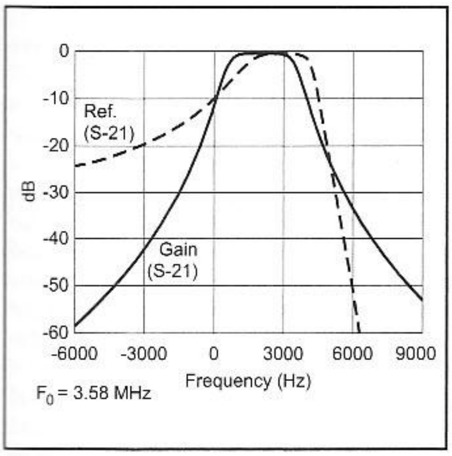


Fig 3.39—The response of two crystal filters built from 3.58-MHz color burst crystals. One uses ideal crystals with zero C0 to produce a symmetrical shape. The other (with dashed line) uses C0=4 pF crystals.

solid curve is the response we would like, designed with ideal crystals with zero parallel capacitance. C_0=4 pF produces the other response. The filter bandwidth is too narrow and the attenuation is markedly increased. It is for this reason that this circuit is named the lower sideband ladder filter.

Response distortion results because the parallel C_0 makes the series resonators behave as if they had a larger motional L than is measured. This effect is plotted in **Fig 3.40** for the 5-MHz crystals used in the earlier CW filter design. The lower curve shows the effect of a 2-pF parallel capacitance while the upper curve is for C_0 = 5 pF. Here, X is the ratio of L_{eff} to L_m. The horizontal axis in the curve is δF, the offset from the series resonant frequency. These effects were discussed in greater detail in *QEX* for June, 1995, where detailed design equations are given. The corrections related to the effective inductance are included in the program *XLAD.exe*. Both the program and the 1995 *QEX* paper are included on the book CD.

The effective inductance is larger than the normal motional L by a factor of 2 or more. This reduces the effective motional capacitance by the same factor. Accordingly, the coupling capacitors must be reduced by the same factor. The change also alters the calculation of end resistance. The new terminations and reduced coupling capacitors will then alter the filter tuning.

One can build symmetric filters if the effect of parallel capacitance is eliminated. One way to do this parallels each crystal with a large inductance. The value required is one that resonates with C_0, forming a parallel trap that is then bridged by the series resonant portion of the crystal. An experimental filter was built to examine this idea. The inductance used was smaller than required for resonance, so small trimmer capacitors were added. The filter, built with 3.58-MHz color burst crystals for a 3.5-kHz bandwidth, is shown in **Fig 3.41**. The measured response is presented in **Fig 3.42**.

Crystal filters built with paralleled inductors suffer from degraded stopband response. Although the performance around the filter center is as designed, it degrades a few hundred kHz away from center, necessitating the crystal filter be supplemented with an LC bandpass.

