circuit, with S1 open. The generator is tuned again for a peak response. Both the series-resonant frequency, F_o, and the meter response are carefully noted. S1 is then closed to produce an increase in output. The generator is tuned to the two sides (above and below F_o) until the meter reads the same as it did earlier. The two frequencies are noted and the difference is recorded as Δf, a parameter used for later calculations. Note that there is no need for amplitude calibration anywhere in this system.

This procedure is repeated for a reasonable sampling of the crystals on hand. The work that the writer has done would suggest that the values for F_o, R_s and Δf may be averaged for later calculation as long as the spread is not excessive. One batch of 20 surplus TV color-burst crystals showed an average R_s value of 20.78 ohms, with a standard deviation of 7.2 ohms. The average series-resonant frequency was 3577.257, with a standard deviation of only 67 Hz.

The designs which follow are based on having all crystals in a filter at the same frequency. Hence, frequency matching is required. A rule of thumb is that the deviations should be less than about 30% of the bandwidth of the filter. The center frequency measured in the test set will be the series-resonant value. This is not necessarily the value that would come from an oscillator. A simple oscillator is shown in Fig. 4. It may be used for matching the crystals. This circuit operates at a frequency slightly higher than the series-resonance. It is still suitable for frequency matching. It will serve also for BFO applications. The operating frequency may be increased further by insertion of a variable capacitor in series with the crystal.

Simplified Filter Design

Now that data is available on existing crystals, filter design may commence. See Fig. 5. A few approximate equations may be used. They require additional data and normalized filter parameters. These are presented in Tables 1 and 2, respectively,

