Designing and Building High-Performance Crystal Ladder Filters

Designing crystal filters for SSB is made easier using readily available software.

By Jacob Makhinson, N6NWP

Despite the several excellent articles about crystal filters that have been published in amateur magazines over the years, building high-quality crystal filters is still seen by many amateurs as either black magic or as a complicated procedure beyond the reach of the average builder.

A crystal filter, being the heart of a superheterodyne receiver, has a profound effect on its selectivity. A low-quality crystal filter in even a high-priced commercial transceiver can degrade its selectivity and dynamic range. On the other hand, a good crystal filter can significantly enhance receiver performance, whether in a simple "weekend" project or in a competition-grade station.

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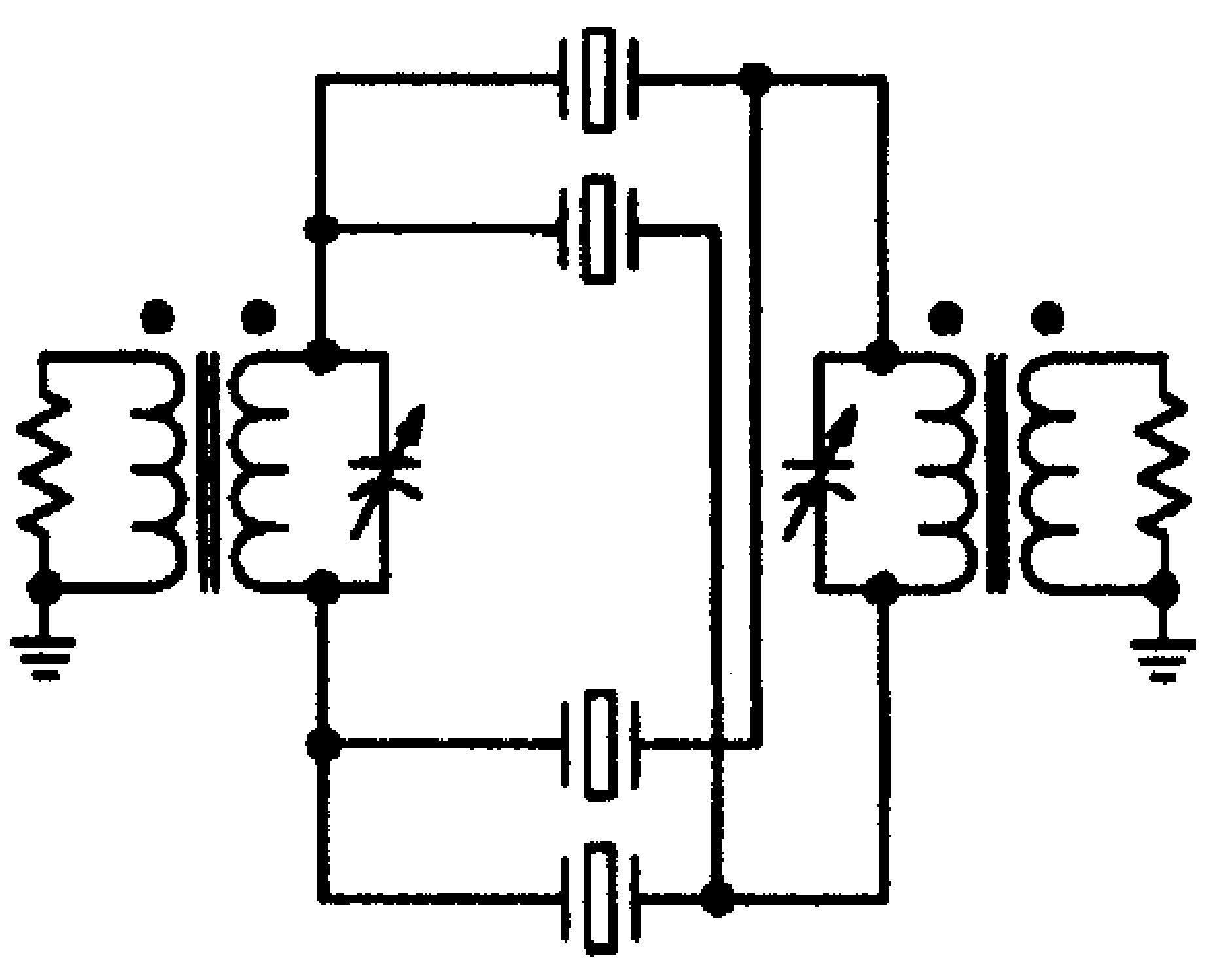
Commercially available crystal filters are usually expensive and often discourage construction-minded amateurs from pursuing projects that include crystal filters. In addition, studies conducted in recent years conclude that in a high-performance receiver, a crystal filter may become the "bottleneck" restricting the receiver's dynamic range. So, the goal of this article is to provide design and building methods that can be used to construct crystal filters that rival or exceed the quality of commercially available filters. I will describe a simple, practical step-by-step procedure to design, construct and align crystal filters using equipment available to most construction-minded amateurs. The resulting filters achieve top-quality performance at a fraction of the cost of commercially available crystal filters.

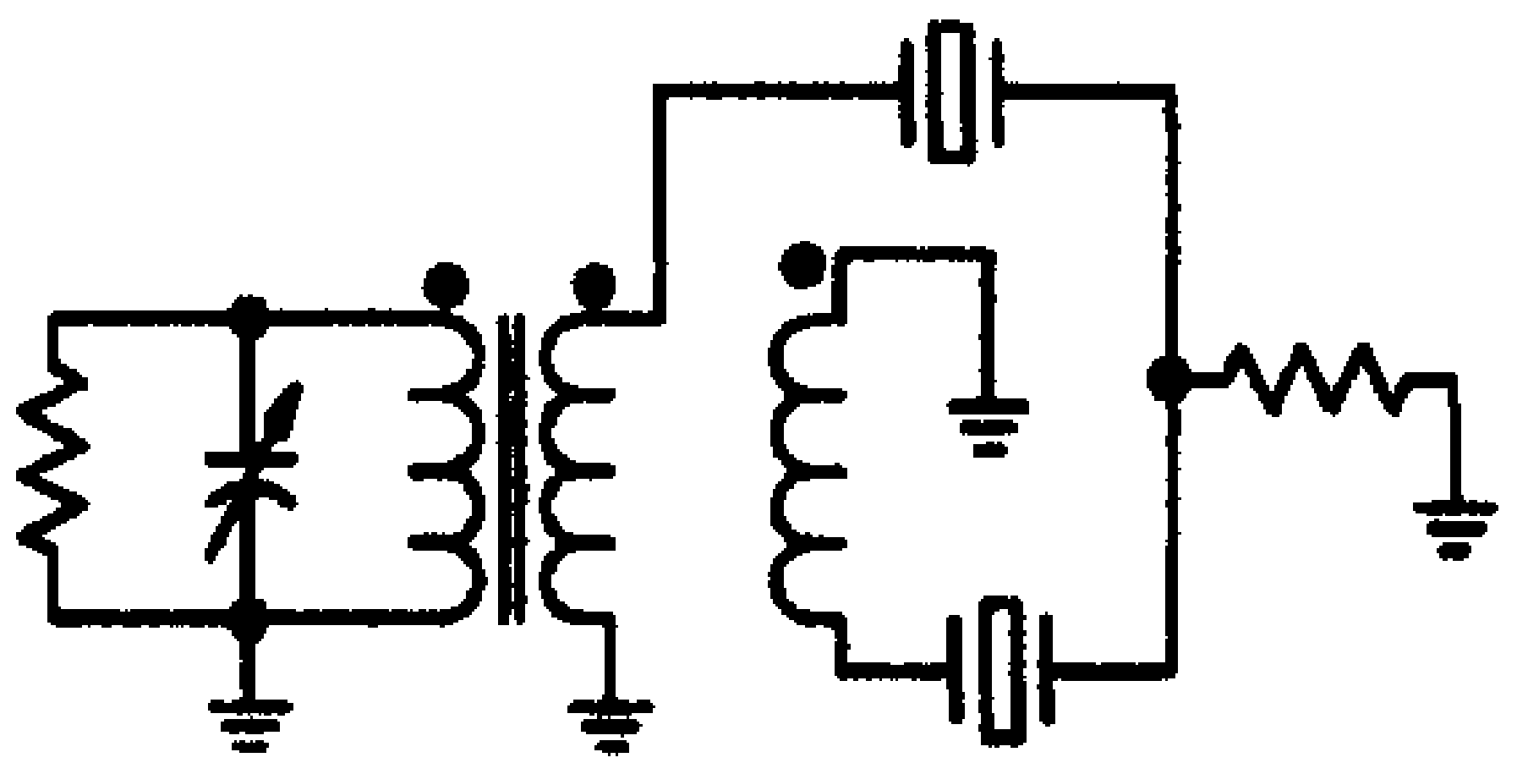
Most of the crystal filters described in amateur projects and those being sold commercially are lattice, half-lattice or cascaded half-lattice filters like those shown in Fig 1. A two- or four-crystal filter of this type can provide a symmetrical response with reasonably steep skirts. But the bandwidth of such filters is a function of the frequency separation of the crystals. If a steeper response is desired, designing a half-lattice filter with more than four crystals becomes more complex, requiring matched pairs of crystals and several adjustments. While it is reasonably easy to obtain matched crystal pairs for CW filters, it becomes considerably more problematic to obtain pairs of crystals separated by a couple of thousand hertz for use in SSB filters. In addition, the coils used for lattice filter alignment often use small cores, which can result in the degradation of dynamic range because of core saturation at high signal levels.

Another form of filter—which is the subject of this article—is the ladder filter shown in Fig 2. It typically has an asymmetrical response and is sometimes called the "lower-sideband ladder" configuration. But as we'll see, with a sufficient number of poles this asymmetry is significantly reduced. Ladder filters offer several advantages to the amateur experimenter:

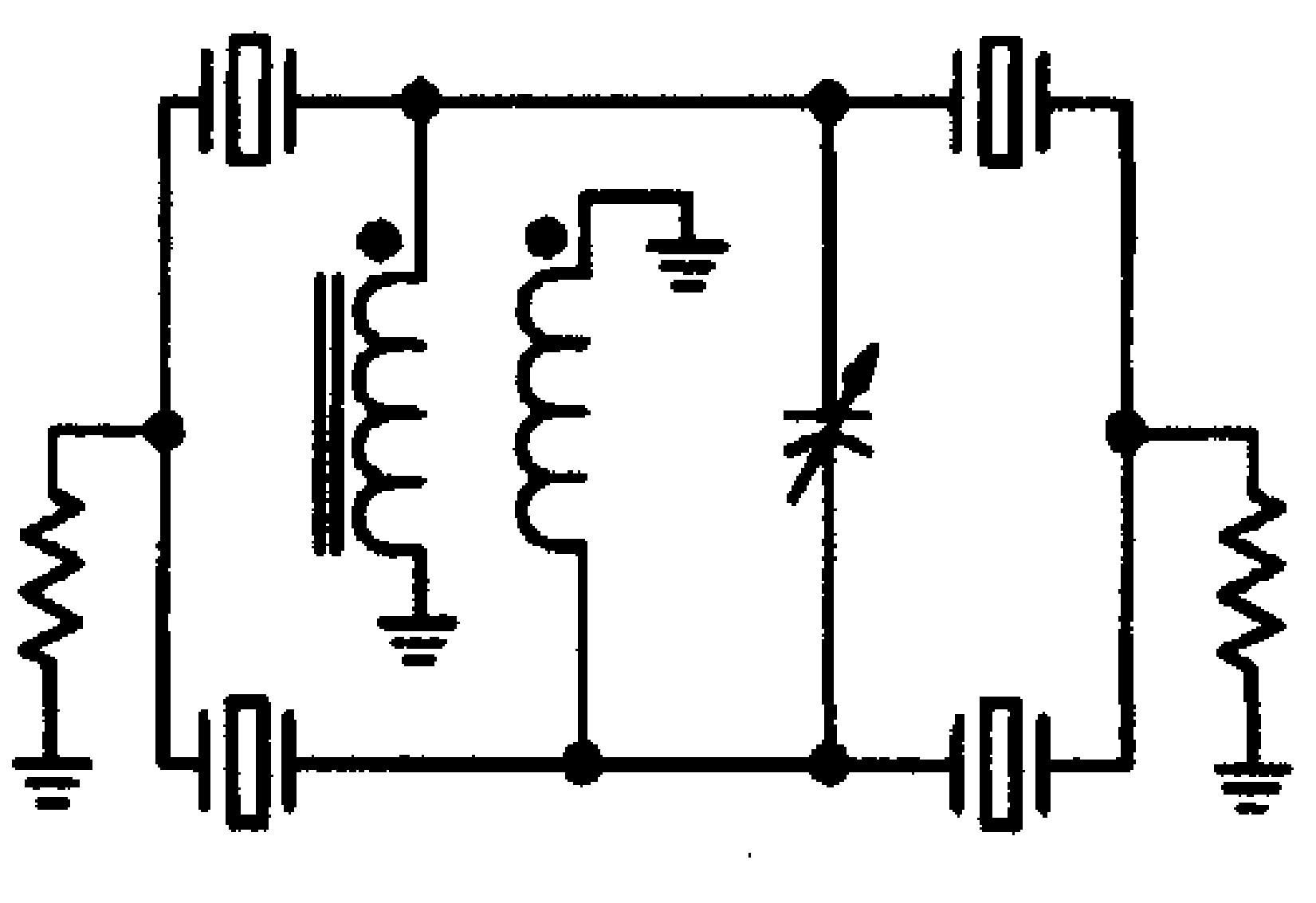
- there is no need to pick crystals for proper frequency separation and no need for matched crystal pairs;
- the inherently simpler filter topology results in simple construction methods;
- no adjustable components are required after alignment is completed;
- the absence of coils allows a compact assembly and reduces the possibility of dynamic range degradation;
- the simple topology is conducive to a high number of poles, which allows very steep skirts; and
- a computer program is available that eliminates the need for empirical approaches or cut-and-try methods and allows the designer to shape the filter response with great accuracy.



A) Lattice Crystal Filter



B) Half-Lattice Crystal Filter



C) Cascaded Half-Lattice Crystal Filter

Fig 1—Lattice crystal filter circuits.

This work was inspired by an article by Bill Carver, K6OLG/7.[1] Carver's work is quite remarkable; first, it proves that it is possible to build high-quality CW and SSB crystal filters with a predetermined frequency response "without black magic," and second (but of no less importance), it proves that the performance of filters built in a home lab using home-built equipment successfully rivals that of filters built using sophisticated professional equipment.

This article builds on Carver's work, refines the crystal filter design criteria and methodology, walks the reader through a complete design example, provides the results of measurements on several crystal ladder filters and analyzes the results.

The scope of this study has been limited to SSB filters, although most of the methods and conclusions are also applicable to CW filters.

The computer-design stage is based on a collection of computer programs designed by Wes Hayward, W7ZOI. The ARRL has just republished Wes Hayward's textbook *Introduction to Radio Frequency Design*, now including the software as part of the package.[2] The computer programs (which I will refer to as *IRFD*) run on an IBM PC or compatible computer. The computer requirements are minimal, since *IRFD* fits on a single floppy disk and the computer's speed is of no concern. A VGA card is required for graphic display, however.

The Design Procedure

Design and construction of these ladder crystal filters are performed using these steps:

- selection of the filter center frequency;
- measurement of crystal parameters;
- selection of the shape of the response;
- computer design of the filter; and
- construction and alignment.

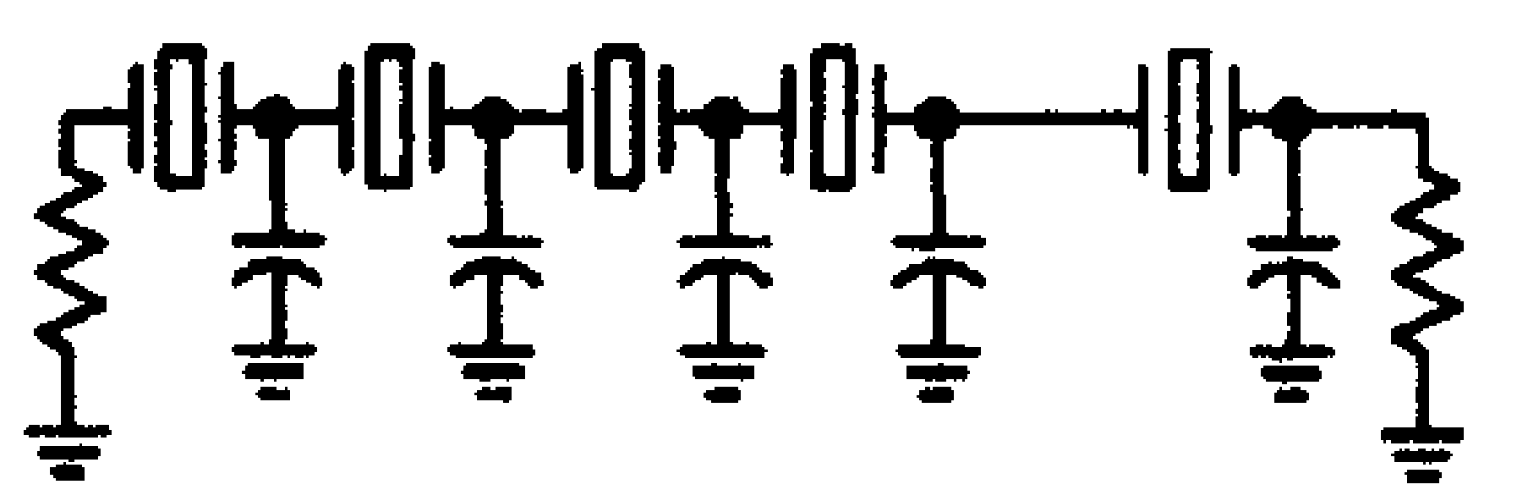


Fig 2—Circuit of a ladder crystal filter.