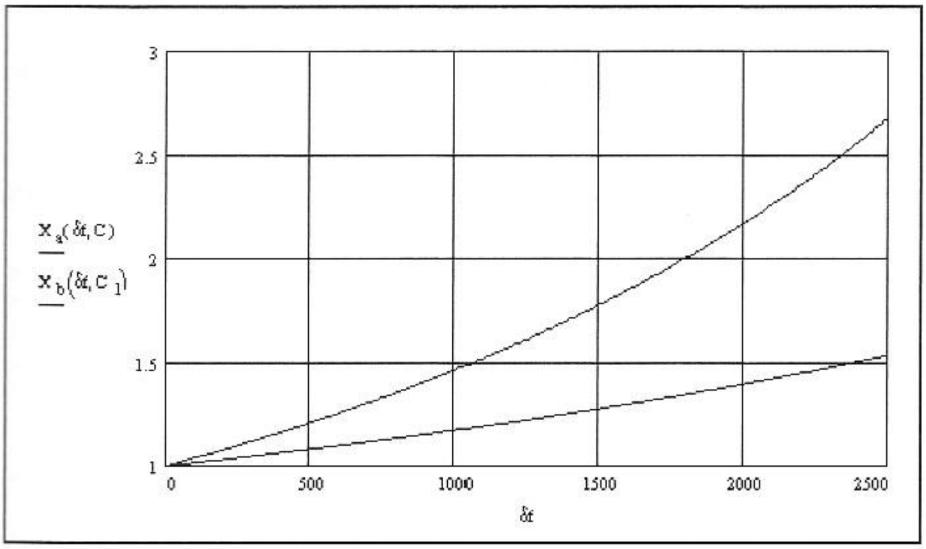


Fig 3.40—X, defined as L_{eff}/L_m, is plotted for frequency offset, δf, above crystal series resonance in Hz. These 5-MHz crystals had parallel C of 2 and 5 pF.

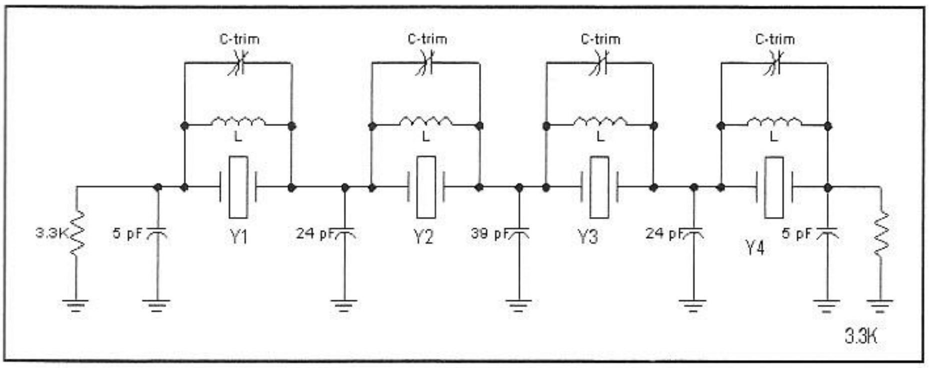


Fig 3.41—Experimental crystal filter.
Y1,2,3,4 = 3.58-MHz surplus color burst crystals. (L_m=0.117H, C_0=4 pF)
L = 151 µH, 48 turns #30 on FT-50-61 Ferrite toroid.(Amidon)
C-trim = 3-12 pF ceramic trimmer. See the referenced *QEX* paper for adjustment procedure.

The Min-Loss Filter of Cohn and other Simplified Forms

A simplified non-mathematical scheme for building crystal filters uses the Min-Loss circuit. This circuit is the result of fundamental work by S. B. Cohn where he described a family of coupled resonator filters that achieved very low insertion loss while maintaining good stopband attenuation.[16] A really interesting property of these filters was the fact that they used identical resonators that were coupled to each other with equal values of coupling. This means that all shunt coupling capacitors in a Min-Loss crystal filter are equal. If the filters are designed without shunt end loading capacitors, tuning is greatly simplified. A Min-Loss type crystal filter is properly tuned if

- all crystals have the same frequency,
- all coupling capacitors are of the same value, C,
- series capacitors having the same capacitance as the coupling C are placed in series