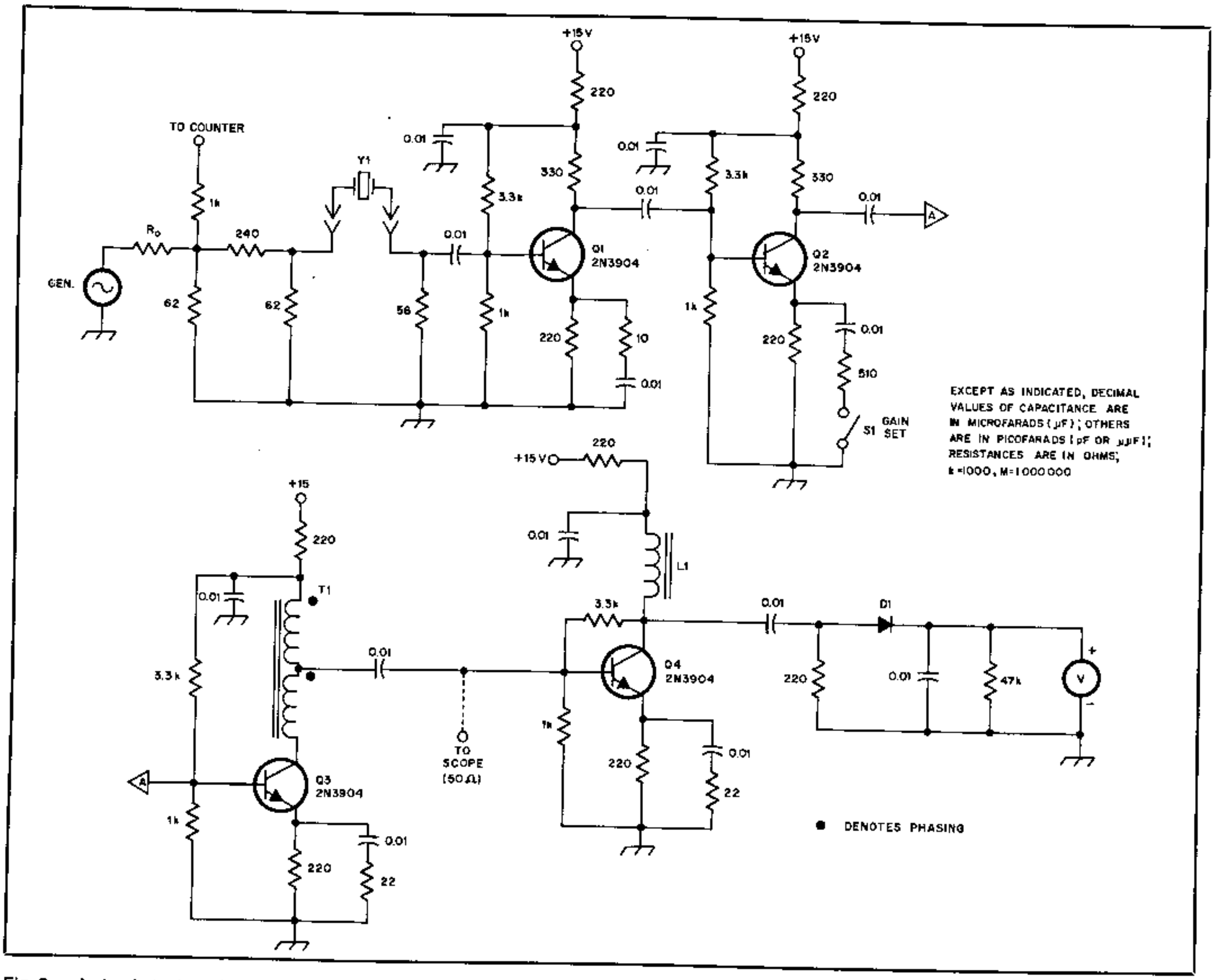


Fig. 3 — A simple test set for the evaluation of crystals to be used in filters. Construction is not critical.

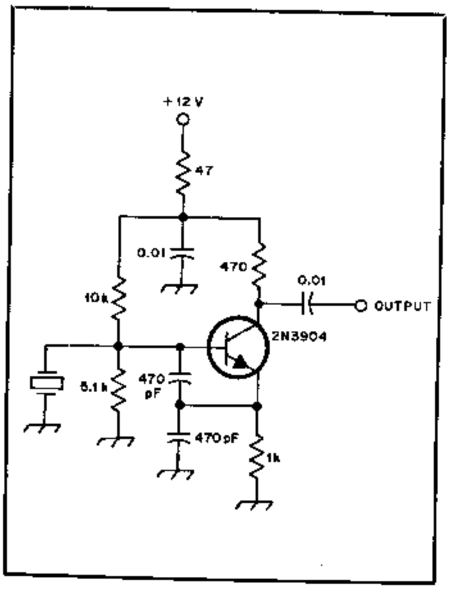


Fig. 4 — A simple crystal oscillator that may be used for crystal frequency matching. The 470-pF capacitors may be ceramic, mica or polystyrene. This circuit will function with crystals from 1.8 MHz to over 10 MHz.

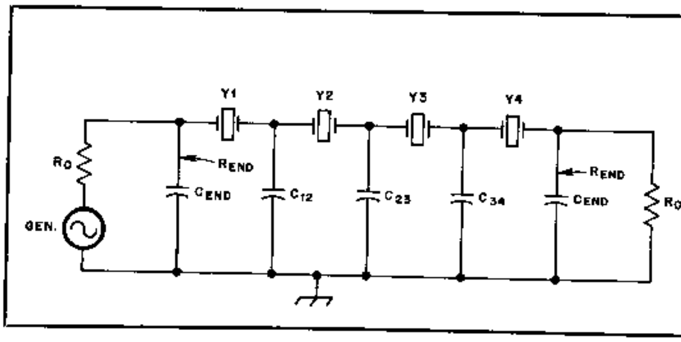


Fig. 5 — A four-pole crystal ladder filter used for illustration. The circuit may be designed for an arbitrary number of crystals.

Table 1

Normalized k and q Values for a Butterworth Response Without Predistortion

N	*q*	k_{12}	k_{23}	k_{34}	k_{45}
2	1.414	0.7071			
3	1	0.7071	0.7071		
4	0.7654	0.8409	0.4512	0.8409	
5	0.6180	1	0.5559	0.5559	1

Table 2

Normalized k and q Values for a 0.1-dB-Ripple Chebyshev Filter Without Predistortion

N	*q*	k_{12}	k_{23}	k_{34}	k_{45}
2	1.6382	0.7106			
3	1.4328	0.6618	0.6618		
4	1.3451	0.685	0.5421	0.685	
5	1.3013	0.7028	0.5355	0.5355	0.7028

for the Butterworth and the 0.1-dB ripple Chebyshev filters. More exacting designs may be done with the exhaustive tables presented by Zverev.[3] His work considers the effects of response-shape distortion, a consequence of loss in filter elements. The Zverev tables are termed "predistorted."