Frequency Selection

If the required filter frequency is not already defined, you can select an IF to suit your needs. In doing so, consider that certain frequencies may result in in-band intermodulation products. Tables and charts have been developed to help designers avoid these frequencies.[3] Practical considerations also impose some limitations on IF selection.

The crystals used in color-burst generators at 3.579 and 4.433 MHz are the most inexpensive crystals around and are widely available as surplus components. Unfortunately, the required termination resistances of filters built with such crystals may exceed 10 kΩ, which necessitates an impedance transformation with a very high ratio (for a 50-Ω system). As a result, very high voltage levels may be developed at the filter input, which may cause an overload condition. In addition, the required values of the coupling capacitors may be under 5 pF, making construction difficult due to stray capacitances. For these reasons, crystal filters with center frequencies under 6 MHz are not recommended.

The useful upper frequency limit is determined by the influence of stray capacitances at frequencies above 10 MHz and by the limitations imposed on the VFO circuit for multiband HF operation. Consequently, the recommended frequency range for an HF SSB crystal filter is between 6 and 12 MHz. The remaining criteria for the crystal frequency selection are the crystal Q and the price. Microprocessor crystals in HC18/U or HC49/U cases are reasonably inexpensive, but, being manufactured in large quantities, they are optimized for parameters other than Q.

Q is typically not specified by the manufacturer, and it varies significantly from batch to batch and from device to device within a batch. Therefore, the only way to find the Q of a specific type of crystal is to obtain several samples and to measure the parameters. This should be done before buying a large batch of crystals.

I originally intended to build crystal filters at 9 MHz, which is a popular IF within the amateur community, but it turned out that all the 9-MHz crystals I obtained (from different vendors)

[1] Notes appear on page 17.

had Qs below 80,000. On the other hand, I found 8-MHz crystals with much higher Qs, so all of the crystal filters described in this article are built using 8-MHz (series resonance) crystals.

Crystal Parameters

The equivalent circuit of a quartz crystal is shown in Fig 3. The computer software we will use to design the ladder filter requires entry of the crystal parameters. These parameters are easily measured with the use of a lab-quality impedance analyzer, but they also can be measured quite accurately using home-built equipment. The test equipment required to measure crystal parameters has been described previously and is beyond the scope of this article.[1,4,5] The parameters needed for the design process are: ΔF, the frequency offset or deviation from the specified center frequency; r, the series resistance of the crystal; f_L and f_H, the 3-dB points required for the Q calculation; and L_m, the motional inductance, which is derived from the Q and r. C_0, the parallel or "holder" capacitance, can be measured, but an assumption that C_0 is 5 pF (which I verified for several crystals in HC49/U cases) appears to be adequate in most cases.

There are several practical considerations in selecting and handling the crystals you will use. For one thing, the design process is easier if the crystals to be used in a particular filter are selected from a large pool of crystals. Although it's not essential, the crystals can be matched for Q, L_m and ΔF. Buying a large batch of crystals may provide a volume discount and furnish you with several sets of filter crystals. To illustrate the point, I bought 100 8-MHz crystals for a total of $60. Out of that batch I used 14 crystals with an average Q of 145,000 for a 14-pole filter, 10 crystals with an average Q of 122,000 for a 10-pole filter and 12 crystals with an average Q of 110,000 for a 12-pole filter. I rejected the remaining 64 crystals. Three high-quality crystal filters for $60—not bad!

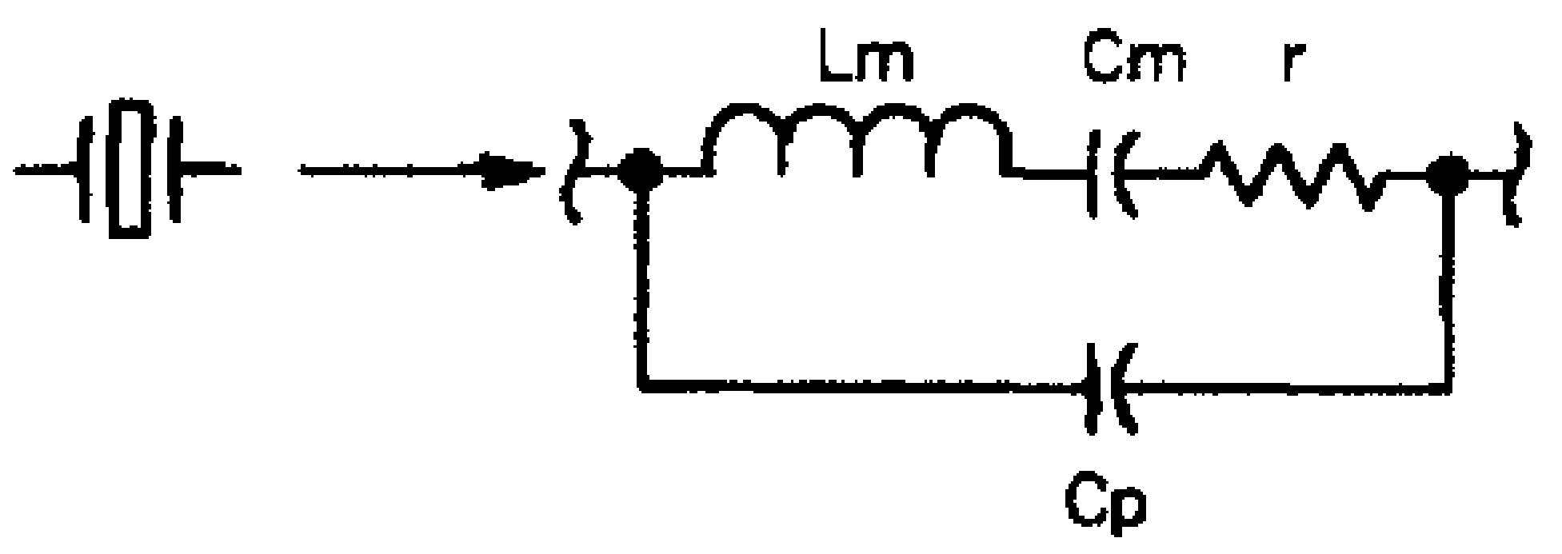


Fig 3—Equivalent circuit of a quartz crystal.

The crystals should be tagged before measurement, and the measurement results should be logged for future use. Invest sufficient time in this initial stage of the design since the accuracy of the data will affect the shape of the frequency response.

Take care to avoid heat transfer from your hands to the crystal cases, and allow 40 to 60 seconds between handling the crystals and performing the measurements to let the resonant frequency stabilize.

Once the measurements are completed, a preliminary group or groups of crystals with sufficiently high Q can be identified (grouped by Q within a certain range). Calculate the average motional inductance ($L_{m\text{-}av}$) and average Q (Q_{av}) for each group of crystals.

Filter Selection

An important part of the design process is selection of the desired filter parameters. The parameters you need to select are:

- the filter response type—Chebyshev, Butterworth, Gaussian, etc,
- the number of poles,
- the filter bandwidth, and
- the value of terminating resistances.

The Chebyshev response with 0.1 dB of ripple is the most commonly used response type for SSB HF filters. It may be advantageous in the final filter design to deviate slightly from the 0.1-dB ripple value to obtain more convenient values for the end coupling capacitors. Decreasing the ripple level value will result in a slightly smoother frequency response but will degrade the shape factor; an increase in the ripple value causes the opposite effect.

Several factors have a significant influence on the number of poles chosen for the crystal ladder filter:

- the desired shape factor,
- the insertion loss,
- the degree of asymmetry of the frequency response,
- construction considerations, and
- the size and weight (for portable use).

The shape factor is defined as the ratio of the filter bandwidth at a level of –80 or –60 dB to its bandwidth at the –6-dB level. In this article I'll use the –80/–6 dB shape factor, $SF_{6:80} = \Delta f_{-80}/\Delta f_{-6}$.

The required shape factor depends on the complexity of the receiver, its architecture and its specifications. Filters with more poles have better shape factors. (For example, the XF-9B10, a 10-pole, 9-MHz SSB filter manufactured by KVG Inc, has $SF_{6:80}$ = 1:1.8.) Fig 4 may help you select the needed number of poles,

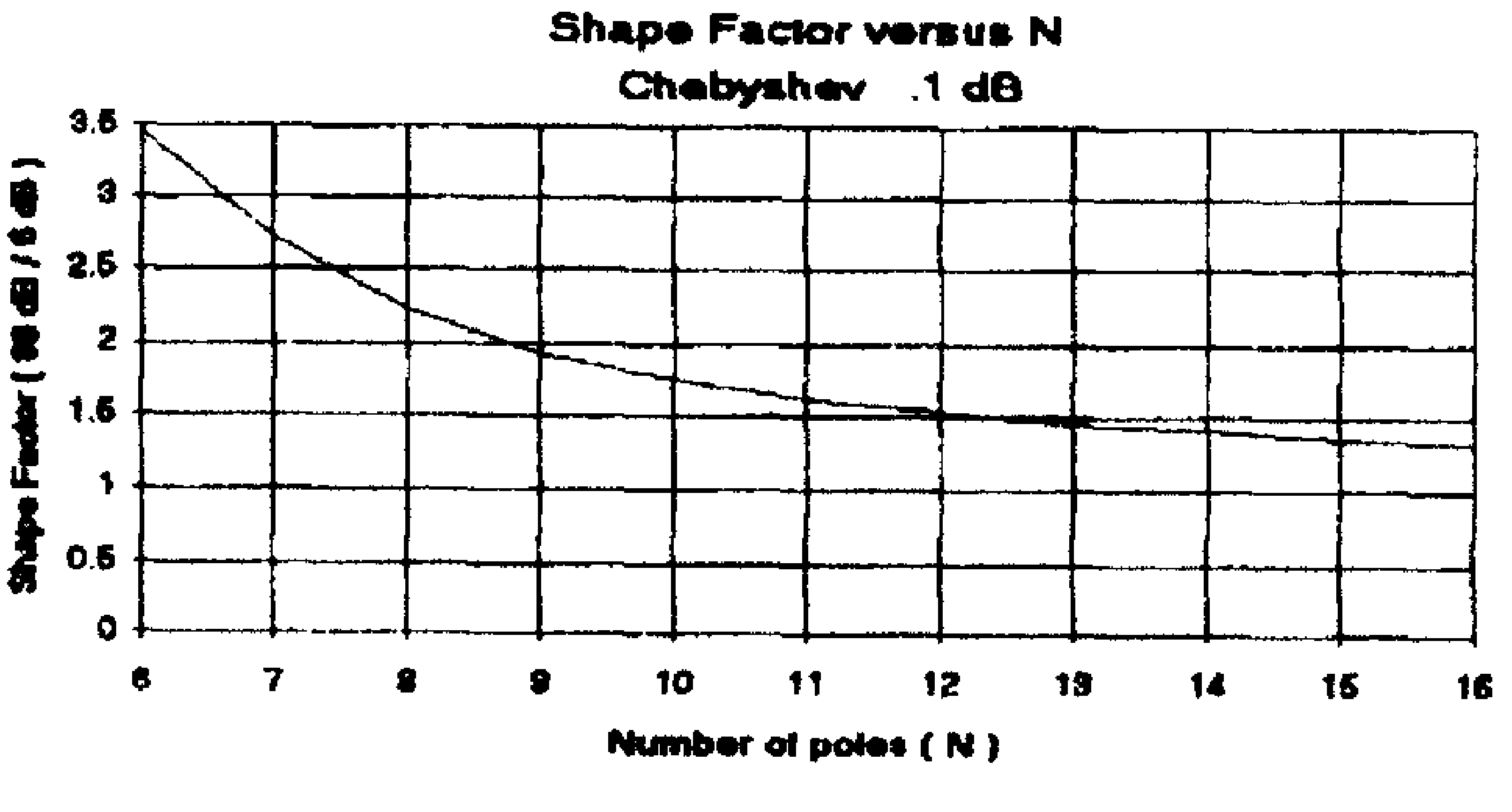


Fig 4—Graph of ladder filter shape factor (6:80) versus the number of poles for a Chebyshev response with 0.1 dB of ripple.

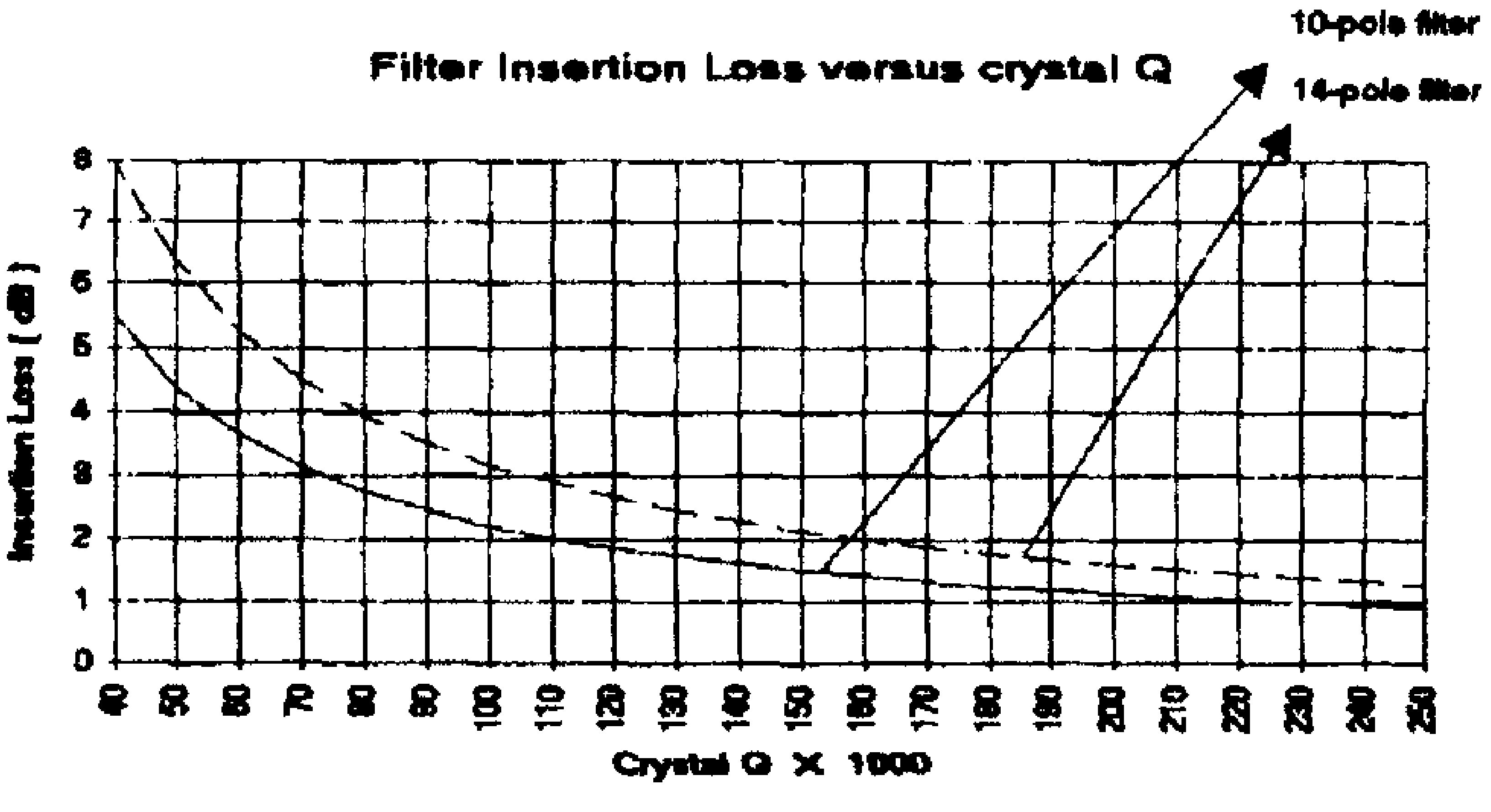


Fig 5—Graphs of filter insertion loss versus crystal Q.

based on the desired shape factor. Receivers having filters with good shape factors exhibit improved selectivity and a distinct "crisp" quality when tuning from one station to another.

Insertion loss, while strongly influenced by the Q of the crystals, also depends on the number of poles. The curves in Fig 5 show these effects. All other factors aside, the availability of good-quality crystals may be the deciding or limiting factor in selecting the number of poles. As shown in Fig 5, a 14-pole filter made of crystals having Qs of 160,000 has the same insertion loss as a 10-pole filter made of crystals having Qs of 110,000. The curves in Fig 5 were generated using *IRFD* and represent theoretical calculations performed by the program. Due to several limitations I'll discuss later, the practical results differ somewhat from the predicted values. But it is possible with a good degree of accuracy to make an estimate of the practical value of the insertion loss by adding 0.8 dB to the value obtained from Fig 5.