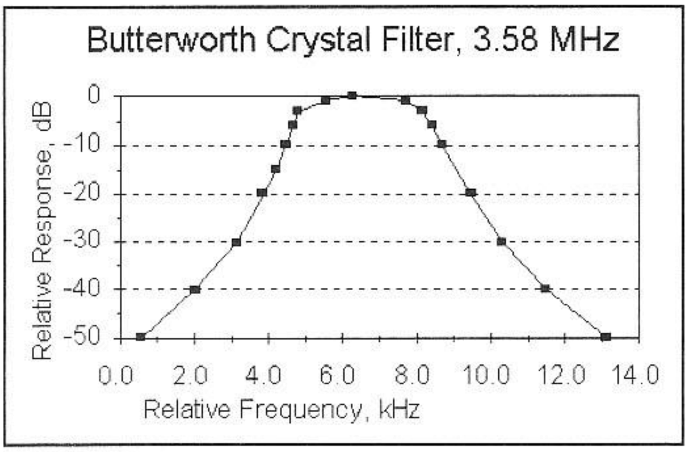
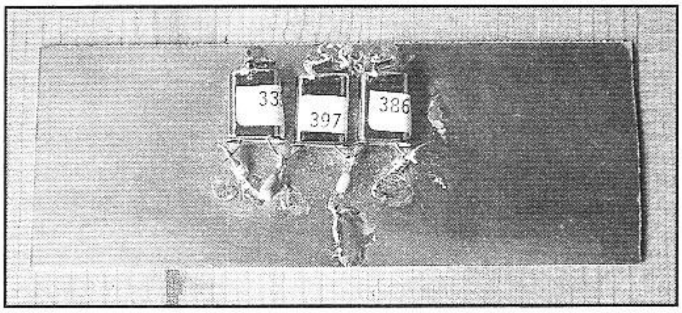
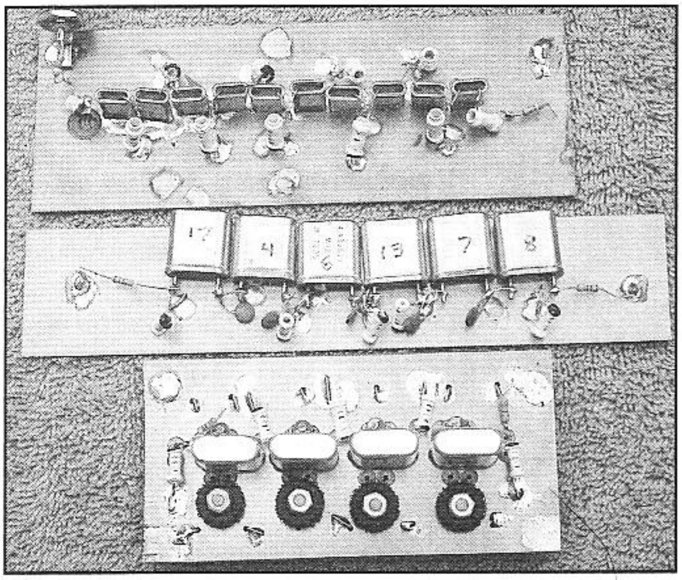


Fig 3.42—Measured response for the filter shown in Fig 3.41.



A three element crystal filter at 10 MHz. The metal can crystals have small wires soldered to them that are then grounded to the foil.



Three experimental crystal filters. The top circuit uses 10 crystals in a circuit with equal coupling between resonators (Cohn). The bottom filter is that from Fig 3.41.

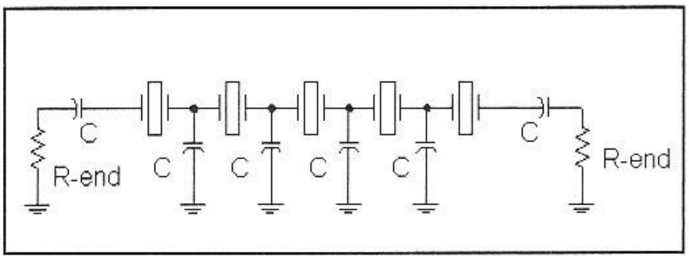


Fig 3.43—Min-Loss type crystal filter with equal coupling and simplified tuning.

with both end crystals
• both terminations are equal and properly related to coupling.

A crystal filter of this type, with five resonators, is shown in **Fig 3.43.**[17]

This filter topology often appears with the name "Cohn Filter," titled for the original circuit theorist who contributed so extensively to our design methods. Other filters have also appeared with the Cohn name. Here we have divorced the name from this simple crystal filter, for it is but one example from Cohn's body of work, a collection that is much richer and more extensive than has been presented in the amateur literature.

While most of the Min-Loss crystal filters we build are fabricated without design (i.e., without any mathematical analysis), they may certainly be studied and designed on the computer. The normalized coupling coefficients and end section Q for this filter type are approximately given by

$$k_{jk} = \frac{1}{2} \cdot \exp\left(\frac{\mathrm{Ln}\,(2)}{N}\right) \qquad \textbf{Eq 3.16}$$

$$q = \frac{1}{k_{jk}} \qquad \textbf{Eq 3.17}$$

where *n* is the number of resonators. These values are tabulated for *n* from 2 to 10 in **Table 3.5**. (The first few points appeared in the original Cohn paper, while *k* and *q* for N>5 are extrapolations via our above equations.)