The motional crystal components, L_m and C_m, have been factored into the equations and need not be calculated. Equations are given for them, though. An equation is also given for the unloaded crystal Q (Q_u). This parameter is not needed directly for filter design, but should be evaluated, nonetheless. The Q_u value should exceed the filter Q by a factor of 10 or more to allow simple filters to be built. Filter Q is defined by F_{center} ÷ bandwidth, where both are in hertz. Some surplus crystals may have a Q_u value that is too low for filter applications. The parameters are defined with respect to Fig. 5 as:

Δf = bandwidth measured in test fixture (Hz)
B = filter bandwidth in Hz
R_o = end termination to be used (must be greater than R_{end})
R_{end} = end resistance required to terminate the filter without matching capacitors
C_{end} = matching end capacitor (pF)
C_m = crystal motional capacitance (F)
L_m = crystal motional inductance (H)
F_o = crystal center frequency (MHz)
R_s = crystal series-loss resistance as measured in test set
C_{jk} = coupling capacitor (pF)
C_p = crystal parallel capacitance (assumed to be 5 pF in all equations)
k_{jk} = normalized coupling coefficient, given in Tables 1 and 2
q = normalized end-section Q, given in Tables 1 and 2
N = number of crystals to be used in the filter

The simplified design equations are

$$C_{jk} = 1326 \left[\frac{\Delta f}{B\, k_{jk} F_o}\right] - 10 \text{ (pF)} \quad \text{(Eq. 1)}$$

$$R_{end} = \left[\frac{120\, B}{q \Delta f}\right] - R_s \text{ (ohms)} \quad \text{(Eq. 2)}$$

$$C_{end} = \left[\frac{1.59 \times 10^5}{R_o F_o}\right] \times \sqrt{\frac{R_o}{R_{end}} - 1} - 5 \text{ (pF)} \quad \text{(Eq. 3)}$$

Additional equations not mandatory for simple designs are

$$Q_u = \frac{1.2 \times 10^8\, F}{\Delta f\, R_s} \quad \text{(Eq. 4)}$$

$$C_m = 1.326 \times 10^{-15} \left[\frac{\Delta f}{F_o^2}\right] \text{ (farad)} \quad \text{(Eq. 5)}$$

$$L_m = \frac{19.1}{\Delta f} \text{ (henrys)} \quad \text{(Eq. 6)}$$

The design process will be illustrated with an example. Note that the equations use the units given in the list of parameters. Assume that a small group of crystals is frequency matched and found to have the average parameters f = 294 Hz, ΔF_o = 3.577 MHz and R_s = 23 ohms. This data is typical of inexpensive TV color-burst crystals. These crystals will be used to design a 3-pole Butterworth crystal filter with a 250-Hz bandwidth. We eventually would like to terminate the filter in 50 ohms, but will not pick a termination, R_o, just yet.

The normalized coupling and loading values are found in Table 1 with N = 3. We see that $k_{12} = k_{23}$. Hence the coupling capacitors (Fig. 5) will be equal. The capacitor value is evaluated with Eq. 1.

$$C_{12} = C_{23} = 1326 \times \left[\frac{294}{250 \times 0.7071 \times 3.577}\right] - 10 = 606.5 \text{ pF} \quad \text{(Eq. 7)}$$

The end resistance needed to terminate the filter is given by Eq. 2.

$$R_{end} = \left[\frac{120 \times 250}{1 \times 294}\right] - 23 = 79 \text{ ohms} \quad \text{(Eq. 8)}$$

A value for R_o may now be picked. It may be any resistance greater than 79 ohms. A value of 200 ohms is chosen, and an end-

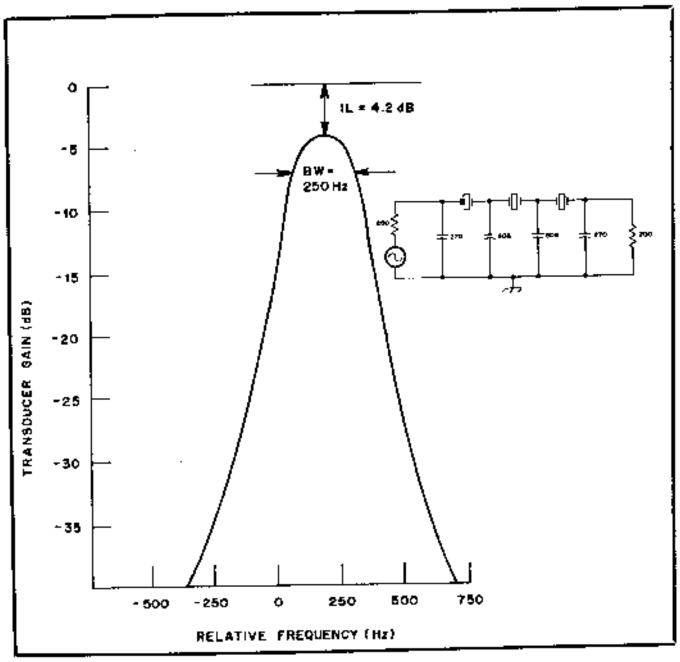


Fig. 6 — Circuit and calculated response for a 3-pole crystal filter at 3.577 MHz with a 250-Hz bandwidth. The design is based on measurements on surplus TV color-burst crystals.