The asymmetry of the frequency response is inherent in crystal ladder filters, but by increasing the number of poles it is possible to overcome this shortcoming. While the asymmetry is obvious in a 10-pole filter, it becomes almost unnoticeable in a 14-pole filter.

Construction considerations will undoubtedly differ from one builder to another, but one observation is worth mentioning: I noticed during the construction of several ladder filters that to achieve good ultimate attenuation (more than 120 dB), the requirements for shielding between filter sections are considerably more stringent for a 10-pole filter than for a 12 or 14-pole filter.

Considering all the factors listed above, I recommend keeping the number of poles between 10 and 14. There is an advantage in having an even number of poles—it results in a symmetrical design, minimizing the number of different capacitor values needed.

Several factors influence the choice of bandwidth of the crystal filter:

- the desired selectivity—narrower filters may be preferred for contest work while wider filters may be more appropriate for casual rag-chewing,
- receiver sensitivity and dynamic range, and
- personal preference.

All of the filters discussed in this article have a bandwidth of 2500 Hz—mostly due to the last factor.

The value of the terminating resistance should be as low as possible to minimize the transformation ratio of the impedance-matching transformers, and the value should exceed the *IRFD* recommended value by an amount that ensures that the end coupling capacitors are at least 15 pF. You should choose the lowest impedance value consistent with these two criteria from Table 1. (The transformer ratios assume you want to match the filter to 50-Ω source and load impedances.)

Computer Design

Before starting the computer design, make sure you have calculated the average Q (Q_{av}) and motional inductance ($L_{m\text{-}av}$) of the crystals and have selected the desired bandwidth, number of poles and the ripple value.

Note that if the actual desired bandwidth is used directly in the crystal filter design, the filter designed by the *IRFD* program will have a bandwidth narrower than predicted. (This occurs because of simplifying assumptions used in the equations and the use of *k*

Table 1—Termination Resistances and Transformer Design

Impedance ratio	*Termination resistance (Ω)*	*Primary turns*	*Secondary turns*
1:1.5	75	4	5
1:2	100	5	7
1:3	150	4	7
1:4	200	4	8
1:5	250	4	9
1:6.25	312	4	10
1:7.5	375	4	11
1:9	450	4	12
1:10.6	530	4	13
1:12.25	612	4	14
1:14	700	4	15
1:16	800	4	16

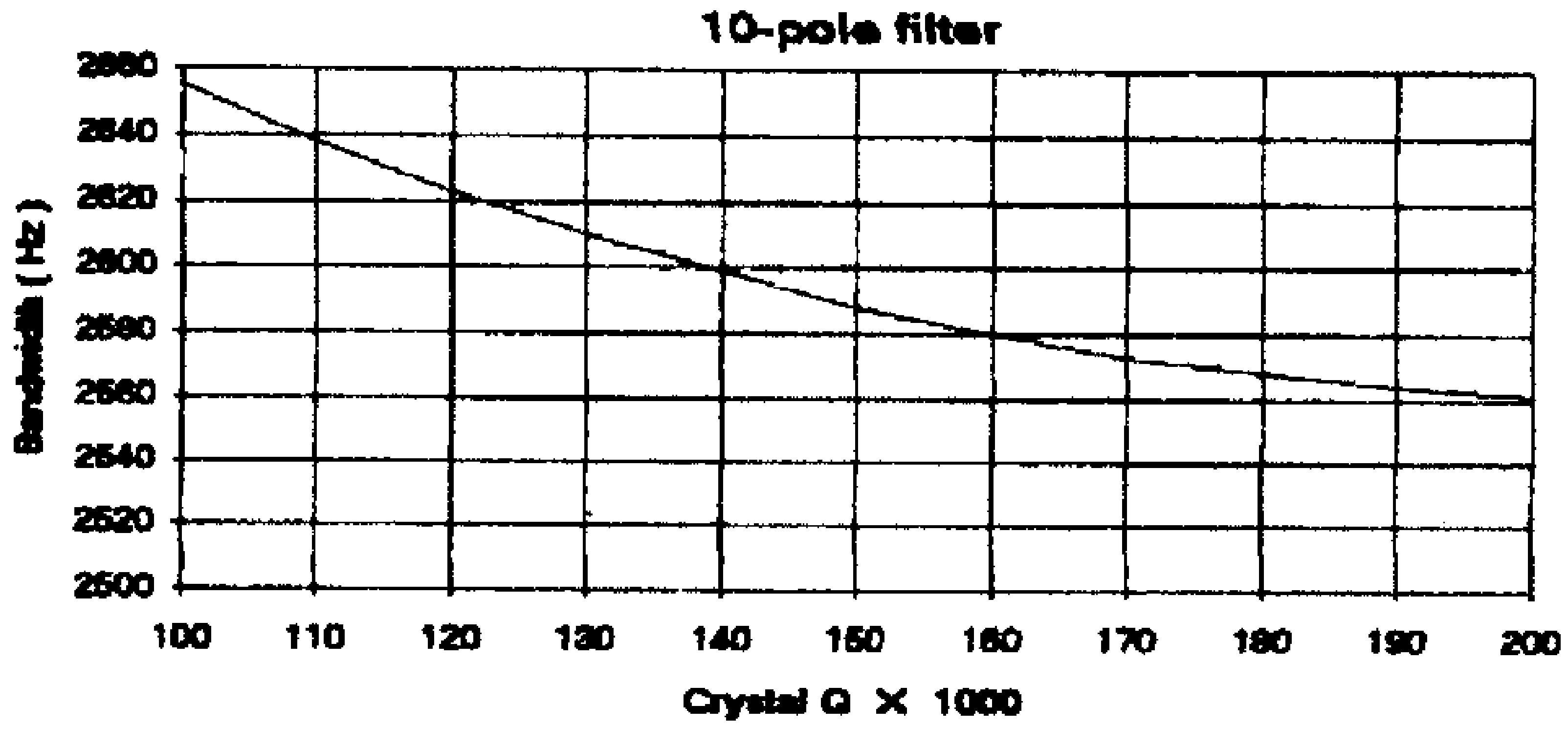


Fig 6—Graph of calculation bandwidth versus crystal Q for a 2500-Hz, 10-pole filter.

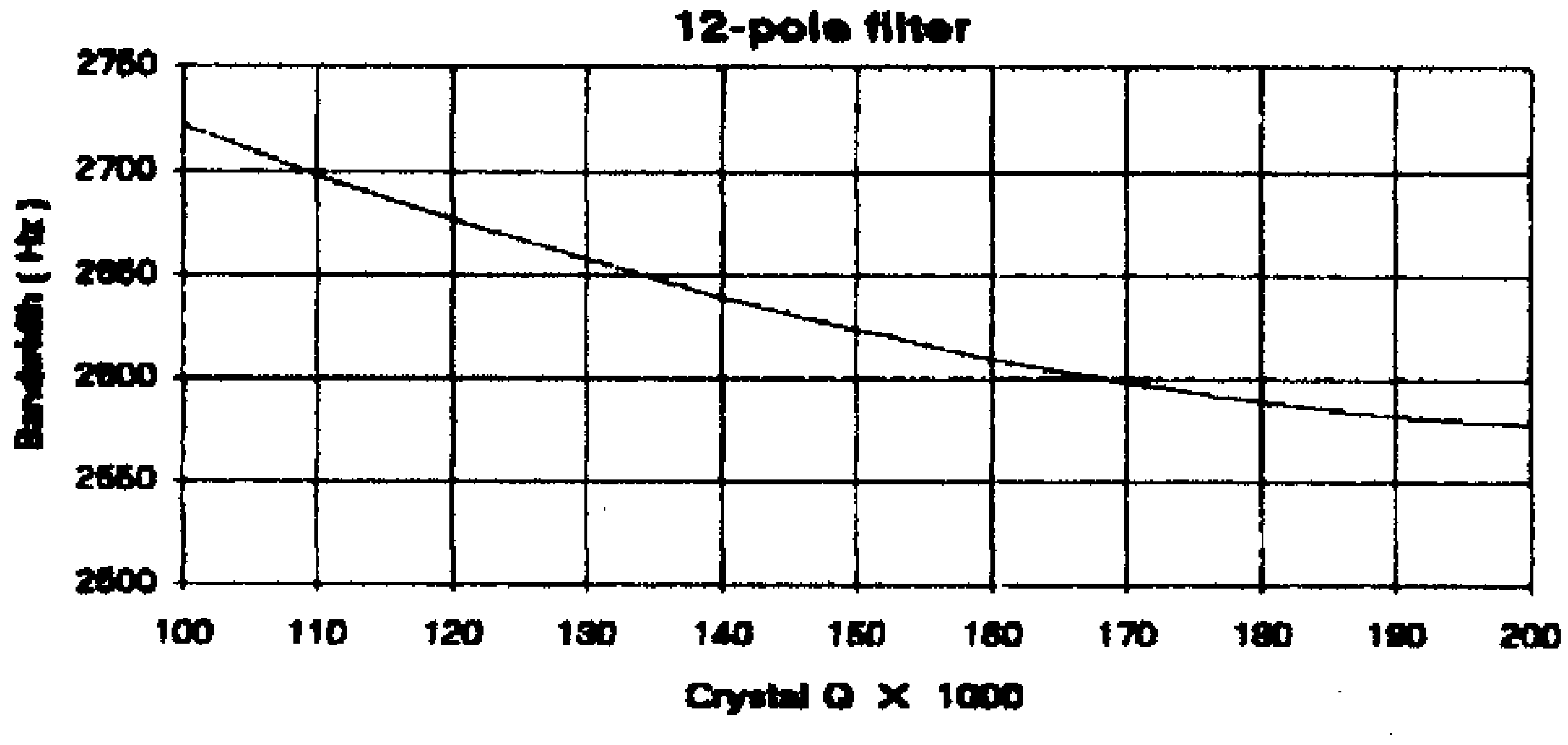


Fig 7—Graph of calculation bandwidth versus crystal Q for a 2500-Hz, 12-pole filter.

and *q* values based on lossless crystals.[4]) I've developed correction factors to compensate for this discrepancy. The bandwidth used for the computer calculations will be referred to as the calculation bandwidth (*BWc*), which can be obtained from the charts in Figs 6 through 8 for a desired bandwidth (*BWd*) of 2500 Hz.

To illustrate the design process, let's walk through the steps of an actual filter design. We'll begin by listing the design parameters:

Number of poles (*N*): 12
Desired bandwidth (*BWd*): 2500 Hz
Filter response type: Chebyshev, 0.1-dB ripple
Crystal (Q_{av}): 110,000
Motional inductance ($L_{m\text{-}av}$): 0.0155 H
Parallel capacitance (C_o): 5 pF
Nominal crystal frequency: 8 MHz

Four programs from the *IRFD* software package will be used to accomplish the design: *GPLA*, the *g*eneral purpose ladder analysis program; *L*, the low-pass filter design program; *X*, the ladder crystal filter design program; and *MESHTUNE*, a utility for tuning meshes in a crystal filter. In each program, the menu selections are selected by typing the appropriate letter key. Entry of numeric values is done by typing the value, then pressing the **Enter** key. (See the IRFD2MAN.TXT file supplied with *IRFD* for details of program operation.)

To start the design process, use the *L* program to generate *k* and *q* values for the filter. Run *L*, then select **K** from the menu. Type **12** for the number of poles, then **0.1** for the ripple, in dB. (The program calculates the needed values and stores them in a disk file for the *X* program to use.) Press the **Enter** key until the *L* program exits.

Next, run the *X* program to perform the ladder filter design. Select **K** from the menu to load the *k* and *q* values from the disk file. Type **12** for the number of meshes, **8** for the nominal crystal frequency, **0.0155** for the motional inductance in henries, **1** for the overtone, **5** for the parallel capacitance in pF (assumed), and **110** for the crystal Q in thousands. *X* now wants you to enter the *k* and *q* values. Since they are on disk, you can just press the **Enter** key repeatedly to load the data generated by the *L* program, until *X* stops asking for the values and instead asks for the bandwidth in hertz. The bandwidth you enter, **2700**, is the bandwidth obtained from the chart in Fig 7, for a 12-pole filter with a desired bandwidth of 2500 Hz. Press **Enter** to get to the source termination resistance prompt. Although the end resistance value given by the *X* program in this step is 206 Ω, an attempt to use the 250 Ω given in Table 1 fails—the actual minimum possible termination is 274 Ω. But the use of that termination value would make for very small (2.2 pF) end coupling capacitors, so the next highest termination value is selected from Table 1. Enter **312**. *X* will next ask for the termination value for the load end of the filter. Just press **Enter**, as 312 is now the default. At this point the values of the coupling capacitors are displayed on the screen. You can print a hard copy by using your computer's print-screen key. The values of all the capacitors are practical and can be easily realized with either a single capacitor or two capacitors in parallel. The values of the coupling capacitors will not be altered during the alignment stage and should be considered final. Pressing **Enter** displays the second set of data vital to the design: the mesh offset frequencies. You should print this screen as well, as this data will be used later in the design procedure. Another **Enter** displays the menu. It's useful at this point to closely examine the coupling capacitor values. If they appear satisfactory, you are done with this stage of the design and can save the designed filter to disk by pressing the **D** key. If you want to change the design, you can alter the termination resistances with the **R** key or change the calculation bandwidth with the **W** key.

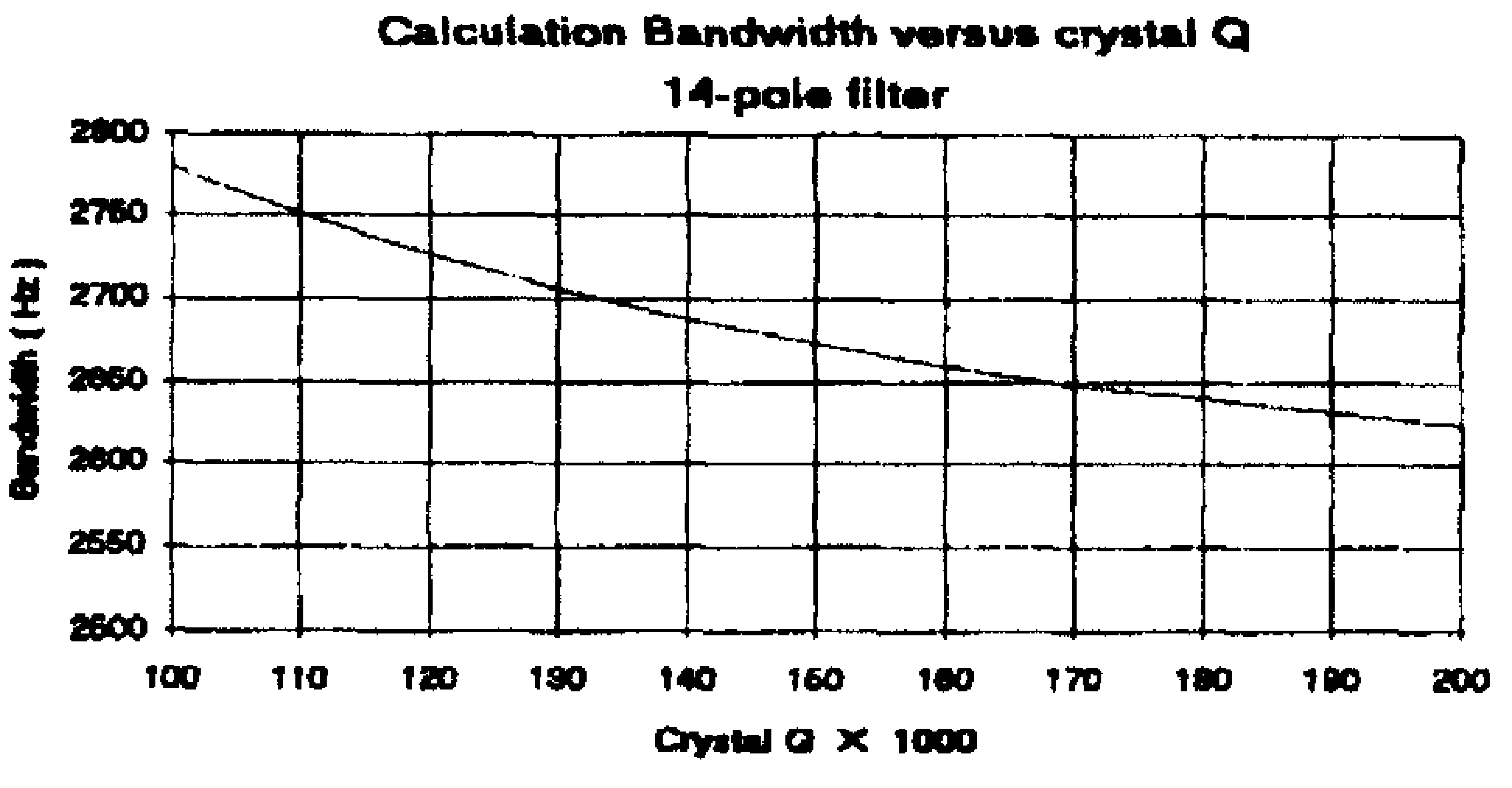


Fig 8—Graph of calculation bandwidth versus crystal Q for a 2500-Hz, 14-pole filter.