Shown in **Fig 3.44A** are transfer function plots for two different filters of this type. The wider, lower loss one has 3 resonators while the other has 8 crystals. Both circuits were designed for 5 MHz with a 500-Hz bandwidth using high Q crystals with L_m=0.098 H. Part A of the figure shows close-in details while Fig 3.44B shows the response to the –80 dB level. Part C of the figure shows the group delay for the filter with 8 resonators. (More will be said about group delay shortly.) All three plots are computer generated re-

Table 3.5

N	*k*	*q*
2	0.707	1.414
3	0.63	1.587
4	0.595	1.683
5	0.574	1.741
6	0.561	1.782
7	0.552	1.811
8	0.545	1.834
9	0.54	1.852
10	0.536	1.866

sponses, although they are in good agreement with measurements on similar filters. We have built Min-Loss crystal filters up to 10th order.

The data of Fig 3.44 illustrate the salient properties of the Cohn filter. The passband shape is smooth with minimal ripple for the low order filters (N=3), but becomes distorted as the number of resonator grows beyond five. The ripples on the passband edges near the skirts become extreme with wider bandwidth filters. The N=8 data of Fig 3.44B illustrate the excellent shape afforded by the Min-Loss filter. However, the time domain performance as depicted in the group delay plot suggests that this filter may have severe ringing if built for narrow (CW) bandwidths.

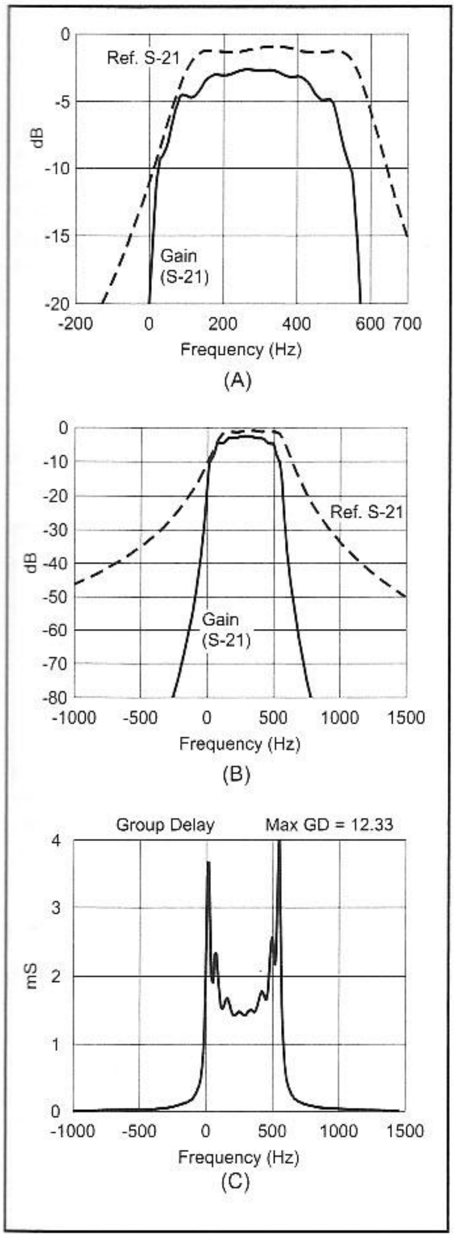


Fig 3.44—Min-Loss crystal filter responses. A and B compare 3rd and 8th order filters in responses to −20 and −80 dB. C shows the group delay for the 8th order filter.

Although the two filters (N=3 and N=8) described in Fig 3.44 have different responses, they are remarkably similar in component values. The N=3 filter used 146-pF capacitors and 181-Ω terminations while the N=8 filter used 168 pF and 155 Ω. A filter designed with two or three crystals can be extended with the same capacitor values and terminations. This becomes extremely useful for the experimenter.