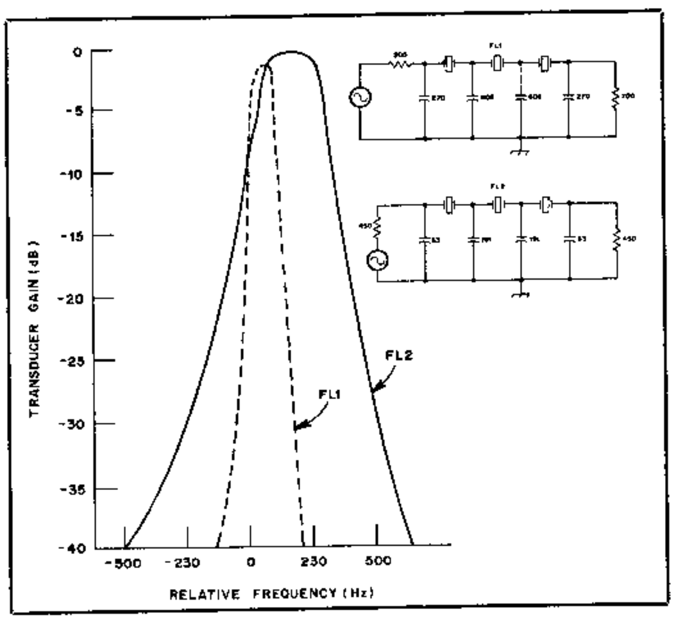


Fig. 7 — The response curves show the effect of using the wrong crystals in a design. The narrow response uses the circuit of Fig. 6 (FL1) with high-quality crystals. The wider response uses the circuit shown (FL2), designed on the basis of measurements on the crystals. Crystal data: F_o = 3.579 MHz, R_s = 6.2 and Q_u = 721,000.

matching capacitor is calculated from Eq. 3.

$$C_{end} = \left[\frac{1.59 \times 10^5}{200 \times 3.577}\right] \times \sqrt{\frac{200}{79} - 1} - 5 = 270 \text{ pF} \quad \text{(Eq. 9)}$$

The final circuit is shown in Fig. 6. The calculated response is also shown. These calculations were done using the Ladder Method,[6] and accounted for the 5-pF C_p value.

The 200-ohm resistance levels may be transformed to 50 ohms with ferrite transformers. This may not be needed in a circuit application, but is certainly useful for measurements.

Note that the filter has an insertion loss of 4.2 dB. This results from the crystal loss with a relatively low crystal Q (Q_u = 63,000), evaluated with Eq. 4. The bandwidth is very close to the desired 250-Hz value, but the peak shape is much more rounded than would be expected from a Butterworth filter. This is also a result of crystal loss.

Consider now the effect of using the circuit of Fig. 6 with other crystals. A group of high-quality 3.579-MHz crystals were measured in the test set. The results were very different than those found with the surplus crystals. The Δf was 96 Hz, and R_s was only 6.2 ohms. The calculated Q_u was 721,000 — over 10 times that of the surplus crystals. L_m was also much different.

The filter of Fig. 6, designed for the low-Q surplus crystals, was evaluated with the parameters of the high-Q crystals. The result is shown in the narrow response of Fig. 7. The bandwidth is much narrower than the desired 250-Hz value, and would be nearly useless in a cw receiver, owing to excessive ringing.

A filter was then designed around the measured crystal parameters. This response is also shown in Fig. 7, as is the circuit, FL2. This filter has a low insertion loss of only 0.4 dB and a shape like that expected of a Butterworth design. A comparison of Fig. 6 and Fig. 7 illustrates the effects of shape distortion.

The data in Figs. 6 and 7 are calculated. An obvious question regarding any experimental pursuit is how well do calculated curves compare with measured data? This comparison is presented in Fig. 8 for a 5-MHz, 250-Hz bandwidth filter. The three-pole circuit is also shown in the figure. The comparison between calculation and measurement is very good. The offset in center frequency is of no significance — it resulted from using 4.999 MHz for F_o during the calculation, rather than a more accurate value. The measurements were done with the writer's receiver synthesizer as a signal generator, followed by a step attenuator and then the filter. This was followed by a broadband amplifier and a 50-ohm-terminated oscilloscope. Similar results have been obtained with filters at 3.579 MHz.