Altering the termination resistances affects only the values of the end coupling capacitors; it is easy to vary these values and see the effect, so feel free to experiment. Altering the bandwidth affects all of the coupling capacitors. You shouldn't change the bandwidth by more than about 30 Hz from the initial value since it will invalidate the later stages of the design procedure.

Changing the ripple value is another option, but the design will have to be repeated from scratch since the *k* and *q* values have to be changed by the *L* program. Possible values for the filter ripple may be between 0.07 and 0.15 dB.

Be sure to store the final design in a file using the **D** key. For this example, we'll call the file **12POL1**. (The *X* program will automatically add .CIR to the end of the file name.) The stored file can be viewed or edited with a text editor. Make a hard copy of the file for future reference.

We can investigate the response of the filter we've designed using the *GPLA* program. If you have a VGA display, *GPLA* can plot the frequency response of your screen. Run *GPLA* and read in the saved circuit using the **R** key. Once the file has been read in, press the **P** key to select plotting, then press the **H** key to get the filter gain plot. The filter response should be displayed. After viewing the plot, press the **Esc** key to return to the menu. To find the theoretical insertion loss of the filter, we need to adjust the sweep parameters to get a close-in look at the pass-band response. Press **S** to set up the sweep, type **400** for the beginning frequency, **3500** for the end frequency, **30** for the frequency step, **310** for the grid spacing, **10** for the screen bottom, and **1** for the dB/division. Then press **P** followed by **H**. The theoretical insertion loss of the filter is the distance from the top of the plot to the highest point on the response curve, at 1 dB per division. The loss appears to be slightly over 2 dB. A practical value for the loss may be estimated by adding 0.8 dB to the theoretical loss, for a result of about 3 dB. To exit this screen press **Esc**.

If crystal resonators with frequency offsets equal to the mesh offset frequencies listed by the *X* program were available, the computer design would be finished at this point. Since that's unlikely, additional steps are required in order to tune the crystals to the required offset frequencies, making the use of crystals with random (but known) offset frequencies possible.

To accomplish this, tuning capacitors are inserted in series with the crystals. These capacitors allow considerable design flexibility and tune every crystal to the same "loop frequency."[1,4] This modification results in the schematic diagram shown in Fig 9.

Our next step is to "build" this new filter circuit for analysis using a utility program and the *IRFD* software. We will do this by creating a modified copy of the 12POL1.CIR circuit file. Our new circuit file adds series tuning capacitances to the circuit and changes the original crystal offset frequencies calculated by the *X* program to the actual measured offset frequencies (ΔF) of the crystals we will use in the filter. All of the values we need to deal with are shown in Table 2.

If you investigate the coupling capacitor values and the mesh offset frequencies shown in Table 2 (or on your hard copy from the *X* program), you'll find that the values are symmetrical around the middle. Although it's not essential, it is helpful to arrange the crystals in pairs in an attempt to preserve the symmetry. Columns A and B in Table 2 help to illustrate the arrangement. The two crystals with the highest positive frequency offset are placed at the edges (X2 and X35). The two crystals with the highest negative offset are placed next (X5 and X32). The remaining crystals are arranged monotonically and symmetrically around the middle.

The *CLFMOD* program (see Listing 1) is a simple utility program written in BASIC by Jon Bloom, KE3Z, of ARRL HQ.[6] It reads the original filter circuit file output by the *X* program and writes the modified circuit file we will work with (call it 12POL2.CIR). This file adds the tuning capacitors to the original filter circuit, setting the value of each tuning capacitor to 200 pF. It will ask you to enter the measured frequency offsets of the crystals, as shown in column B of Table 2, and it will calculate and display the combined offset shown in column D of Table 2. These values will also be written to the OFFSETS.CLF file. (It's helpful to make a table like Table 2 so you don't get lost.) Note that if you arranged the crystals as recommended, the spread of the offset frequencies in the middle of column D is minimized, which leads to a narrow spread of the eventual tuning capacitor values, as shown in column F. (The coupling capacitor values obtained earlier are presented in column J.)

Now the values of the tuning capacitors should be calculated and entered into the circuit. We will use the

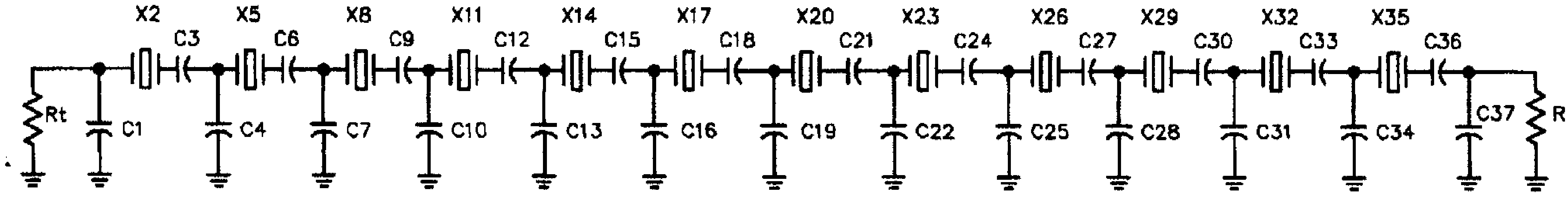


Fig 9—Schematic diagram of the example 12-pole crystal filter.

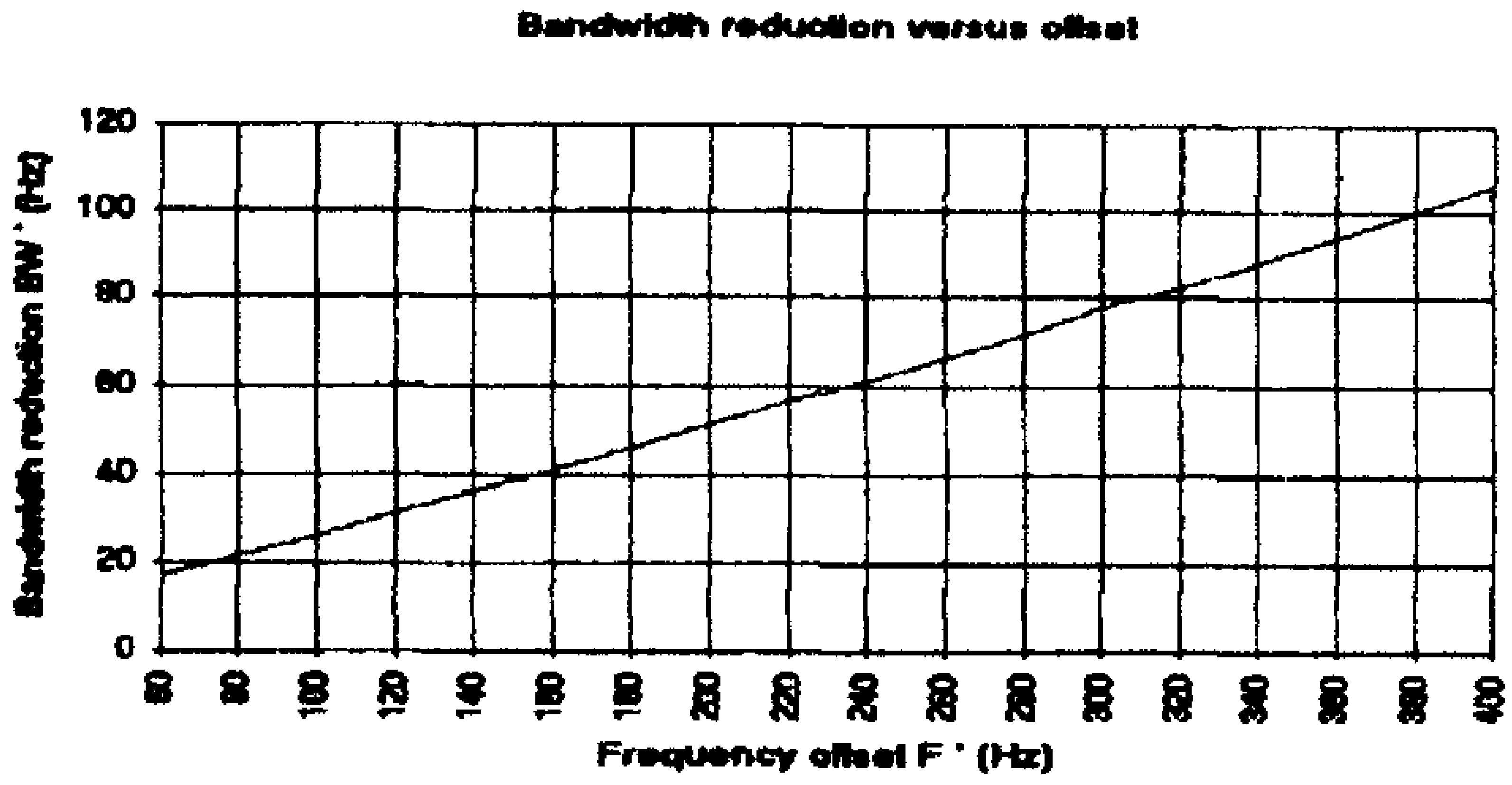


Fig 10—Bandwidth-reduction graph. The needed frequency offset can be obtained once the desired bandwidth reduction is found.

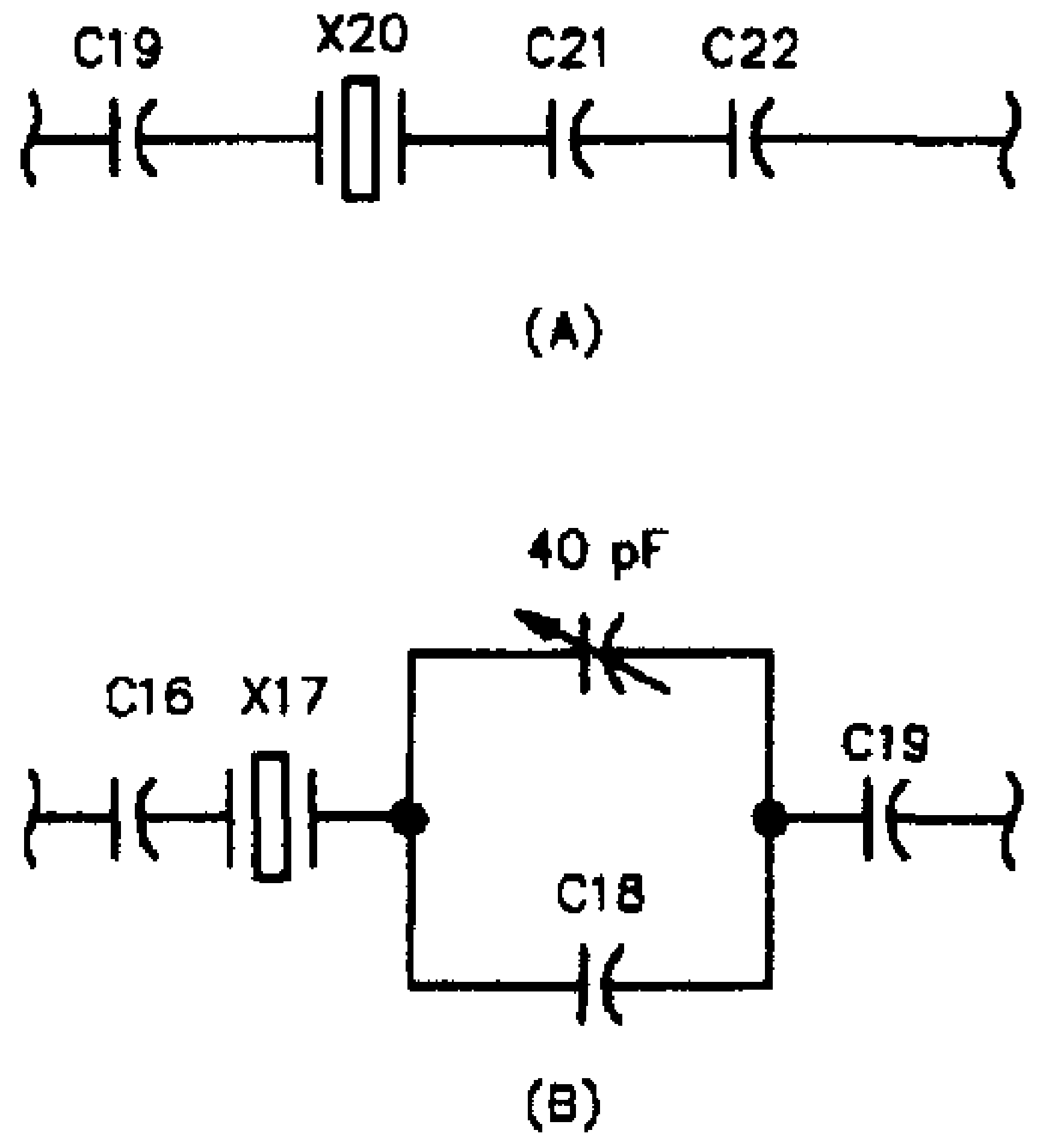


Fig 11—Filter alignment circuits. The resonant frequency of the reference loop is measured using the circuit at A. For the other loops, the required tuning capacitance is found by adjusting the variable capacitor at B to get the same resonant frequency.

MESHTUNE program to find the required tuning capacitor values. Run *MESHTUNE* and press **B** to start a new mesh. Type **8** for the nominal crystal frequency and press **Enter** for the crystal offset frequency. (Do *not* enter an offset frequency!) Type **0.0155** for the motional inductance and **0** for the crystal parallel capacitance. Press **Enter** to get to the interior/exterior prompt, then press **I**. Enter **10000000000** (1 followed by 10 zeroes) for the left-hand coupling capacitor and the same value for the right-hand coupling capacitor. Enter **300** for the initial value for the tuning capacitor. For the target offset frequency, enter the target offset frequency calculated by *CLFMOD* for this mesh (column D of Table 2). The actual mesh offset frequency and the target offset frequency will be displayed. Note whether the mesh is tuned too low or too high. (It's too low in this case.) Press **Enter** to get back to the menu. If the mesh was tuned too low, press the down arrow key to reduce the tuning capacitor; if the mesh is tuned high, press the up arrow key instead. The new tuning capacitor value will be displayed, as will the target and new actual mesh frequencies. Continue pressing the same key until the mesh frequency crosses over the target frequency.

To fine-tune the capacitor value, press the **S** key to set the tuning capacitor step. Enter **0.1** for the step size. Now, using the arrow keys, tune back across the target frequency until it again changes from too high to too low, or vice versa. At the point where it changes, the displayed tuning capacitor value will be within 0.1 pF of the perfect value—close enough! Enter the final capacitor value into column F of the table.

To obtain the next tuning capacitor value, start over by pressing **B**. Note now that most of the values you entered previously default to the correct numbers, so you can just press **Enter** for those parameters. Remember to enter the correct target offset frequency for the crystal you are tuning. Repeat the tuning process. For some crystals, the required value of tuning capacitance may be quite large. In such cases, you may want to increase the tuning step size using the **S** command. It's easy to watch the actual mesh frequency as you tune and get a feel for whether you need to raise or lower the step size for effective tuning.

The above tuning procedure may seem cumbersome, but once you get the hang of it, things go pretty quickly.

We now need to create the final filter circuit file so we can check its response using *GPLA*. Use a text editor such as DOS *EDIT* or *Windows Notepad* to open the 12POL2.CIR file. Each tuning capacitor entry consists of three lines:

```
cap   <ref>
ser
200
```

where <ref> is the reference designator of the component (e.g., C3). For each tuning capacitor, C3, C6,...C36, change the line reading 200 to the value for that capacitor from column F of Table 2. For C3, the result is:

```
cap   c3
ser
279.8
```

Do not change any of the other lines in the file. When all of the tuning capacitor values have been changed, save the file as 12POL3.CIR.

Next, run *GPLA* and press **R** to read in the 12POL3.CIR file. Then press **S** to set up the sweeps for a beginning frequency of **0**, an end frequency of **4000** a frequency step of **40**, a frequency grid spacing of **200**, a screen bottom of **10** and **1** dB per division. Then press **P** followed by **H** to see the filter response curve. Make an estimate of the insertion loss in the middle of the pass-band. Press **Esc** to return to the menu.

