increases, just as for LC filters. The insertion loss for a given order and bandwidth is higher for high-ripple Chebyshev designs than it is for low-ripple designs, and Butterworth designs have lower insertion loss than any Chebyshev type for equivalent order.

Passband amplitude response and shape factor are important parameters for assessing the performance of filters used for speech communications. However, group delay is also important for data and narrow-band CW reception. Differential group delay (different group delays for signals of different frequencies) can cause signal distortion on data signals if the variations are greater than the data recovery system's automatic equalizer can handle. Ringing can be an annoying problem when using very narrow CW filters, and group delay must be minimized to reduce this effect.

When narrow bandwidth filters are being considered, shape factor has to be sacrificed to reduce group delay and its associated ringing problems. It's no good having a narrow Chebyshev design with a shape factor of 2 if the filter produces unacceptable ringing. Both Bessel and *linear phase* (equiripple 0.05°) responses have practically constant, low group delay across the entire passband and well beyond on either side, making both types good choices for narrow CW or specialized data use. They also have the great advantage of offering the lowest possible insertion loss of all the types of response currently in use, which is important when Q_o is low, as it often is for very narrow bandwidth filters. The insertion loss of the Bessel design is marginally lower than that of the linear phase, but the latter has a superior shape factor giving it the best balance of low group delay and good selectivity. A 6-pole linear phase (equiripple 0.05°) design has a shape factor of 3.39, whereas a 6-pole Bessel has 3.96.

11.6.2 Crystal Filter Design

A wide variety of crystals are produced for use with microprocessors and other digital integrated circuits. They are offered in several case styles, but the most common are HC-49/U and HC-49/US. Crystal resonators in the HC-49/U style case are fabricated on 8 mm diameter quartz discs, whereas those in the low-profile HC-49/US cases are fabricated on 8 mm by 2 mm strips of quartz. At any given frequency, C_m will be lower for HC-49/US crystals because the active area is smaller than it is in the larger HC-49/U crystals.

Both types of crystals are cheap and have relatively small frequency spreads (the variation in resonant frequency of a batch of crystals), making them ideal for use in the LSB ladder configuration suggested by Dishal (Ref 2) — see **Fig 11.66**. This arrangement requires the motional inductances of all the

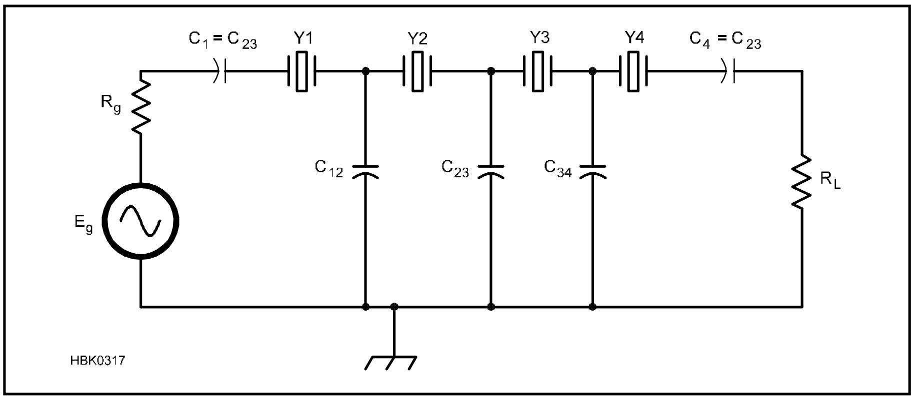

Fig 11.66 — Dishal LSB crystal-ladder filter configuration. Crystals must have identical motional inductances, and the coupling capacitors and termination resistors are selected according to the bandwidth and type of passband response required.

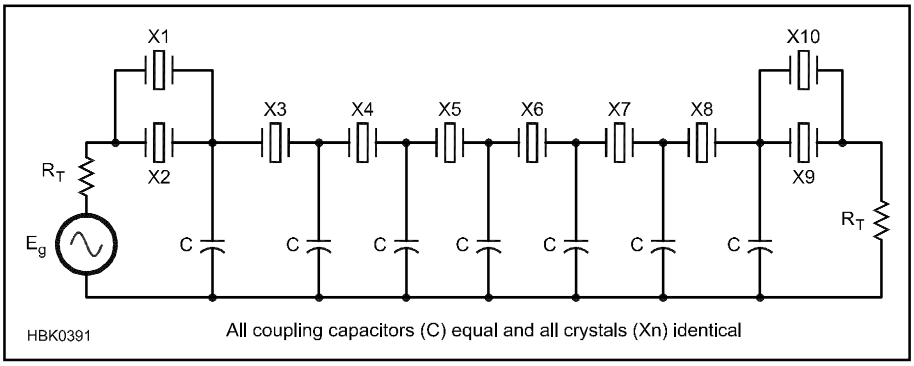

Fig 11.67 — Configuration of improved crystal ladder filter using identical crystals and equal coupling capacitor values. The parallel resonator end-sections (PRES) can provide excellent passband responses, giving either quasi-equiripple (QER) or minimum-loss (PRESML) responses with just a change in termination resistance.