The experimental curve of Fig. 8 is marked with a BFO frequency. This would be the proper frequency to provide a 700-Hz beat note and to ensure good suppression of the opposite sideband. This filter would be very practical in a simple superhet receiver for cw application, especially if it were supplemented with an R-C active low-pass audio filter. This scheme has been used very successfully by the writer in a portable Field Day transceiver.[7]

A simple three-pole filter is also practical for some ssb applications. Such a filter at 5 MHz is shown in Fig. 9. Measured and calculated frequency-response curves are also shown. Note that the filter shape is lacking in symmetry. Indeed, this is an illustration of why this type of circuit is termed a "lower sideband ladder." This also justifies the position of the BFO in Fig. 8. In spite of the poor attenuation slope on the low-frequency side, the filter of Fig. 9 would be practical for a simple ssb exciter. This passband ripple may be eliminated by tuning, a detail shown in the figure and covered in the following section.

Filter Tuning

The method presented so far has assumed that all crystals are exactly at the same frequency. This simplification is sufficient for many applications, especially with narrow-bandwidth filters. It is not adequate for critical designs. Additional tuning is required if we want to design filters with an exactly predicted bandwidth, achieve a desired shape more accurately, or build wide-bandwidth filters with more than 3 or 4 crystals.

Modern filter theory has been used to calculate coupling and end-matching capacitors. The detail that we have ignored is that the individual crystals have

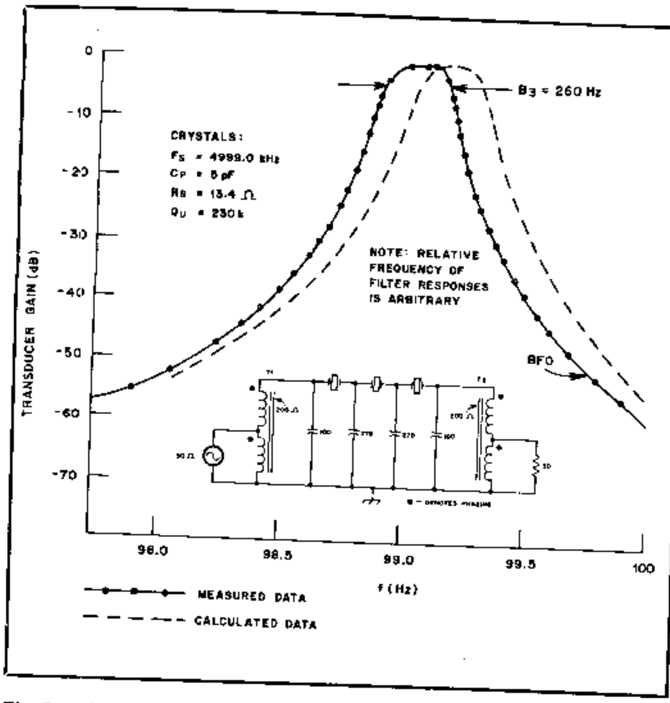


Fig. 8 — Comparison of calculated and measured results on a 5-MHz cw filter. The crystals had F_o = 4.999 MHz, C_p = 5 pF, R_s = 13.4 ohm and Q_u = 230,000. A proper BFO frequency is marked. See text for discussion.

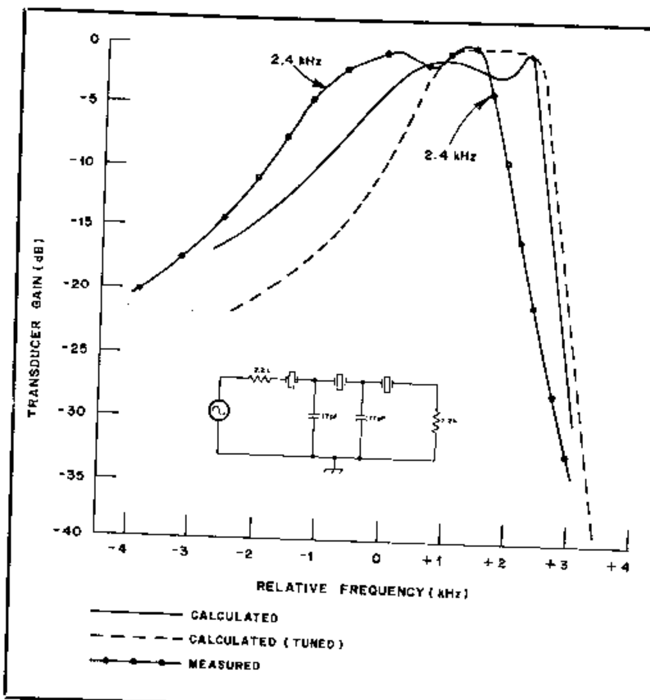


Fig. 9 — Measured and calculated (with and without tuning) results for a wider bandwidth filter for use in a simple ssb exciter. Crystals are the same as used for the filter of Fig. 8.

been detuned by the shunt capacitors. The detuning may be "fixed" through proper choice of crystal frequencies or with the insertion of additional capacitors in the circuit.