Determine the –3 dB points by changing the sweep settings to make the bottom of the screen 3 dB below the insertion loss. The insertion loss in this example is about 2.3 dB, so set the bottom to 2.3 + 3 = 5.3. When you redisplay the gain plot, the –3 dB level will be at the bottom of the screen, and a rough estimate of the bandwidth can be done by determining the two points at which the filter response curve meets the bottom of the chart. A more accurate estimate can be performed by modifying the sweep such that the gain curve originates at the beginning of the sweep interval and finishes at the end of the sweep interval. This sweep modification may require several tries to get it just right. In this example, you should end up with a sweep range of about 520 to 3225. The –3-dB bandwidth can be easily calcu-

Table 2—Design Parameters for the Example 12-Pole Filter

A	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*
Crystal #	*Crystal offset (Hz)*	*Mesh offset (Hz)*	*Combined offset (Hz)*	*C#*	*Tuning capacitor (pF)*	*New offset (Hz)*	*New tuning capacitor (pF)*	*C#*	*Coupling capacitor (pF)*
2	+17	381.99	364.99	3	279.8	534.99	190.9	1	23.84
5	- 67	0	67.0	6	1524	237	431.0	4	77.20
8	- 60	320.66	380.66	9	268.3	550.66	185.5	7	103.26
11	- 55	383.96	438.96	12	232.7	608.96	167.7	10	109.54
14	- 15	405.96	420.96	15	242.6	590.96	172.8	13	111.79
17	- 4	413.86	417.86	18	244.4	587.86	173.7	16	112.70
20	0	413.86	413.86	21	246.8	583.86	174.9	19	112.95
23	- 9	405.96	414.96	24	246.1	584.96	174.6	22	112.70
26	- 34	383.96	417.96	27	244.4	587.96	173.7	25	111.79
29	- 55	320.66	375.66	30	271.9	545.66	187.2	28	109.54
32	- 61	0	61.0	33	1674	231	442.1	31	103.26
35	+26	381.99	355.99	36	286.9	525.99	194.2	34	77.20
								37	23.84

lated: $BW_3 = 3225 - 520 = 2705$ Hz.

This bandwidth is too high for the final design, but that was done intentionally. The final step in the computer design involves adding an additional frequency offset to reduce the bandwidth to a predetermined value. The purpose of this procedure is twofold: first, it reduces the value of the tuning capacitors, making it more practical to use two parallel capacitors; second, it further narrows the range of capacitor values (see column H of Table 2), possibly minimizing the number of required capacitor values.

The target bandwidth for the computer design is 6.5% higher than the desired bandwidth: $BW_t = 1.065 \times BW_d = 1.065 \times 2500 = 2662$ Hz.

The bandwidth reduction: $BW' = BW_3 - BW_t = 2705 - 2662 = 43$ Hz. The additional frequency offset required to accomplish this bandwidth reduction can be obtained from Fig 10. From the chart, a 43-Hz reduction requires an additional frequency offset, $F' = 170$ Hz. Offset F' is added to the value of the combined offset in column D of Table 2, and the new value is entered in column G. (The *CLFOFS* program, included with the *CLFMOD* program, can be used to perform these calculations.) By using the *MESHTUNE* program and the tuning procedure described earlier new values for the tuning capacitors are obtained and entered in column H of Table 2. File 12POL3.CIR should be modified one more time to include the updated capacitor values and saved as 12POL4.CIR.

Finally, the filter bandwidth should be checked again. If the −3 dB bandwidth (BW_3) is within 15 Hz of the target bandwidth ($BW_t = 2662$ Hz), the computer design is completed. Otherwise modify the value of offset F' using the chart in Fig 10 as a guideline and calculate new tuning capacitor values to obtain the required target bandwidth.

Construction and Alignment

The construction method described in this section is an alternative to a printed-circuit board. The filter components are mounted on a piece of Vector board (Vector part no. 8007). The crystals, matching transformers and the attenuator are mounted on the copper side, which is used as a ground plane. All ground connections are made directly to the ground plane. The capacitors and the intersection shields are mounted on the pad side of the board. The interface with other stages is done through BNC connectors which can be soldered directly to the board, or via coaxial cables which can be soldered to Vector pins (Vector part no. T44). Photo 1 shows the filter assembly.

The construction involves several steps. In the first step, only the crystals are mounted on the board. The crystals identified previously should be arranged on the board in the sequence determined in column A of Table 2. The separation between the leads of adjacent crystals is 0.2". The leads should be soldered to the pads while making sure that the crystals are mounted firmly against the ground plane. I do not recommend you ground each crystal case via a wire ground strap; the risk of altering the crystal parameters during soldering is too great to take. The crystal leads should be clipped to ⅛ inch. It is helpful at this point to label the crystals on the pad side of the board for easy identification.

The second step is the formation of the coupling capacitances (see column J of Table 2). These are formed by paralleling capacitors, taking into account the approximately 3 pF of stray capacitance present:

C1, C37: 10 pF + 10 pF (+ 3.84 pF of stray capacitance)

C4, C34: 47 pF + 27 pF (+ 3.20 pF of stray capacitance)

C7, C31: 100 pF (+ 3.26 pF of stray capacitance)

C10, C28: 68 pF + 39 pF (+ 2.54 pF of stray capacitance)

C13, C25: 82 pF + 27 pF (+ 2.79 pF of stray capacitance)

C16, C22: 100 pF + 10 pF (+ 2.70 pF of stray capacitance)

C19: 100 pF + 10 pF (+ 2.85 pF of stray capacitance)

The selection process is greatly facilitated if the capacitors are picked from a 5% or 10% stock using a capacitance meter with at least 0.1-pF resolution. The parallel combinations of the selected capacitors should be formed by soldering them together and trimming the leads to 3/16 inch. The capacitors should then be tagged with their component number for easy identification.

To complete the design, the final values of the tuning capacitors must be determined. The values calculated in column H of Table 2 are preliminary but indicative of the capacitance range required for tuning. The tuning procedure is based on the fact, from filter theory, that each loop in the ladder filter should be resonant at the same frequency.[1,4] In other words, each crystal-and-tuning-capacitor combination, when put in series with the coupling capacitors on each side of it, should resonate at the same loop frequency.

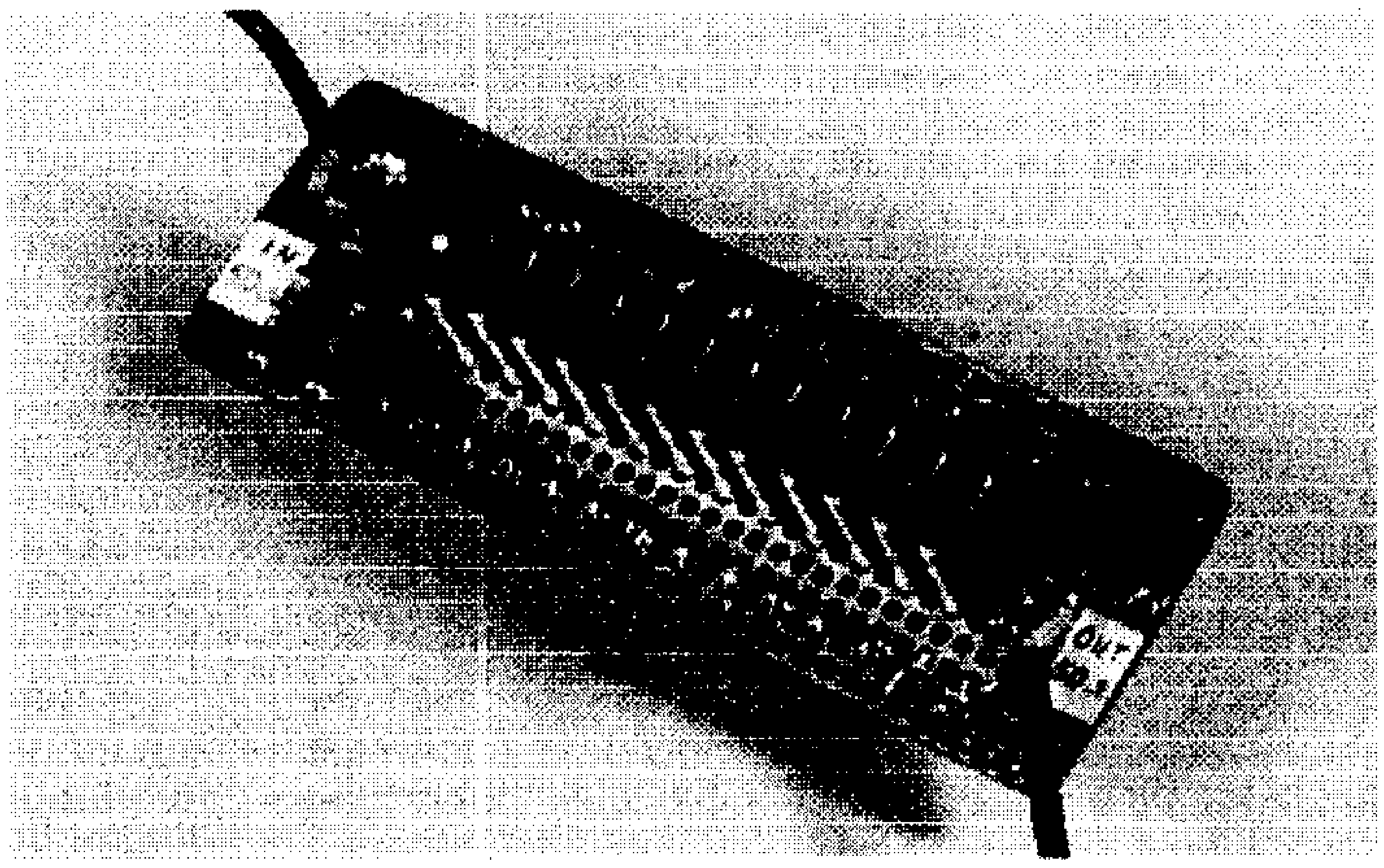


Photo 1

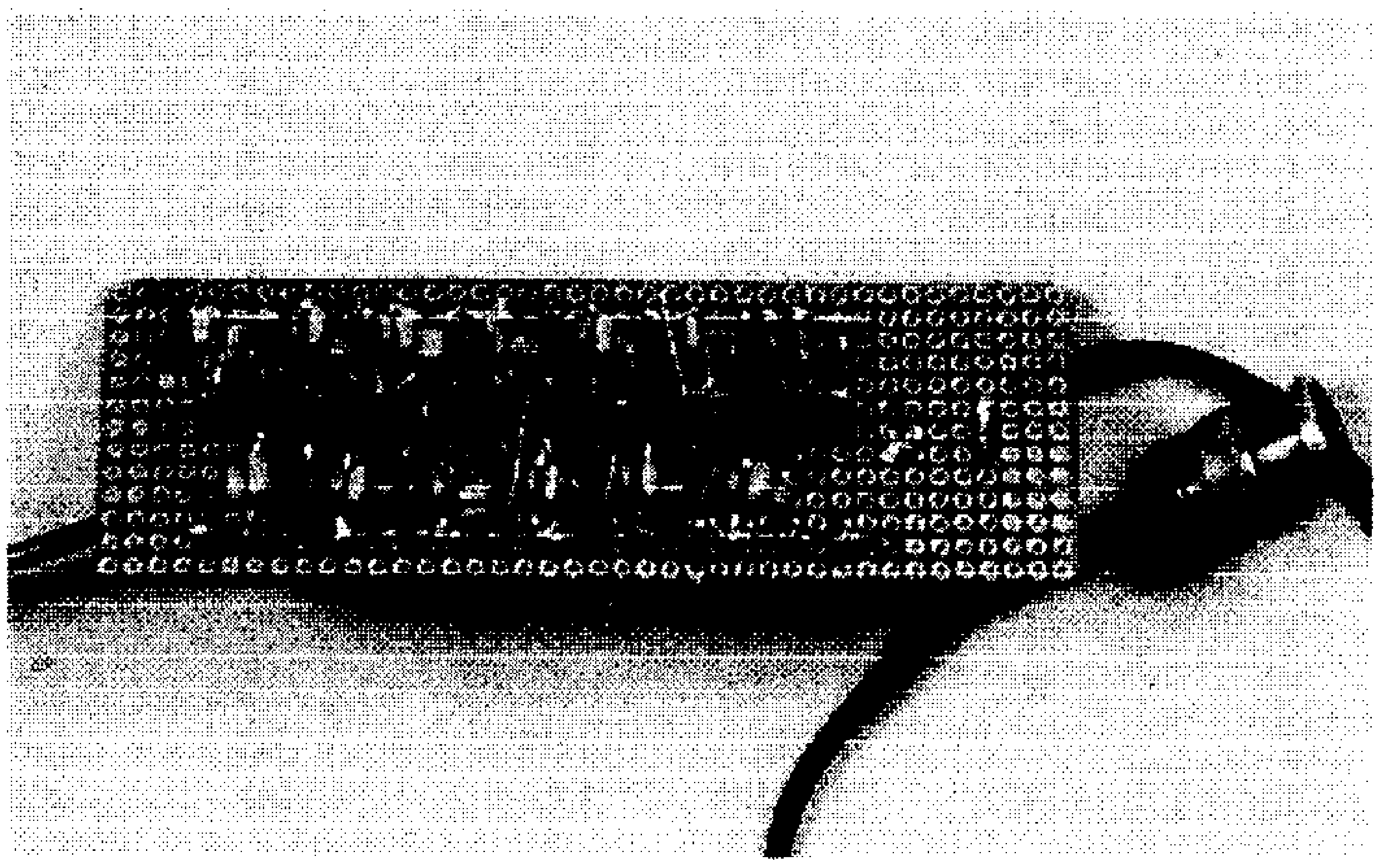


Photo 2

To find a starting point, refer to column H of Table 2. A convenient value from the middle of the column is selected: C21 = 174.93 pF = 150 pF + 22 pF (+ 2.93 pF of stray capacitance). Connect this parallel combination of two capacitors in series with crystal X20 (see Fig 9) and the two coupling capacitors on either side of the crystal, C19 and C22, as shown in Fig 11A. The series-resonant frequency of this circuit can be found with the aid of a crystal tester. This becomes the loop frequency, and all remaining loops have to be tuned to this frequency. Note that the predicted values of the tuning capacitors in the center section of the filter vary within a narrow range.

To determine the value of the next tuning capacitor, connect a parallel combination of a 150-pF capacitor and a 40-pF variable capacitor in series with crystal X17 (see Fig 10) and the two coupling capacitors on either side of the crystal, C16 and C19 (see Fig 11B). Use the crystal tester to measure the resonant frequency of this series combination, tuning the variable capacitor until the circuit is resonant at the loop frequency. The proper value for C18 is then found by measuring the value of the parallel combination of the 150-pF capacitor and the variable capacitor. Form this capacitance using paralleled fixed-value capacitors and tag it as C18. This procedure is repeated for all of the tuning capacitors except those at either end of the filter. During this procedure, each coupling capacitor is used twice: once while selecting a tuning capacitor on its left and again while selecting a tuning capacitor on its right.

The procedure for determining the values of the tuning capacitors at the ends of the filter differs only slightly: A 316-Ω resistor (the termination resistance) is placed across the end coupling capacitor, C1, when determining the value of C3 and across capacitor C37 when determining the value of C36. The terminating resistors lower the Q of the circuit, so the tuning of C3 and C36 is not very critical. Remember that when you perform filter measurements the scope probe capacitance (approximately 10 pF) and the generator output capacitance (approximately 5 pF) will be added to the respective terminals. Therefore, after the tuning process has been accomplished the values of capacitors C1 and C37 have to be modified to compensate for the source and load capacitances.

Once the values of all of the tuning capacitors have been determined, filter construction can continue. Construct the ground bars and mount them on the pad side of the board before installing the capacitors. Each ground bar is made from #16 copper wire (stripped of insulation), cut to a length of [(0.2 × N) + 0.5] inches, where N is the number of crystals. Place each ground bar symmetrically, 0.35-inch away from the pins of the crystals (see Fig 12) and solder it to the ground plane every 0.2 inch (every other hole) using jumpers made out of small-diameter hook-up wire. Next, solder the tuning capacitors in place following the placement diagram shown in Fig 12. Take care not to overheat the crystals during soldering. The load coupling capacitor, C37, and tuning capacitor, C36, are soldered to a Vector pin.

Install the coupling capacitors following the diagram of Fig 12. While the tuning capacitors are mounted horizontally, the coupling capacitors are placed vertically to conserve space. Make the capacitor leads as short as practical, keeping in mind that longer leads can cause excessive crosstalk between sections, and very short leads can lead to capacitor cracking during the soldering process. Provide sufficient clearance between adjacent sections to accommodate the shield ribs. These are made from ⅜-inch-wide strips of metal. Brass, copper or tinned 0.02-inch steel will do, providing it can be easily soldered to the ground plane. The shield is arranged in a "fish-bone" fashion. The center section is cut to a length of [(0.2 × N) + 3/16] inches and is placed vertically exactly in the middle between the pins of the crystals (see Photo 2). Keep it in place by soldering it to ⌈ shaped posts. These are made from #18 copper wire (stripped of insulation), with the short end soldered to the ground plane. Insert the intersection ribs between adjacent sections of the filter and solder them to the center rib on one side (at the top only) and to the ground bars on the other side. More comprehensive shielding can be accomplished by fully encapsulating the filter components in a metal enclosure, but I've obtained adequate performance without this precaution.

