A Crystal Filter Tutorial

Abstract: The general topic of crystal filters will be discussed in a manner that is intended to help the user to better understand, specify, test, and use them. The center frequency and bandwidth regions where practical crystal filters can be built are defined. A section is devoted to how to write a specification," and what wording should be avoided. The testing of crystal filters is covered and a section is devoted to using the personal computer to improve accuracies and extend the testing capabilities.

Operating Region Crystal filters can be built at center frequencies from less than 1 kHz up to several hundred MHz. Their bandwidth can range from as little as 1 Hz and, in certain regions, up to 1 MHz. Figure 1 shows the wide region that they can cover. However, the region is continually changing and so it is always best to check with your supplier to see what's available today.

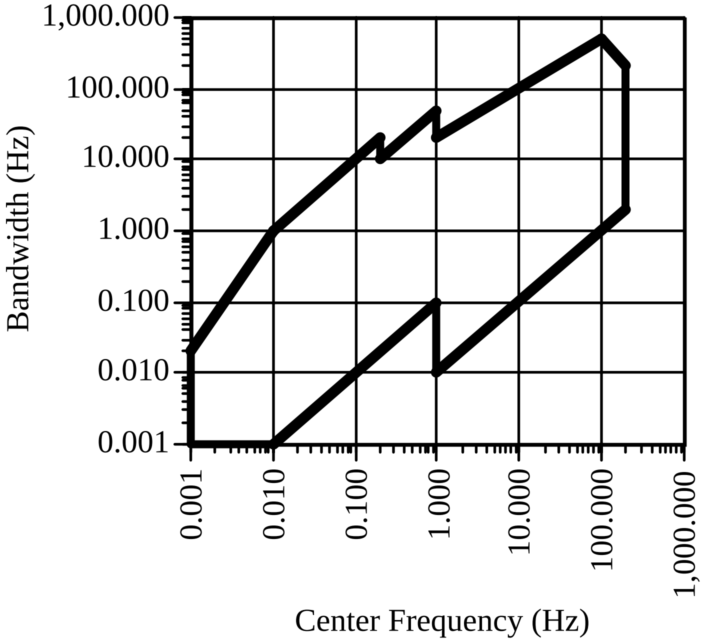

Figure 1. Crystal Filter Operating Region

Figure 2 shows the more common regions where they are usually built. There are several areas within the main one (shown in Figure 2) where the most practical and cost effective filters are built. The center frequencies range from around 5 MHz up to 40 MHz with bandwidths ranging from .05 to 1.5 %.

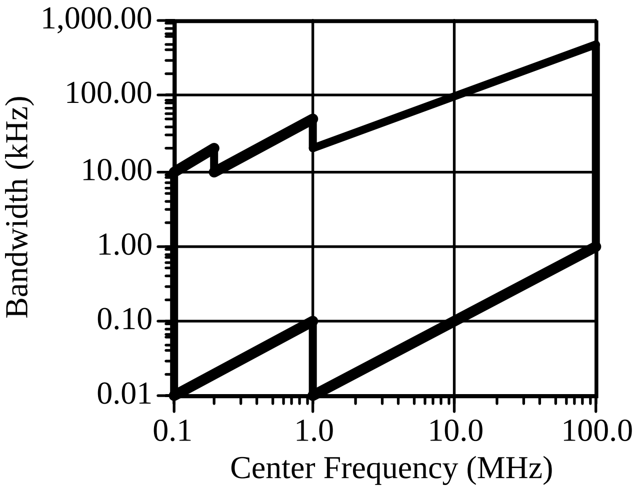

Figure 2. Common Crystal Filter Operating Regions

The narrowest bandwidth that can be achieved is controlled by two factors: the available Q of the crystal resonators and their temperature stability. For example, a filter can be made with a bandwidth of 10 Hz at a center frequency of 1 MHz. However, if the temperature range extends from -55 to +85°C the crystals could drift±20 ppM (or more) and so the center frequency would drift ±20 Hz, or twice as much as the bandwidth.

Figure 3 shows the frequency-temperature characteristics for AT cut resonators. The family of curves are for crystals cut out of the quartz crystal at slightly different angles. Each adjacent curve is separated by 2 minutes of arc from the preceding one. The designer selects the angle that will give the least change in frequency over the specified temperature range. The normal manufacturing angular spread for practical crystals will be about ±3 degrees of arc. This controls the temperature stability that can be achieved. Tighter control can be obtained, but only at the added expense of 100 % screening.