Fig. 10A shows one end of a crystal filter. The crystals have been replaced with the simplified equivalent circuit without loss resistance. All crystals are assumed to be at the same frequency, which implies that all L_m and C_m values are the same throughout the filter.

Filter theory states that each loop in this circuit should be resonant at the same frequency when that loop is considered alone. Adjacent loops are open-circuited during this evaluation. Consider the interior loop shown in Fig. 10B. The crystal resonance is determined by L_m and C_m. However, the resonant frequency of this loop is determined by L_m and the series equivalent of the three capacitors, C_{12}, C_{23} and C_m. The loop will resonate slightly higher than the crystal frequency. The actual frequency is easily calculated with standard formulas and a hand calculator.

Analysis of end-section resonance is slightly more complicated. The end resistance and the related parallel capacitance must be resolved into a series equivalent, shown in Fig. 10C. The series capacitance is given by

$$C_s = \frac{\frac{1}{R_o^2} + \omega^2 C_{end}^2}{\omega^2 C_{end}} \qquad \text{(Eq. 10)}$$

where $W = 2\pi F_o \times 10^6$.

The resonant frequency of the end loop is then calculated from L_m and the series combination of C_s, C_m and C_{12}.

Consider an example, a 4-pole ssb filter. This circuit, shown in Fig. 11, was designed for a 0.1 dB Chebyshev response using the k and q values from Table 2 and crystals with F_o = 3.577 MHz, R_s = 23 ohms and Q_u = 63,000. Assume for the present that the two 96-pF capacitors are shorted. The filter is symmetrical, so only two frequency calculations must be done — one for the ends and one for the interior loops. The end loops are resonant 1220 Hz above F_o, while the inner two loops resonate 1790 Hz above F_o.

Two methods may be used to tune this filter, to force all loops to resonate at the same frequency. One method requires that the F_o of the crystals in the end sections be increased 570 Hz over that of the inner loops (570 = 1790-1220). This difference is small compared with the filter bandwidth, so we would not expect a dramatic difference in response shape.

The other method places capacitors in series with crystals in those loops requiring a frequency increase — the end sections of Fig. 11. This is the circuit shown in the figure. A value of 96 pF was found to be necessary for the 570-Hz shift. The addition of series capacitors allows more design flexibility, especially when working with surplus crystals. On the other hand, it may be convenient to use stagger-tuned crystals if the batch on hand has the proper frequency spreads. It is, of course, possible to use a combination of the two methods.

The frequency response of the four-pole filter is shown in Fig. 11 for the cases with and without tuning. The center frequency is raised with tuning, and passband ripple is reduced to near the desired 0.1-dB level. Either filter would be practical for amateur applications.

The bandwidth of the ssb filter of Fig. 11 was 2.2 kHz. It was designed for a 2.5-kHz bandwidth. The difference results from simplifying assumptions used to derive the critical equations and using the k and q values from Table 2, where the effect of filter loss is ignored during design. Improved accuracy is obtained with the Zverev tables to supply the k and q values. Suitable amateur filters may be designed by increasing the design bandwidth slightly over the desired one, while using the Table 1 or 2 data.

The effects of shape distortion are more dramatic with narrow-bandwidth cw filters, for the losses are higher with decreased bandwidth. The Butterworth data of Table 1 provide a good starting point for design. As losses increase, the shape of a narrow-bandwidth filter evolves toward one with a more rounded peak shape, approaching something like a Gaussian response. This rounded shape is desired for narrow-band application, for it offers an improved time-domain characteristic with less filter ringing. Chebyshev filters should not be used for cw applications.

The effects of filter tuning were examined experimentally in the filter of Fig. 12. This was a 250-Hz wide design using the 5-MHz crystals applied in other filter experiments. A 5-pole design was chosen. The measured responses with and without tuning are also shown with the circuit. Without tuning, the attenuation slope on the high-frequency side of the response was poor. Tuning the filter improved the shape and reduced the insertion loss. The shape was still not the Butterworth response predicted. This was traced to variations in the crystal frequencies that had not been taken into account during the design. This filter is destined for use in a multiband portable transceiver.

Conclusions and Applications

Home construction of crystal filters is very practical, especially for the experimentally inclined amateur with the usual amount of instrumentation. Laboratory-grade equipment is definitely not needed. It is important, however, that the filters be carefully designed, and that the designs be based on the crystals to be used. Measurements are performed easily in the home lab to obtain the needed crystal parameters. None of the filter circuits presented in this paper is suitable for exact duplication.[9]

Filter tuning may or may not be required, depending on the filter to be built. An interesting filter that would never require tuning is a two-pole circuit. This results from symmetry. Any detuning would be the same in both crystals. Improved stopband attenuation may then be obtained with a cascade of several filters with isolating stages of gain between them.