Matching transformers are used to present a 50-Ω input and output impedance to the outside world. The winding information is taken from Table 1. The transformers are wound with #32 enameled wire on two-hole ferrite balun cores (see Fig 13). In Table 1, "primary turns" refers to the number of turns from the tap to ground, and "secondary turns" refers to the number of turns of the entire winding. Mount both transformers on the ground-plane side of the board in close proximity to the crystals. Solder the tap leads to Vector pins on the ground-plane side of the board. The Vector pin on the input side is also connected to the output of a 3-dB attenuator (see Fig 14). Place the attenuator components on the ground-plane side of the board as well, making the connections on the pad side. Then con-

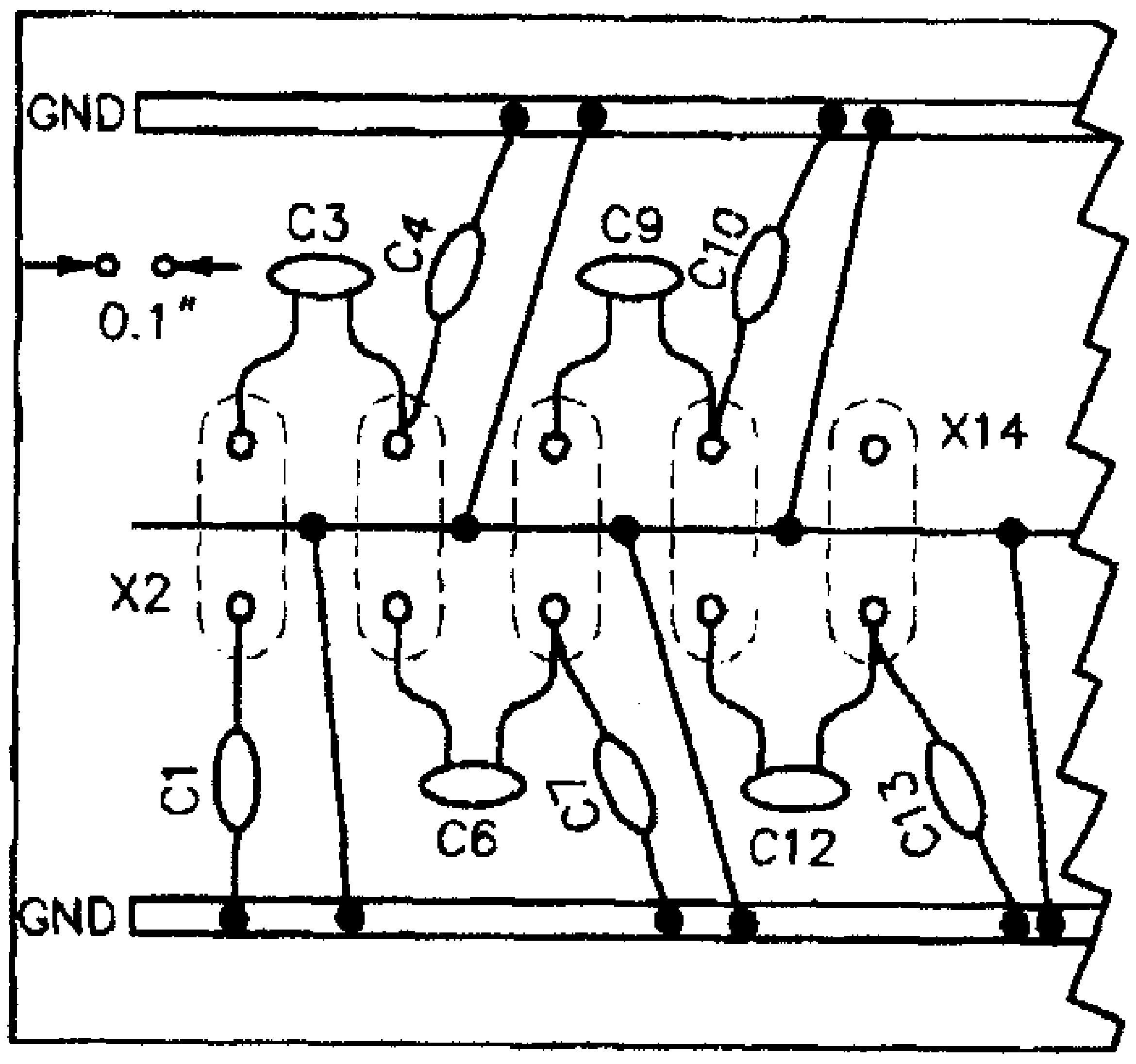


Fig 12—Layout diagram of the crystal filter.

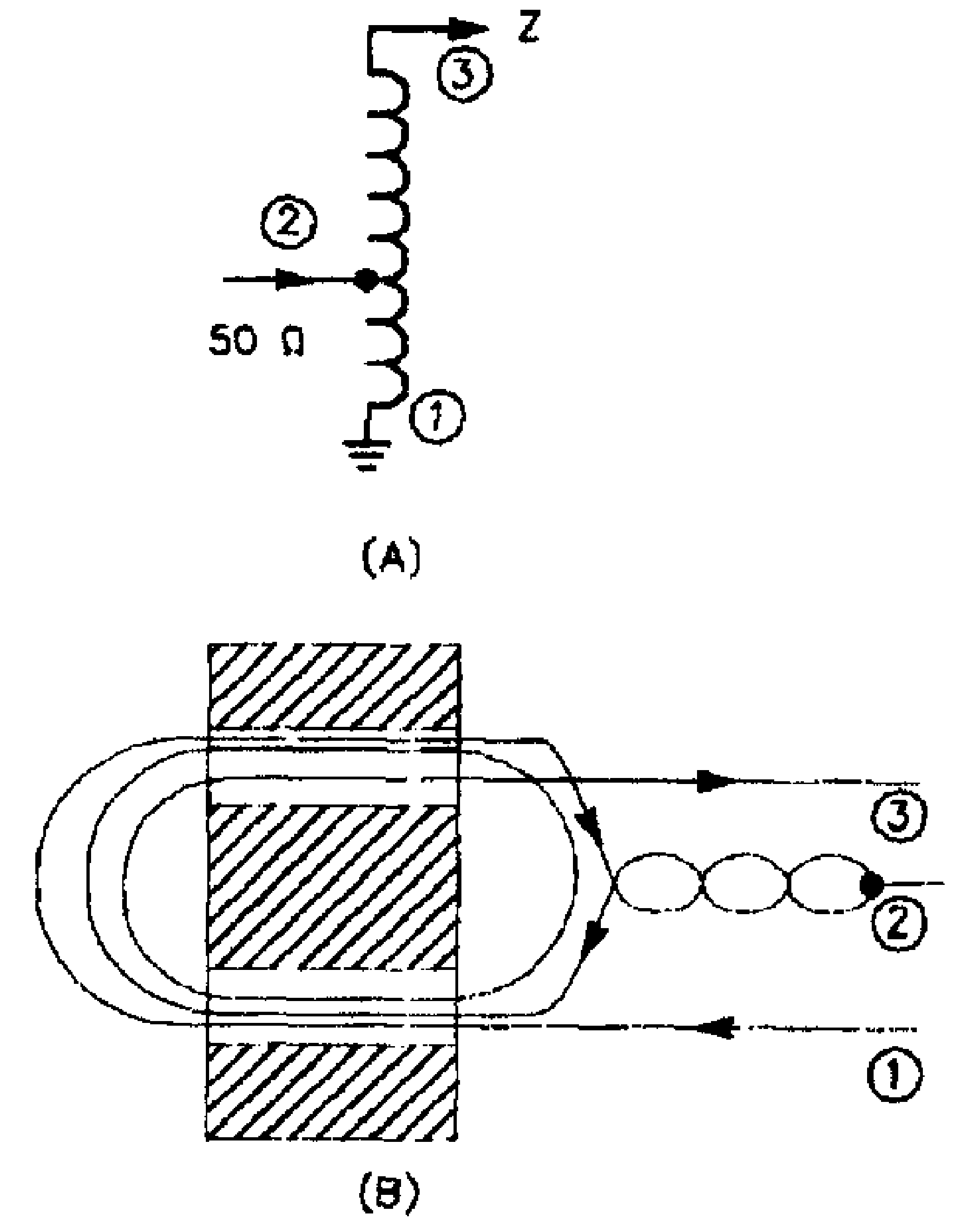


Fig 13—The matching transformers are tapped autotransformers (A), wound as shown at B.

nect the attenuator input to another Vector pin, which serves as the filter input terminal. The board area taken by the entire 12-pole filter circuit is 3¾ × 1⅛ inches.

Measurements

Now that the filter is finished, we need to measure its response, which should match the design objectives: shape of the response, –3 dB points, bandwidth, amount of ripple, insertion loss and the symmetry of the response. Making the measurements is a trivial task when a spectrum analyzer is at hand, or at least a good synthesized generator and a scope. Since few amateurs have the luxury of using lab-quality equipment, I suggest a simple method that should be within reach of the average experimenter. It requires the construction of a variable-frequency crystal oscillator (VXO). The VXO should tune from 8.000 MHz to at least 8.005 MHz. (One of the rejected filter crystals can be used in the VXO—use the one with the most negative offset.) The VXO should have a level adjustment control and adequate buffering at the output to prevent frequency pulling when being loaded by the crystal filter. Many variations of VXO design have been covered in the amateur literature.[4,7,8,9,10] A frequency counter with 1-Hz resolution and an oscilloscope are also needed to perform the measurement.

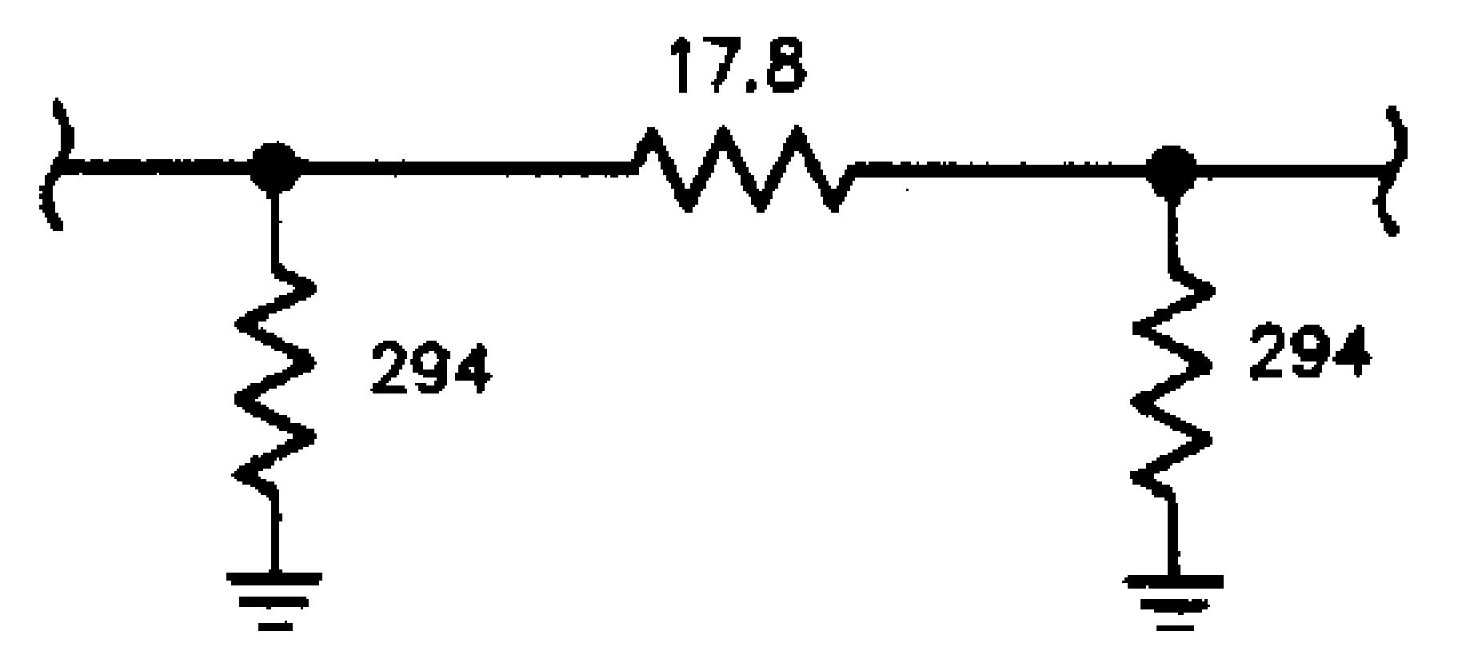


Fig 14—Schematic diagram of the 3-dB input attenuator used with the ladder filter.

The block diagram of the measurement setup is presented in Fig 15. The measurement procedure is to vary the frequency of the VXO in small increments (20 to 80 Hz) while monitoring and recording the signal level at the output of the filter at each frequency. Hold the VXO output level constant at every measurement point.

I used lab-quality test equipment (a Hewlett-Packard HP3585A spectrum analyzer) to measure three ladder filters—10-pole, 12-pole and 14-pole designed and constructed using the procedures outlined in this article. The measured response curves of these filters are shown in Fig 17, with the ripple level for the 14-pole filter shown in Fig 18. The measured bandwidth of all three filters is within 2% of the desired bandwidth, and the shape factor is within 3% of the calculated value. The ripple level is slightly higher than the projected value but significantly better than several commercial units I tested.

To compare the performance of my home-built ladder filters to that of commercially available crystal filters, I made a series of measurements using laboratory-grade measurement equipment. The block diagram of the measurement setup is given in Fig 16. The amplifier used in the measurement has an output third-order intercept point (OIP) of +48 dBm and a –1 dB output compression point of +27 dBm. One of my objectives was to study each crystal filter's dynamic range and its effect on the output intercept point of the driving amplifier.

Four crystal filters have been evaluated: a 2.2-kHz, 8-pole SSB filter from Fox-Tango Corp (part no. 2309) and the three home-built ladder filters mentioned previously. The Fox-Tango filter requires a 500-Ω impedance termination, so it was coupled to the amplifier via a 1:9 transformer. The test results were very similar for all three ladder filters, so they will be referred to collectively as the "ladder crystal filter."

The input impedance of the filters was examined using an HP impedance analyzer and re-examined after inserting an attenuator between the amplifier and the crystal filter. For the ladder filter, a 3-dB attenuator was used; a 6-dB attenuator was used with the Fox-Tango filter. Figs 19 through 22 show the results of these measurements.

To measure the IMD of the filters, I used two equal-level tones placed outside of the filter pass-band. The tone spacing was varied between 2 and 20 kHz without an appreciable effect on the third-order products measured at the output of the amplifier. These measurements were made at two different signal levels (+15 dBm and +10 dBm) in order to gauge the linearity of the system. The measurements were made while driving the filter directly by the amplifier and again

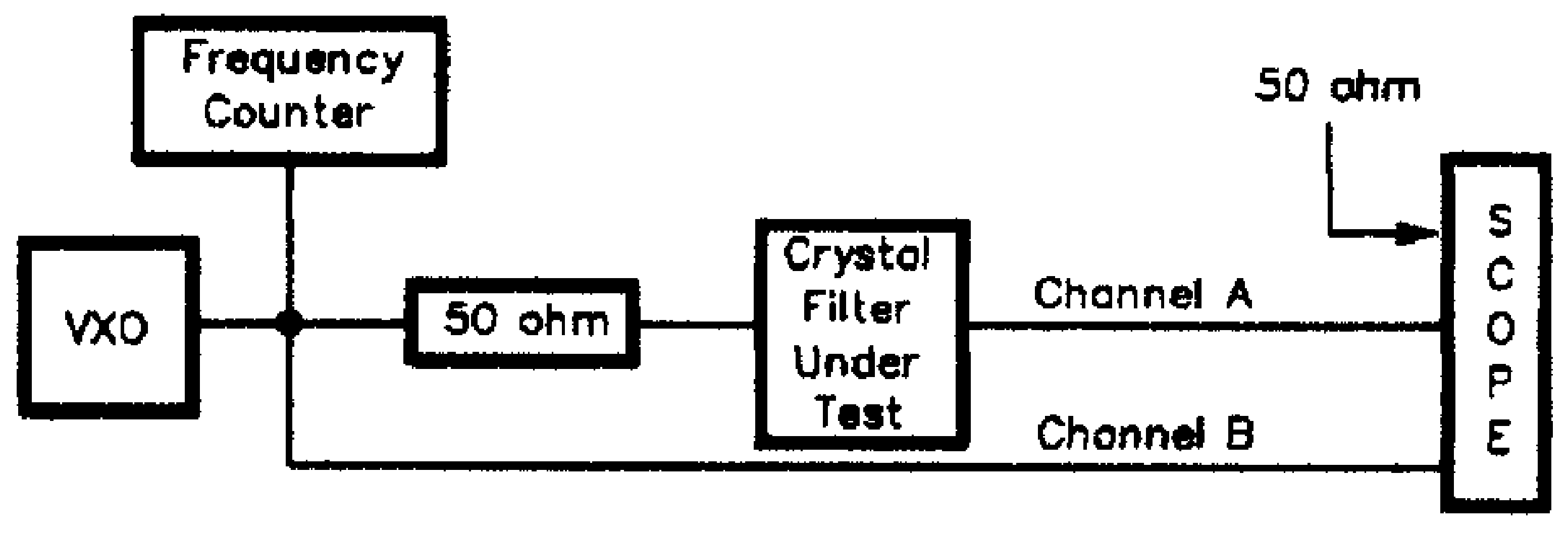


Fig 15—Block diagram of the filter evaluation test set-up.