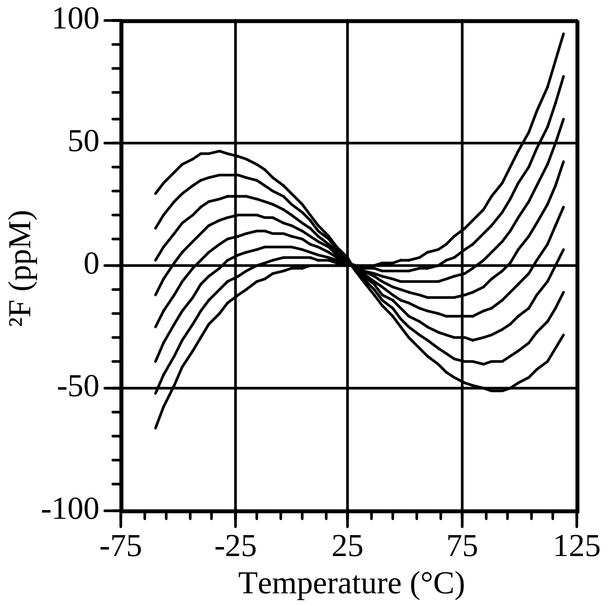

Figure 3. Frequency - Temperature Characteristics for AT Cut Crystals.

The other factor that limits the narrowest bandwidth that can be achieved is the Q of the crystals. The minimum acceptable Q is a function of the type of design used and the number of poles required as well as the center frequency and bandwidth. A 'fair' rule of thumb is the minimum Q must be larger than $2^N \frac{F_o}{BW}$, where N is the number of poles required, Fo is the center frequency and BW is the width of the passband. If this condition cannot be met the passband will be rounded, the insertion loss will be high, the stopband will appear to flare and any attenuation peaks near the passband will round off or even disappear.

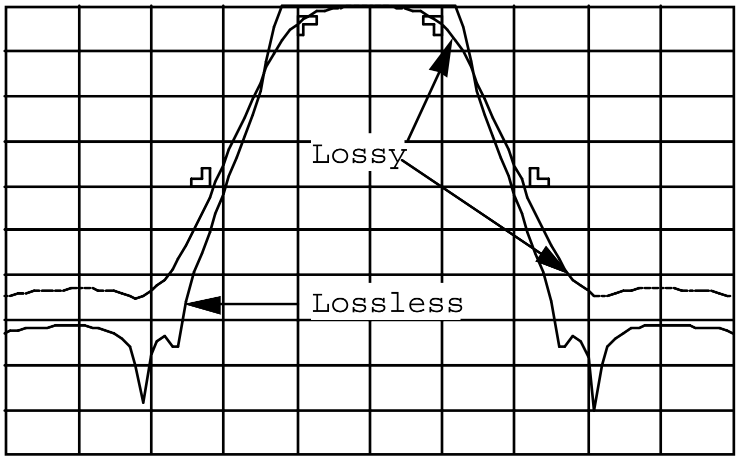

Figure 4. Narrow Band Filter with Inadequate Resonator Q

Figure 4 is an example of a six-pole, 10 MHz filter, with a bandwidth of 1 kHz. The Q minimum value from the formula would require 640,000 but crystal Q's of only 85,000 were available and so the 12 dB of loss and the rounding shown was to be expected.

The maximum bandwidth that can be achieved is controlled by the filter impedance level and the spurious responses of the crystals. Spurious responses are other frequencies of vibration in the crystals that are inharmonically related to the desired response. In AT cut crystals they will usually be located above the desired resonance with the first one appearing anywhere from 50 to 500 kHz above Fo. They continue for the next several hundred kHz to as far as 2 MHz. Figure 5 gives a typical response in the stopband region while Figure 6 shows the response in the passband. The filter was centered at 21.4 MHz with a 300 kHz bandwidth. Only the first spur of each resonator is shown.

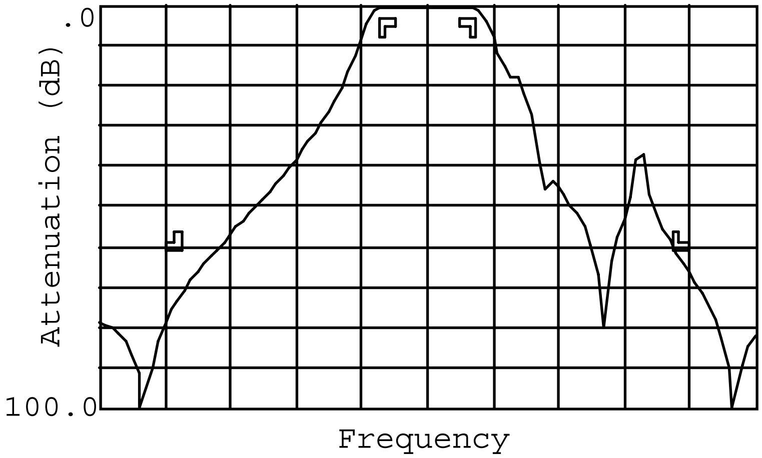

Figure 5. Spurious Response in the Stopband

The location of the spurious responses can be controlled by the size of the electrode that is plated on the crystal - the smaller the electrode the farther away the first spur will be.