Another interesting special case is the three-pole filter with all crystals at the same frequency. The terminating resistance, R_o, may be set equal to the calculated R_{end}. There will then be no shunt capacitors at the ends. This filter may be tuned by placing series capacitors

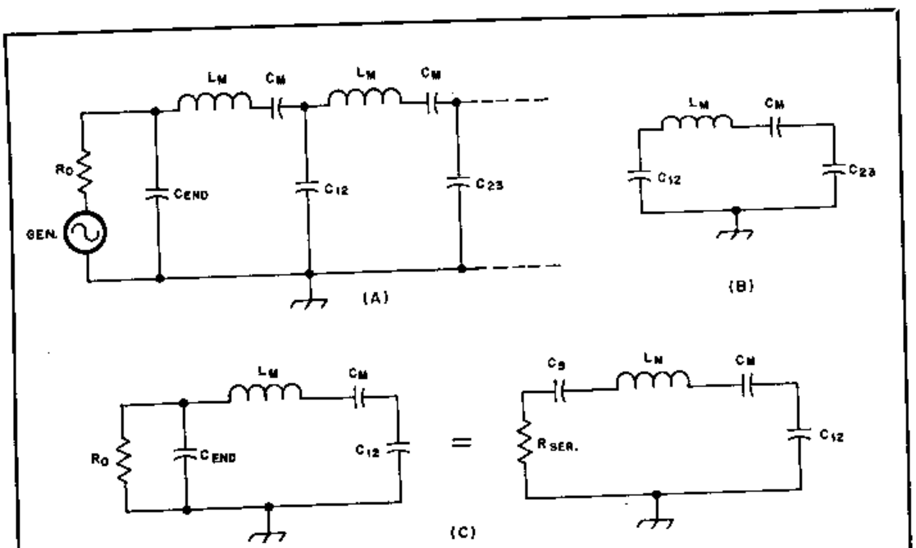


Fig. 10 — Partial filter circuits used in evaluation of tuning of individual loops. See text for details.

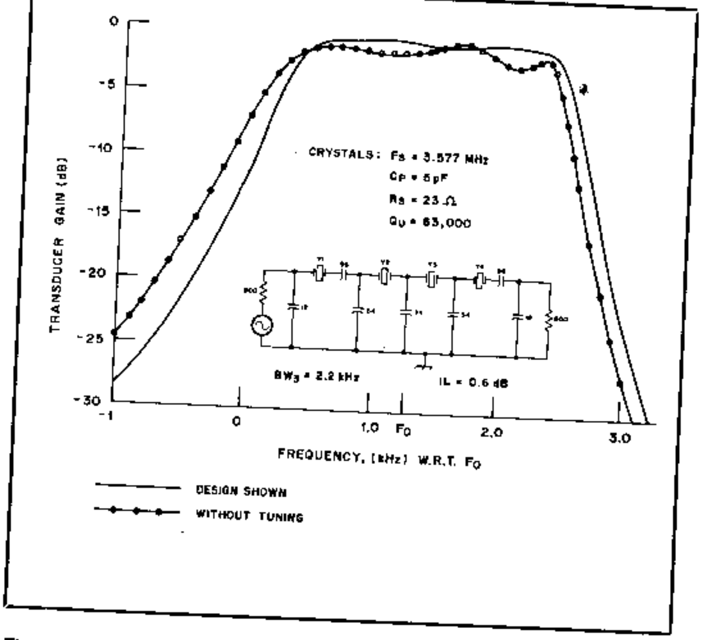


Fig. 11 — Calculated response for the 4-pole ssb filter shown. Surplus color-burst crystals were used for the design. The two response curves show the effects of filter tuning.

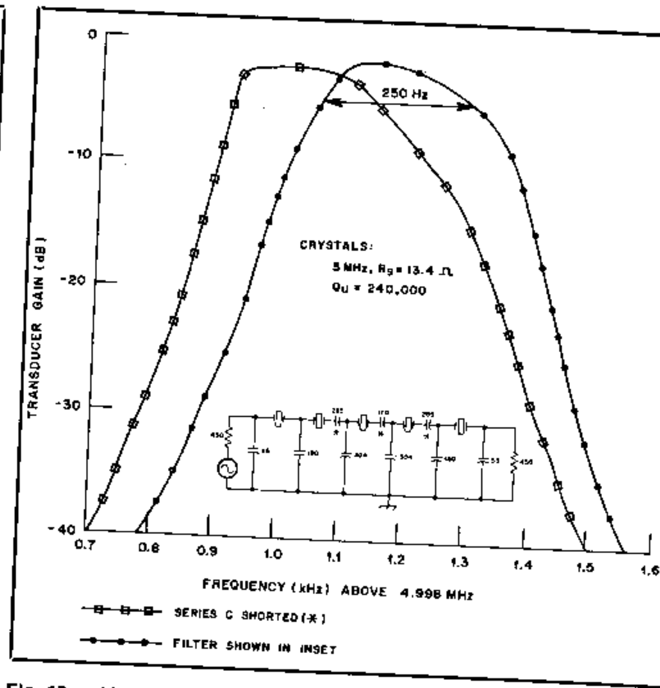


Fig. 12 — Measured response curves for a 5-pole, 5-MHz cw filter. The two curves show the effects of tuning a filter with series capacitors.