The Min-Loss crystal filter has virtues of low insertion loss and good skirts, but at the price of poor passband shape with higher orders. Some other filters offer similar non-mathematical simplicity and better passband performance, with a group of crystals all at the same frequency. **Fig 3.45** shows such a filter. This design is a Butterworth design at 10 MHz with normalized parameters of q=0.765, k_{12}=k_{34}=0.841, and k_{23}=0.541. This filter is designed with a pure resistive termination at the ends (no shunt end capacitors.) The equations predict the end resistance and the shunt capacitors. The series tuning capacitors are yet to be established. However, the values are clear from inspection. If the end capacitors are set to the value of the center capacitor (85 pF,) each mesh has the same capacitors in the related loop.

Design with the equations does not take the parallel crystal capacitance effects into account. This is done with curves like those of Fig 3.40 that establish an increased effective inductance value that can then be applied with the equations. Approximate designs without the curves will still result in practical filters at the higher frequencies (8 MHz and up) although the bandwidth will be a bit narrower than the design values.

Ringing, Group Delay and Filter Passband Shape

All serious receiver experimenters have their favorite efforts, receivers with specifications differing little from others, but with a "crisp sound" that sets them apart from the ordinary. There are numerous phenomenon that tend to degraded performance and remove "crispness." One that can ruin an otherwise excellent receiver is an IF filter with excessive group delay. All filters have time delay, a truth that cannot be avoided. The filters that "sound" the best are those that have small delay for a given bandwidth and, of greater import, behave like a transmission line with little variation in group delay over the passband.

The group delay of an eighth order Min-Loss filter was presented in Fig 3.44C. The delay was high, exceeding 10 milliseconds in part of the passband. The group delay variation over the passband was also severe. This filter, although very selective, would probably not sound good, especially with noise pulses.

Two 5-MHz filters were designed for a bandwidth of 500 Hz, each with five crystals. One filter used a 0.1-dB ripple Chebyshev response while the other used a linear phase response. The Chebyshev results are shown in **Fig 3.46** while the linear phase response is given in **Fig 3.47**. Both plots overlay group delay and gain. The "ears" of the Chebyshev group delay plot line up with the 3-dB edges of the passband, so all delay variations are heard. In contrast, the region of low group delay in the linear phase filter extends well beyond the filter bandwidth edges. Both of these filters have been built and tried in an experimental CW receiver. The linear phase filter was more difficult to build, but sounded much better. The skirts were steep in the Chebyshev, so it presented adequate selectivity. We found the linear phase filter in need of more skirt selectivity. Although not shown in the figures, the Chebyshev filter group delay was 2.5 times as large as the linear phase filter delay.

We have also had good results with an intermediate filter shape, the Gaussian-to-6 dB response. This is a filter with a rounded peak shape for the top 6 dB, but with steep Chebyshev-like skirts. Transitional filters (Gaussian-to-6 dB, Gaussian-to-12 dB, linear phase, and maximum flat delay) are slightly more difficult to build than the Min-Loss, Butterworth, or Chebyshev filters, for they lack the sym-

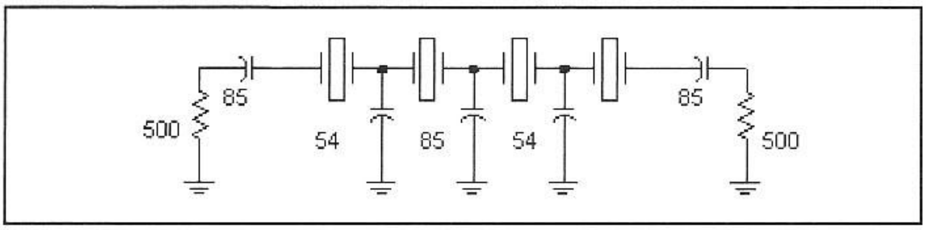


Fig 3.45—10-MHz SSB bandwidth filter using crystals with identical frequencies and "easy" tuning. This filter has a Butterworth shape; the simplified tuning method often works well with N=4 Chebyshev filters.