crystals to be identical, and each loop in isolation (crystal and coupling capacitors either side) to be resonant at the same frequency. Series capacitors to trim individual crystals are needed to achieve this in some of the more advanced designs, where production frequency spreads are not sufficient to satisfy the latter requirement. References 3 through 8 contain design information on Dishal LSB crystal ladder filters.

The *min-loss* or *minimum-loss* form of Cohn ladder filter, where $C_{12} = C_{23} = C_{34}$, has become very popular in recent years because it's so simple to design and build. However, it suffers from the drawback that the ripple in its passband response increases dramatically with increasing order, and ringing can be a real problem at bandwidths below 500 Hz for Cohn min-loss filters of 6th-order or higher. The ripple may not be a problem in most narrow filters because it's smoothed out almost completely by loss, but the ringing can be tiring. For wider bandwidths, where the ratio of Q_u to f_o / BW is much greater, the ripple is not smoothed out, and is very evident.

One way around the problem of ripple, without sacrificing simplicity, is to use an arrangement originally designed for variable bandwidth applications by Dave Gordon-Smith, G3UUR, shown in **Fig 11.67**. It was devised to make the mesh frequencies track together as the amount of coupling varies the bandwidth, and only requires variable resistance terminations ganged to the variable coupling capacitors to give excellent responses at any setting of the bandwidth. These can be optimized for minimum loss at minimum bandwidth and almost equal ripple at maximum bandwidth, making it an ideal alternative for fixed bandwidth speech applications to the Cohn min-loss. Two crystals are used in parallel to halve the motional inductance and double the motional capacitance of the resonators in the end sections. Although the two additional crystals do not increase the order of the filter by two, they do reduce the passband ripple substantially while maintaining the simplicity of design and construction offered by the min-loss filter.

In addition, the group delay of the *parallel-resonator-end-section* (PRES) configuration is less than that of the min-loss. The coupling capacitors are still all equal, and the filter can be terminated to achieve

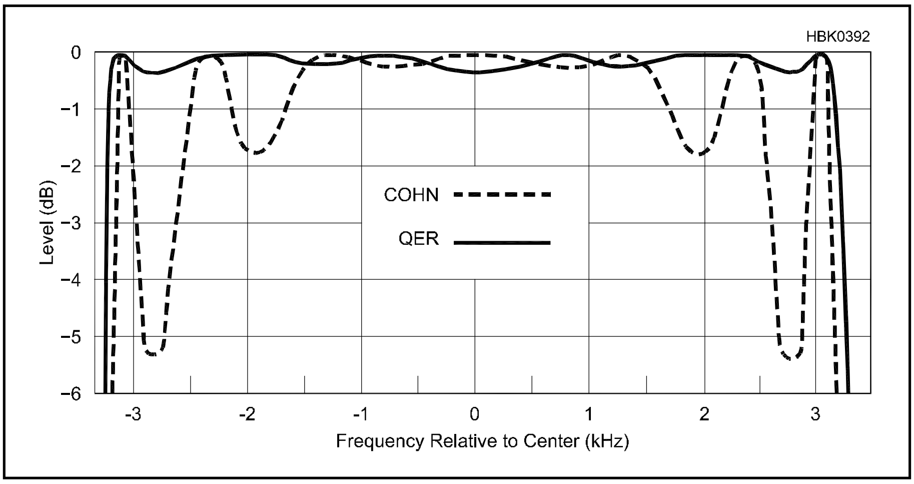

Fig 11.68 — Comparison of 8-pole Cohn min-loss passband response with that of the quasi-equiripple (QER) type. Note the almost equal ripple in the passband of the QER response.