in the end loops, which have a value equal to the coupling capacitors. An example of this is the ssb filter shown earlier in Fig. 9. The tuning was realized with the addition of 17-pF capacitors in series with the two outside crystals. Variable capacitors may be used, of course, in any of the circuits shown. Instrumentation must then be built for alignment.

The 3.58-MHz TV color-burst crystals offer an attractive possibility for a simple cw receiver. A single local oscillator could be built at approximately 10.5 MHz. This will then allow both the 40- and 20-meter cw bands to be received with no band switching in the LO. This scheme is not well suited to an ssb receiver, for harmonics of the BFO appear at 7.16 and 14.32 MHz. This harmonic relationship could also lead to spurious responses in a two-band cw transceiver.

Examination of the design procedure reveals some interesting subtleties. Careful choice of termination, R_o, could lead to filters requiring no tuning. Useful filters *can* be built from poorly matched crystals, although the design may get messy. Excessive tuning with series capacitors will increase the loss of the filter. Finally, careful choice of termination resistance will allow the construction of filters with a switched bandwidth.

Notes

[1]A. I. Zverev, *Handbook of Filter Synthesis* (New York: John Wiley and Sons, 1967), Chapter 8.

[2]J. A. Hardcastle, "Ladder Crystal Filter Design," *QST*, Nov. 1980, pp. 20-23.

[3]W. Hayward, *Introduction to Radio Frequency Design* (Englewood Cliffs, NJ: Prentice-Hall, Inc., 1982). Both filter types are covered in detail in Chapter 3.

[4]W. Hayward and D. DeMaw, *Solid-State Design for the Radio Amateur* (Newington: ARRL, 1977), p. 171.

[5]See note 1, pp. 341-379.

[6]See note 3.

[7]See note 4, p. 214.

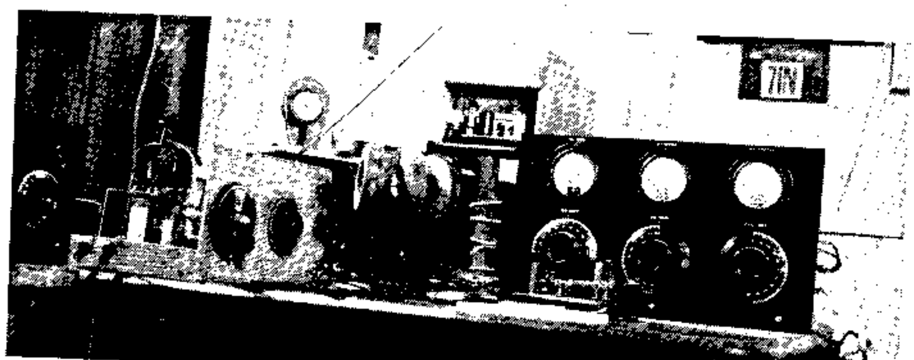
[8]The author has made arrangements to supply crystals at a variety of frequencies that have been characterized for filter applications. Interested readers should send an s.a.s.e. for a data sheet.

Strays

***QST* congratulates . . .**

☐ Retired Army Colonel Fred J. Elser, KH6CZ, of Honolulu, on receiving a PhD in American Studies from the University of Hawaii. His doctoral thesis was entitled "Amateur Radio — An American Phenomenon."

☐ Ira Bechtold, W6NCP, on receiving the Los Distinuidos Award from the La Habra Heights (California) Improvement Association for 10 years of outstanding service to his community.



Bill Staiger, W7IN, of Portland, Oregon, came across this photo while going through an old box buried in his attic. The honeycomb coil receiver (left) was used for arc reception around 15,000 meters and also for l-f reception on 600 meters (500 kHz) with different plug-in coils. The transmitter (right) was a TPTG back-to-back circuit fed with a 60-Hz power supply with a 120-Hz note. The breadboard receiver seemed to work, Bill notes, if he didn't get too close to the coupling unit and disturb the body-capacity effect while tuning. *(photo courtesy W7IN)*