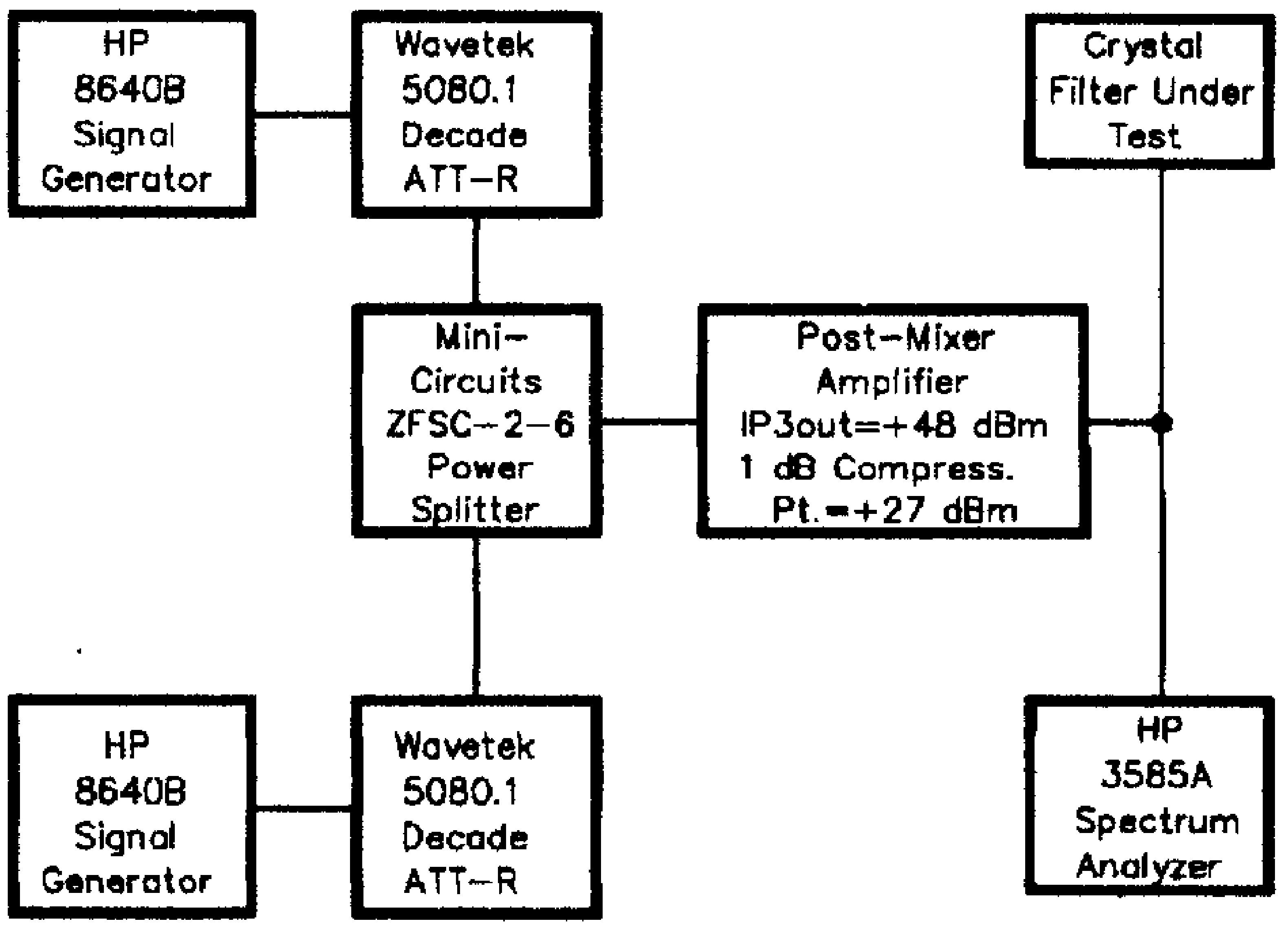
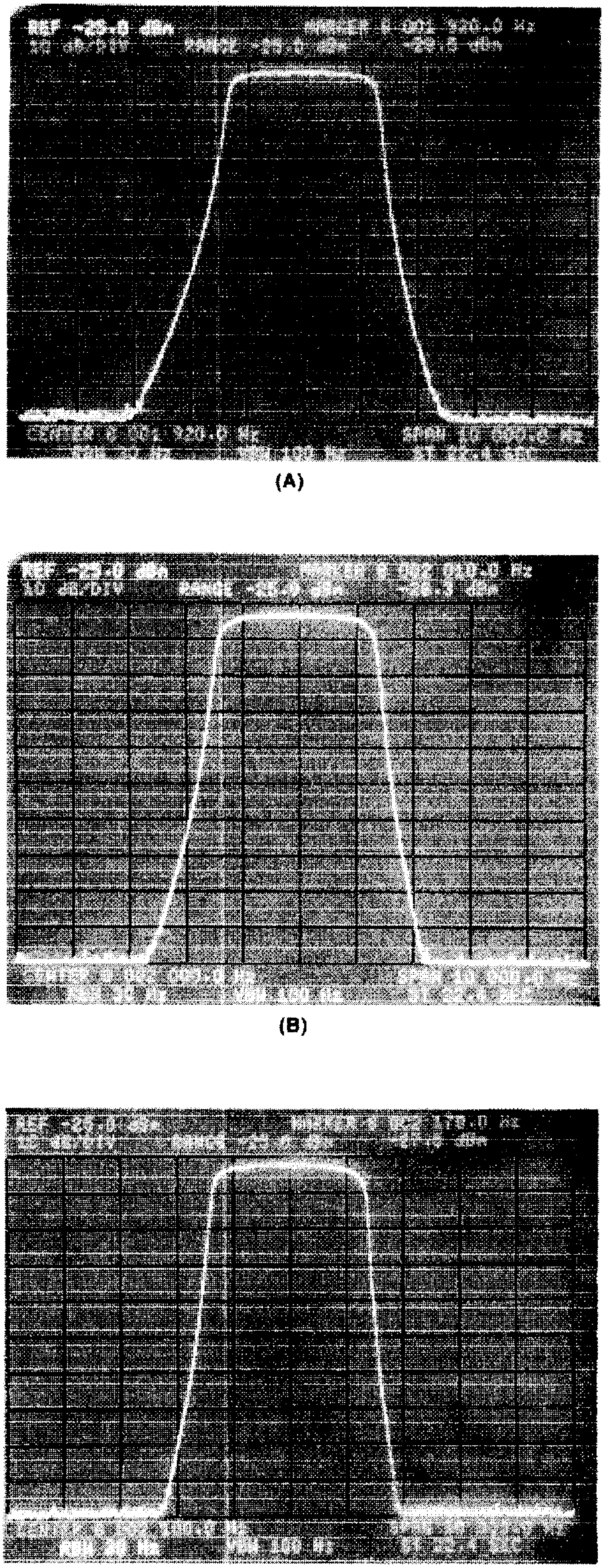


Fig 16—Block diagram of the filter IMD measurement test set-up.



(A)

(B)

(C)

Fig 17—The measured response of a 10-pole (A), 12-pole (B) and 14-pole (C) ladder filter built using the techniques described by the author. Vertical divisions are 10 dB; horizontal divisions are 1 kHz.

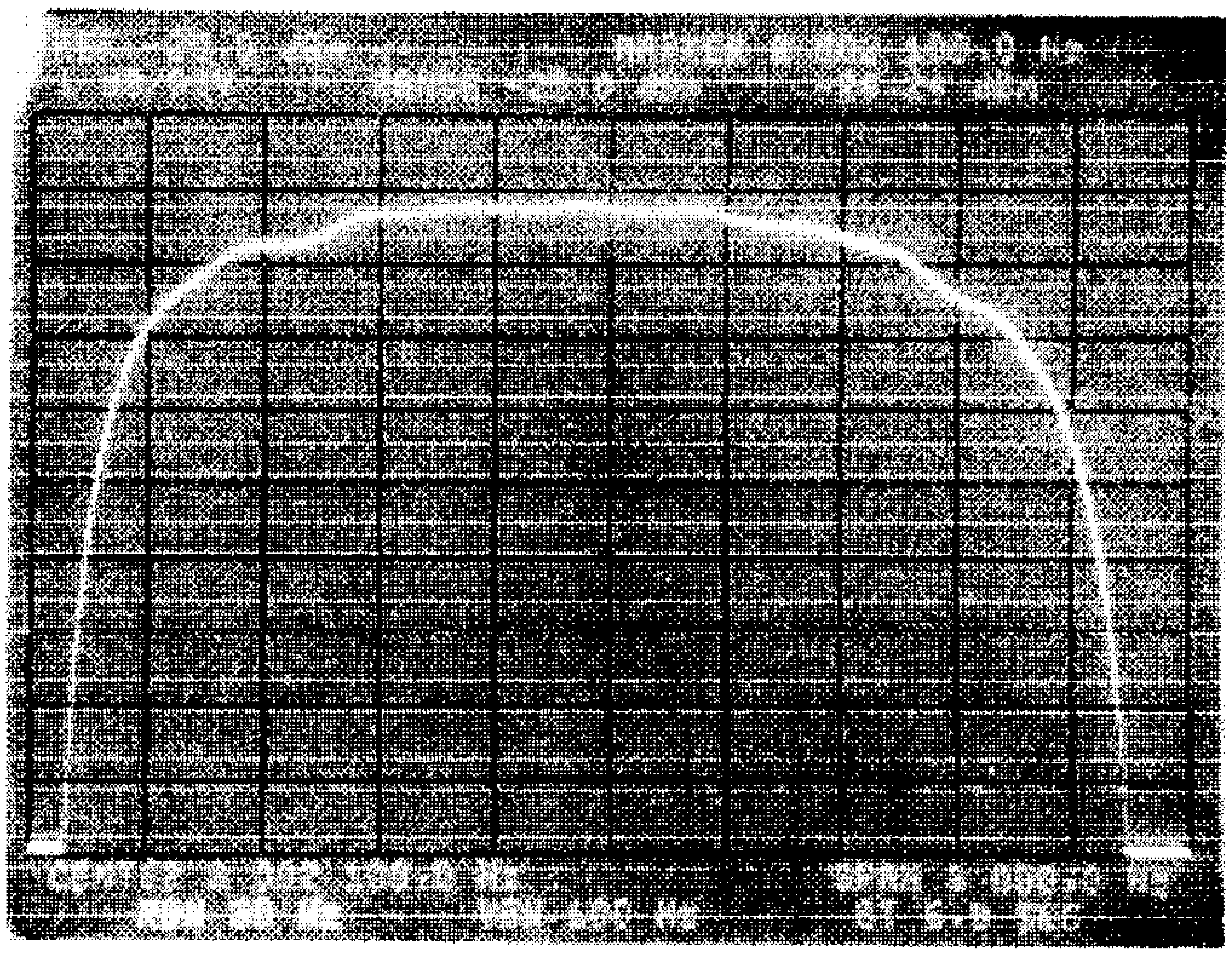


Fig 18—A close-in look at the response of the 14-pole ladder filter shows the pass-band ripple. Vertical divisions are 1 dB; horizontal divisions are 300 Hz.

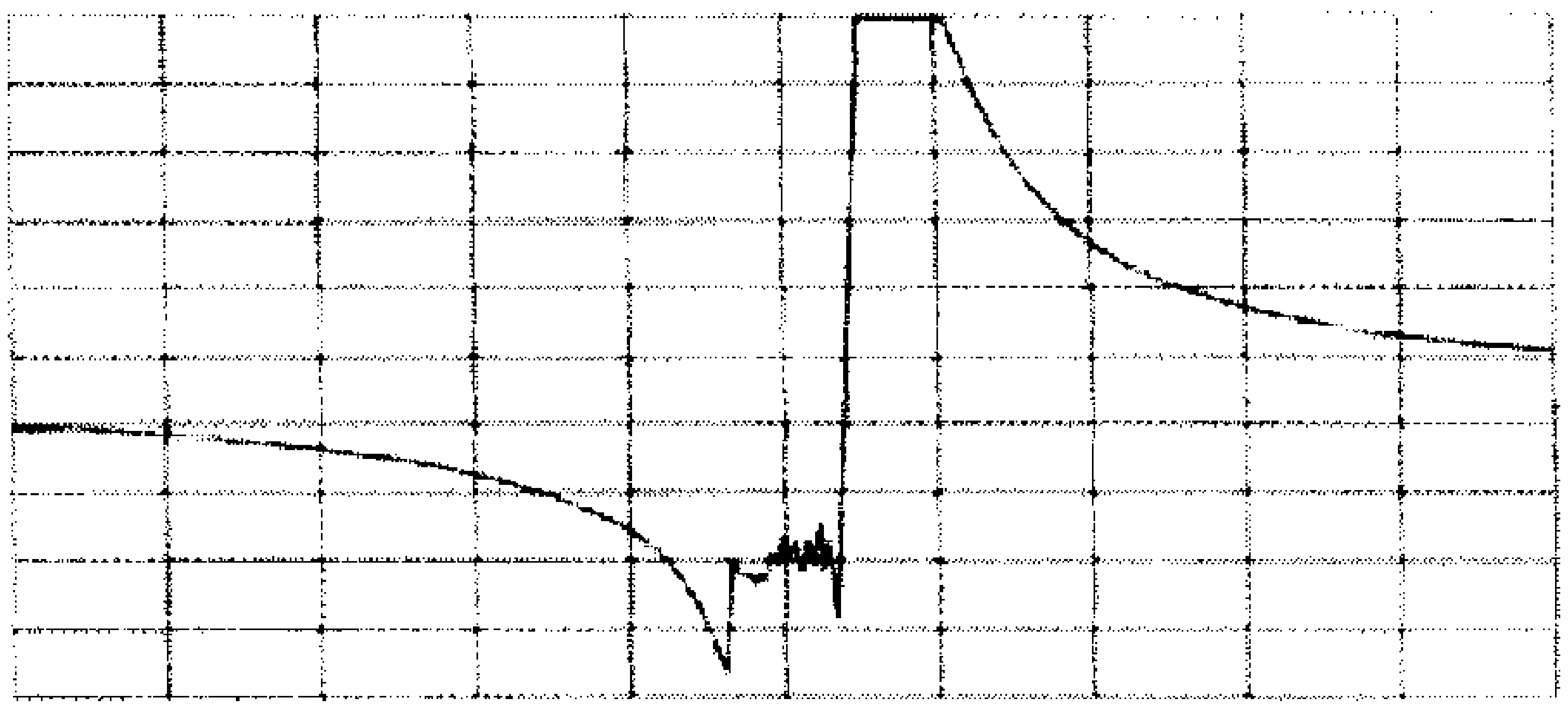


Fig 19—The measured impedance of a 14-pole crystal ladder filter. The vertical divisions are 20 Ω, with zero at the bottom. The horizontal divisions are 4 kHz each.

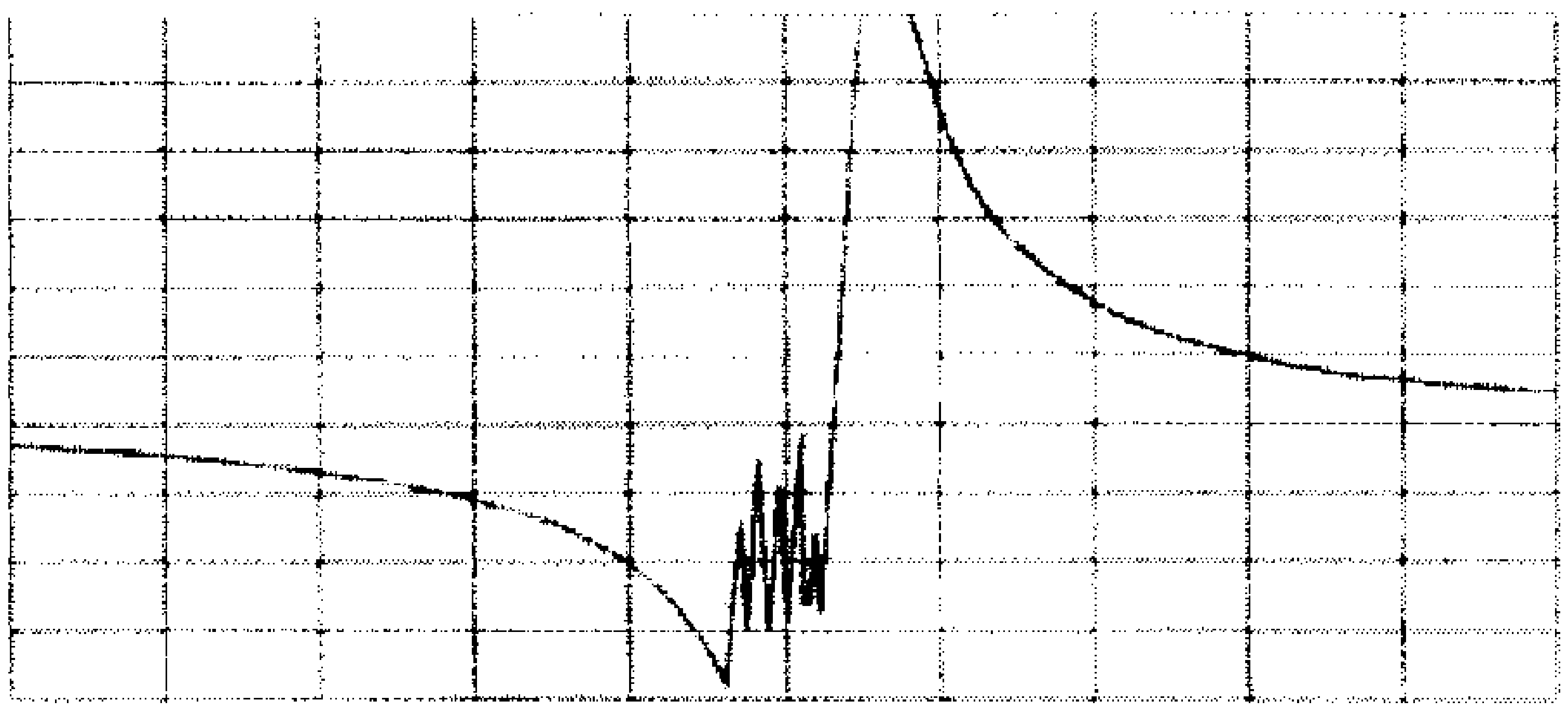


Fig 20—The measured impedance of a Fox-Tango crystal lattice filter. The vertical divisions are 20 Ω, with zero at the bottom. The horizontal divisions are 4 kHz each.

while driving the filter through a resistive pad. The measurement results are given in Table 3. The output intercept point of the amplifier was degraded by 5 dB by the ladder filter and by 12 dB by the Fox-Tango filter. I tried using resistive pads with different attenuation values in an attempt to "smooth out" the impedance presented to the amplifier. A 6-dB pad is required in the case of the Fox-Tango filter to improve the OIP by 5 to 6 dB, and a 3-dB pad is sufficient in the case of the ladder filter to improve the OIP by 3 to 5 dB.