Table 11.21
3 dB-down k & q Values for Quasi-Equiripple (QER) Ladder Filters

Order	*q*	k_{12}	k_{23}	*Shape Factor*	*Max Ripple (dB)*
4	0.9442	0.7660	0.5417	4.56	0.002
5	1.0316	0.7625	0.5391	3.02	0.018
6	1.0808	0.7560	0.5346	2.31	0.09
7	1.1876	0.7459	0.5275	1.90	0.16
8	1.2532	0.7394	0.5228	1.66	0.31
9	1.3439	0.7335	0.5187	1.50	0.42
10	1.4115	0.7294	0.5158	1.40	0.60
11	1.4955	0.7261	0.5134	1.33	0.72
12	1.5506	0.7235	0.5116	1.28	0.90

Table 11.22
Typical Parameters for AT-Cut Quartz Resonators

Freq (MHz)	*Mode n*	*rs (Ω)*	*Cp (pF)*	*Cs (pF)*	*L (mH)*	Q_U
1.0	1	260	3.4	0.0085	2900	72,000
5.0	1	40	3.8	0.011	100	72,000
10.0	1	8	3.5	0.018	14	109,000
20	1	15	4.5	0.020	3.1	26,000
30	3	30	4.0	0.002	14	87,000
75	3	25	4.0	0.002	2.3	43,000
110	5	60	2.7	0.0004	5.0	57,000
150	5	65	3.5	0.0006	1.9	27,000
200	7	100	3.5	0.0004	2.1	26,000

Courtesy of Piezo Crystal Co, Carlisle, Pennsylvania

a *quasi-equiripple response* (QER) so that its passband resembles that of a Chebyshev design, or minimum loss (PRESML) with a response like that of the min-loss. **Fig 11.68** shows the Cohn min-loss and QER passband responses with infinite crystal Q_u for comparison. Values of k and q for QER filters from 4 to 12 poles are given in **Table 11.21,** along with the maximum ripple and shape factor for each order.

The coupling capacitor value for any bandwidth can be determined from k_{23} using equation 8. The end-section resonators formed by the two parallel crystals have twice the effective motional capacitance of the inner resonators, and since k_{12} is always 1.414 times k_{23} for the QER design, the value of C_{12} will be the same as calculated for C_{23} and all the other coupling capacitors, C, in the design.

$$C = \frac{f_0 C_m}{BW k_{23}} \qquad (8)$$

The termination resistance, R_T, must be calculated using half the motional inductance of a single crystal, as illustrated in equation 9, where L_m is the motional inductance of one of the parallel crystals used in the end-sections.

$$R_T = 2\pi\ BW\ L_m / 2q = \pi\ BW\ L_m / q \quad (9)$$

11.6.3 Crystal Characterization

Simple crystal filters can be constructed using cut-and-try methods, but sometimes results can be very disappointing. The only sure way to guarantee good results is to fully characterize the crystals beforehand, so that only those most suitable are used in a design appropriate for the application. When crystal parameters are known, computer modeling can be used to assess the effect of Q_u and C_o on bandwidth, before proceeding to the construction phase. Along with *Elsie* design program on the CD-ROM, *AADE Filter Design and Analysis* (**www.aade.com**) provides free filter modeling. **Table 11.22** lists typical parameters for the common AT-cut quartz crystals.

Crystal characterization can be performed with very modest or very advanced test equipment, the only difference being the accuracy of the results. The *zero phase* method for measuring C_m used in industry can be implemented by amateurs if a dual-channel oscilloscope is available to substitute as a phase detector. (Ref 7 gives details of this method.) However, many successful crystal filter constructors have achieved excellent results with home-built test equipment. Ref 6 describes a simple switched-capacitor method of measuring C_m originated by G3UUR, which only requires a frequency counter in addition to constructing an oscillator. Accurate LC meters that can measure down to 0.01 pF and 1 nH can now be constructed using PIC technology. C_m can usually be estimated to within 10% by using equation 10 and a value for C_o measured on one of these instruments.

$$C_m(\text{pF}) = \frac{C_0 - 0.95}{175} \qquad (10)$$

Commercial LC meters with amazingly good specifications are also available at moderate prices if a PIC LC meter seems too ambitious a project for home construction at this stage.

Values of Q_u for crystals can vary considerably, even within the same batch, and the ratio of the best to the worst, excluding dead ones, can be as high as 6 for cheap mass-produced crystals. The ratio can still be as high as 2 for batches of high-quality crystals.

Q_u needs to be known for each crystal to weed out the poor ones and more accurately model the filter performance prior to construction. The simplest means of doing this, if the switched-capacitor method (Ref 6) is used for determining C_m and a sufficient quantity