In the next experiment, one of the tones was placed in the center of the pass-band and the second tone was –20 kHz away. In this measurement, the OIP of the amplifier was degraded by 4 dB in the case of the ladder filter and by 11 dB in the case of the Fox-Tango filter. A 3-dB resistive pad in front of the ladder filter reduced the degradation by 1 to 3 dB, and a 6-dB pad in front of the Fox-Tango filter reduced the degradation by 6 to 7 dB.

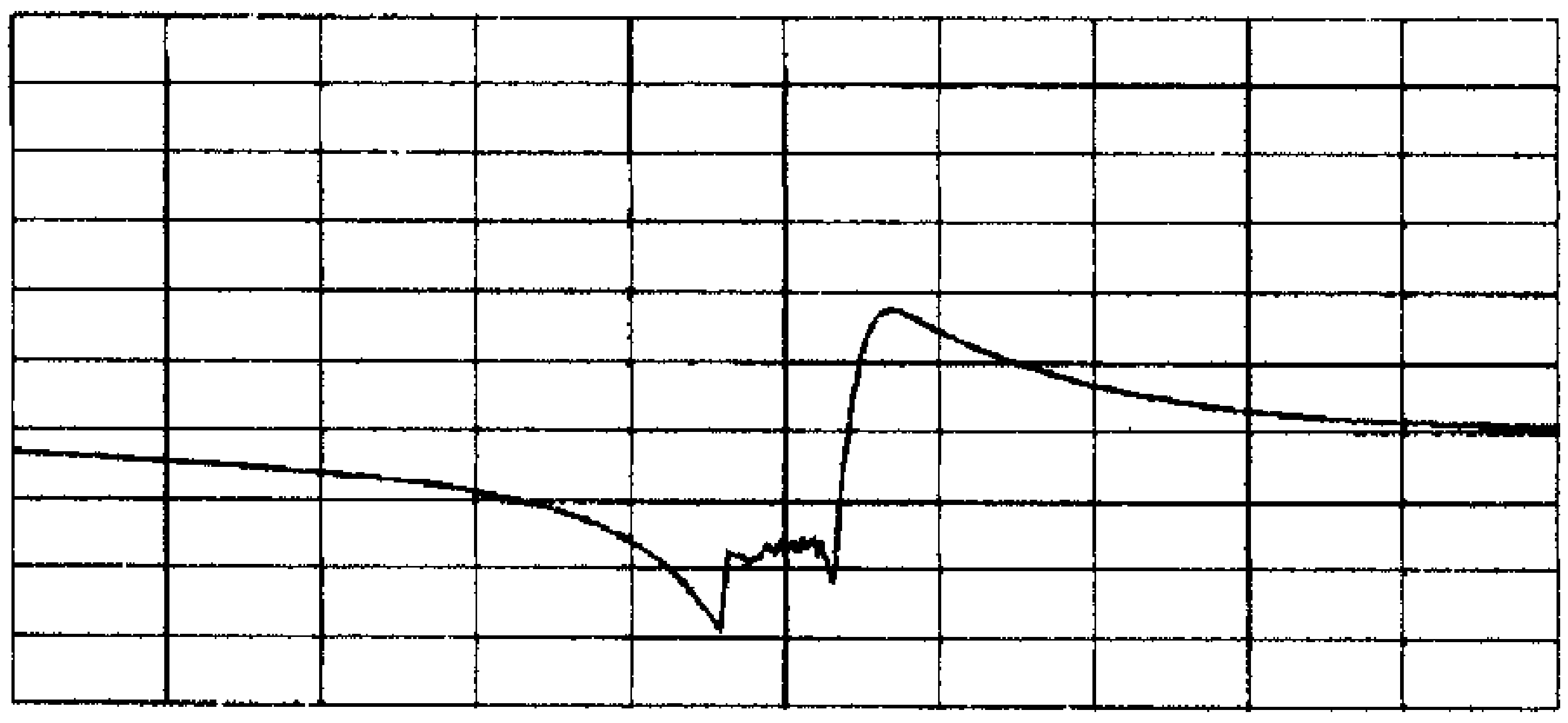


Fig 21—The measured impedance of a 14-pole crystal ladder filter with a 3-dB attenuator at the input. The vertical divisions are 20 Ω, with zero at the bottom. The horizontal divisions are 4 kHz each.

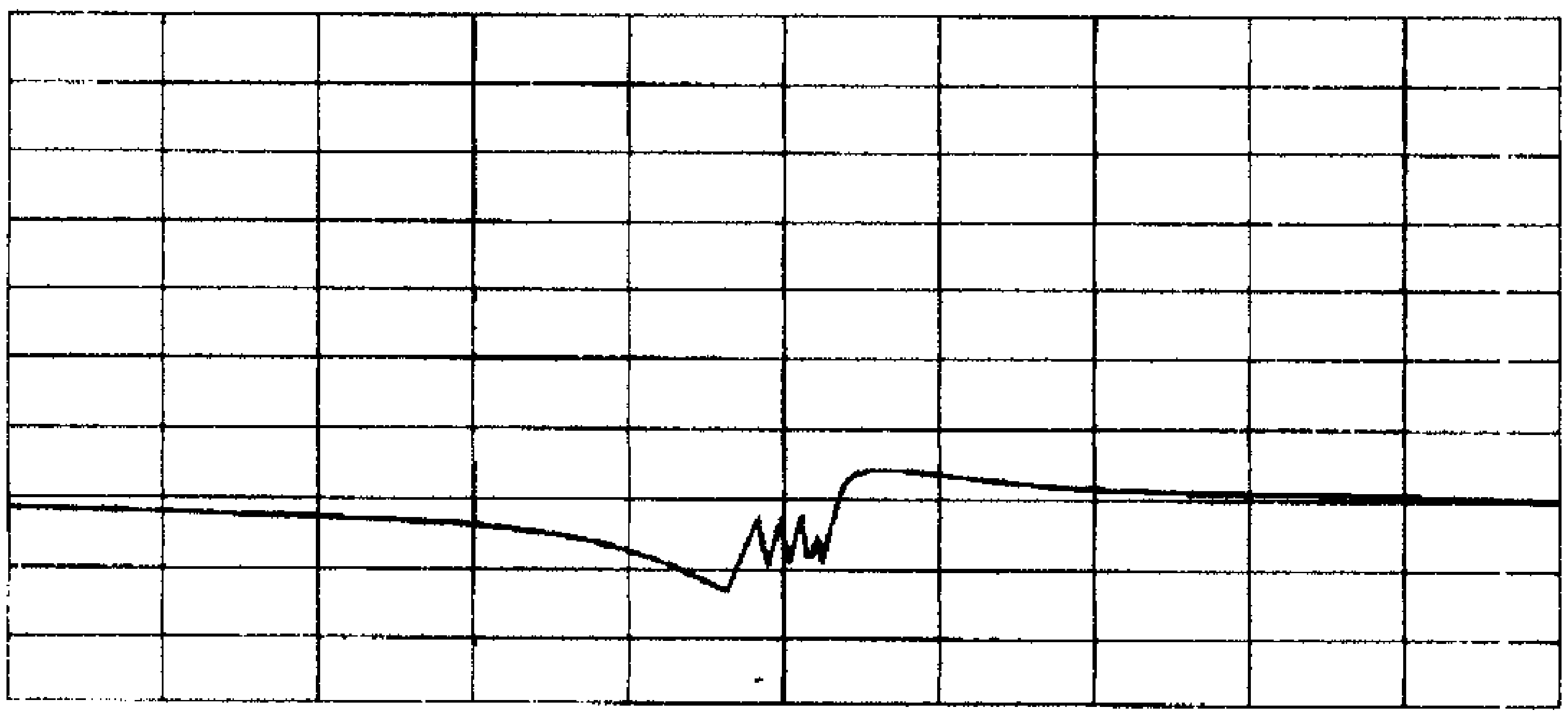


Fig 22—The measured impedance of a Fox-Tango crystal lattice filter with a 6-dB attenuator at the input. The vertical divisions are 20 Ω, with zero at the bottom. The horizontal divisions are 4 kHz each.

Finally, one of the tones was placed at the leading edge of the filter passband (notice the impedance dips in Figs 19 and 20). Due to the severe impedance mismatch presented to the two tones at both frequencies the OIP of the amplifier is degraded by 11 dB in the case of the ladder filter and by 22 dB in the case of the Fox-Tango filter. Resistive pads have a profound effect on the performance in this case: a 3-dB pad in front of the ladder filter reduces the degradation by 5 to 6 dB, and a 6-dB pad in front of the Fox-Tango filter reduces the degradation by up to 17 dB!

The following conclusions can be drawn from these measurement results:

- Because of the highly reactive nature of its input impedance, a crystal filter has a significant loading effect on the preceding stage. This may become the limiting factor when calculating the overall dynamic range of a receiver.
- The experiments suggest that it is more meaningful to evaluate the effect of the filter on the preceding stage than to attempt to measure the OIP of the crystal filter itself.
- Some non-linear behavior was observed (the degradation of the OIP of the preceding stage depends on the signal level). The filter behavior is more predict-

Table 3—Measurement results
Third-order output intercept point of the amplifier (+dBm)

Tone location relative to the passband	*Ladder filter*		*Fox-Tango filter*		*Tone level (+dBm)*
	No pad	*3-dB pad*	*No pad*	*6-dB pad*	
Both tones outside of passband	45	47	38	43	15
	43	45	36	42	10
One tone inside of passband	44	46	37	44	15
	45	46	37	43	10
One tone at the edge of passband	38	42	30	43	15
	37	42	26	43	10

Listing 1

Page 1: BASIC

```
' Modify IRFD circuit files contining crystal-ladder filters
' to add tuning capacitors for offset crystal frequencies.
'
' From "Designing and Building High-Performance Crystal Ladder
' Filters," QEX, January, 1995
'
' J. Bloom, KE3Z
' 12/08/94
'
' Note: Little checking of the input file is performed. Only files
' written by the IRFD program "X" should be used as input files.

CLS
PRINT "CLFMOD -- Modifies IRFD ladder crystal filter circuit files for tuning"
PRINT
INPUT "Enter name of original circuit file: ", f1$
OPEN f1$ FOR INPUT AS #1
INPUT "Enter name of output circuit file: ", f2$
OPEN f2$ FOR OUTPUT AS #2
OPEN "OFFSETS.CLF" FOR OUTPUT AS #3
' Get the number of circuit elements
INPUT #1, x
N = (x - 2) / 2       ' Number of poles
' Write the new number of circuit elements, including tuning caps
PRINT #2, N * 3 + 2
' Copy the unchanging parameters
FOR i = 1 TO 14
   INPUT #1, x
   PRINT #2, x
NEXT i
' Loop through each of the meshes, annotating the elements with
' component designators as in Fig 9, adding the tuning capacitors,
' and replacing the crystal offset frequencies with those of the
' real crystals.
FOR i = 0 TO N - 1
   ' Coupling capacitor
   INPUT #1, x$
   PRINT #2, x$, LEFT$(x$, 1) + MID$(STR$(i * 3 + 1), 2)
   INPUT #1, x$
   PRINT #2, x$
   INPUT #1, x
   PRINT #2, x
   ' Crystal
   INPUT #1, x$
   y$ = LEFT$(x$, 1) + MID$(STR$(i * 3 + 2), 2)
   PRINT #2, x$, y$
   INPUT #1, x$
   PRINT #2, x$
   INPUT #1, x
   PRINT "Crystal"; i + 1; "("; y$;
   INPUT ") delta F: ", y
   PRINT #2, y
   PRINT "Target offset frequency for mesh"; i + 1; "= "; x - y
   PRINT #3, x - y
```

Listing 1 (continued)

```
Page 2: BASIC


   ' Tuning capacitor
   PRINT #2, "cap", "c" + MID$(STR$(i * 3 + 3), 2)
   PRINT #2, "ser"
   PRINT #2, 200
NEXT i
' Load end coupling capacitor
INPUT #1, x$
PRINT #2, x$, LEFT$(x$, 1) + MID$(STR$(N * 3 + 1), 2)
INPUT #1, x$
PRINT #2, x$
INPUT #1, x
PRINT #2, x
' Should only be one line left, but "just in case," copy to
' end of file
WHILE NOT EOF(1)
   LINE INPUT #1, x$
   PRINT #2, x$
WEND
' Clean up and exit
CLOSE
SYSTEM

' CLFOFS -- Generates final offsets for ladder crystal filter design
'
' From "Designing and Building High-Performance Crystal Ladder
' Filters," QEX, January, 1995
'
' J. Bloom, KE3Z
' 12/08/94

CLS
PRINT "CLFOFS -- Calculates final design offsets for ladder crystal filters"
PRINT
INPUT "Frequency offset for bandwidth reduction: ", f
OPEN "OFFSETS.CLF" FOR INPUT AS #1
WHILE NOT EOF(1)
   INPUT #1, x
   PRINT x + f
WEND
CLOSE
SYSTEM
```

able at the flat portions of the frequency response and less predictable when extreme impedance changes are encountered. Resistive pads tend to improve the linearity.

- If no resistive pad is used, the degradation of the amplifier's OIP is reduced by at least 7 dB if the Fox-Tango filter is replaced by a ladder filter.
- A 6-dB resistive pad is required to significantly reduce the degradation of the amplifier's OIP in the case of the Fox-Tango filter. A 3-dB pad is sufficient to produce the same effect in the case of the ladder filter.
- The level of the third-order products at the output of the Fox-Tango filter deviates from the calculated value by more than 6 dB, even with a 6-dB resistive pad. In the case of the ladder filter, this deviation is reduced to a value under 1 dB if a 3-dB resistive pad is employed.

- Examination of the plot of input impedance of the two types of filters (Figs 19 and 20) reveals that the ladder filter has a much smoother response in the passband. This must be one of the reasons for the ladder filter's superior performance.

Summary

I've shown that home construction of high-performance crystal filters is quite practical, and that laboratory-grade equipment, although helpful, is not required. Home-built ladder filters can exhibit performance superior to that of commercially available filters at reasonable cost. The design and construction procedure outlined above enables the amateur to tailor the frequency response of the filter to fit the needs of the project.

Acknowledgments

I wish to express my appreciation to Wes Hayward, W7ZOI, Bill Carver, K6OLG/7, Colin Horrabin, G3SBI and Peter Chadwick, G3RZP for the helpful discussions that enabled me to better understand this subject and the encouragement to pursue this project.

Finding Parts

Crystals: The most consistent results were obtained using crystals from Fox Electronics (Tel: 813-693-0099), part number: FOX080. These are series-resonance microprocessor crystals in an HC49/U case. Ask for a list of distributors in your area.

Capacitors: Use monolithic ceramic capacitors from Panasonic or equivalent quality capacitors. Panasonic capacitors are available from Digi-Key Corporation (Tel: 800-344-4539), P4800 series. COG ceramic parts are recommended for good temperature stability. Low loss is an important requirement. 5% or 10% tolerance is acceptable.

Transformer cores: Use two-hole balun cores, part number: BN-43-2402 from Amidon Associates (Tel: 310-763-5770).

Board: The project board, with a ground plane on one side, is part number 8007 from Vector (Tel: 800-423-5659; 800-426-4652 inside California). The Vector pins are part number T44. (Digi-Key is one of the nationwide distributors for Vector.)

Notes

[1] Carver, B., K6OLG/7, "High-Performance Crystal Filter Design," *Communications Quarterly*, Winter 1993, pp 11-18.

[2] Hayward, W., W7ZOI, *Introduction to Radio Frequency Design*, ARRL, Newington, Connecticut, 1994, chapters 2 and 3.

[3] Drentea, C., WB3JZO, *Radio Communications Receivers*, Tab Books Inc, Blue Ridge Summit, 1982, pp 69-75.

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