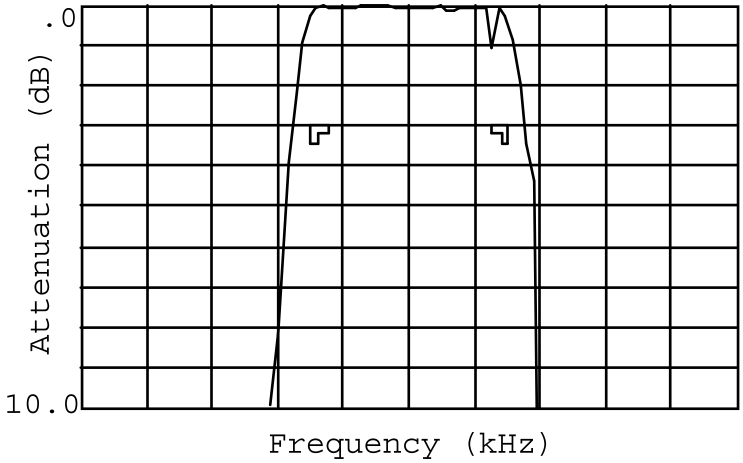

Figure 6. Spurious Response in the Passband

Unfortunately, the smaller the electrode, the higher the natural impedance will be. A high natural impedance demands that the coils and transformers also have a high impedance. Often, wide band filters require the inductance values to be too high to be realizable and so the required bandwidth can’t be achieved.

The lower frequency boundary is set by the large physical size of the resonators and other components and the upper boundary by just the opposite. The size of the resonators gets to be too small to handle to be practical.

Specifications: To specify a filter it is necessary to describe only a few parameters. A complete specification can be accomplished by defining only four parameters: the passband, the stopband, the terminations and the operating environment.

The passband is specified by defining the acceptable attenuation allowed over the required frequency range. This is done by citing the frequency and attenuation allowed at the lower band edge and at the upper edge of the passband. If several levels of attenuation and bandwidth are important to the performance of the system then they should all be specified. As an example, on a filter centered at 10 MHz it is necessary to pass –25 kHz with no more attenuation that 1 dB. It is also required that there be an even flatter region of 0.25 dB over ±10 kHz then it would be defined as follows.

Attenuation	Tolerance	Frequency
1.0 dB	Max	9,975,000.0 Hz
0.25 dB	Max	9,990,000.0
0.25 dB	Max	10,010,000.0 Hz
1.0 dB	Max	10,025,000.0 Hz

The common mistake that is usually made is to specify the 0.25 dB bandwidth as 0.25 dB *ripple*. The reason that this is wrong is because the specification allows the passband to tilt as much as 1 dB. There would be no ripple because there were no slope reversals but the passband would not be flat to within 0.25 dB.

Another way the flatness could be missed but still considered to meet the requirement is illustrated in Figure 7. It shows a filter with specification marks at 3 and 1 dB. Typically the requirement reads: Bandwidth 3 dB min. over Fo±25 kHz with passband ripple of 1 dB max. The problem here is that there is a no-mans-land between the 1 and 3 dB points. If the system performance will be degraded when the attenuation is more than 1 dB then the 3 dB requirement should be changed to 1 dB and the ripple call out deleted. However, if the 1 dB ripple specification is included because you don t think a filter should have a hole in the middle of the passband (even though it doesn’t t impact system performance), then it should be changed to 3 dB, or a level you re comfortable with, and the ripple requirement deleted.

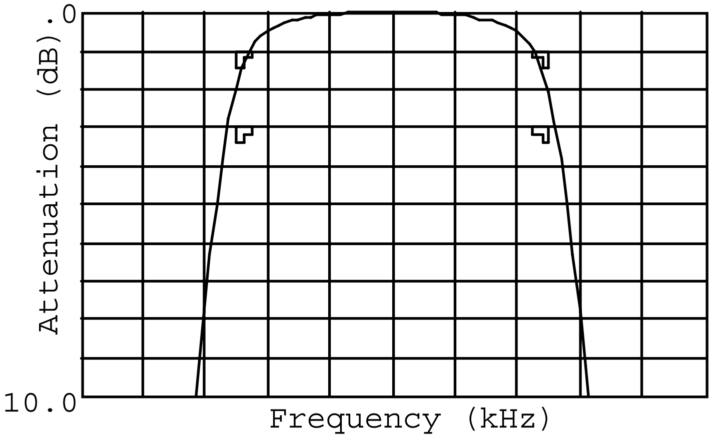

Figure 7. Ripple Confusion

Ripple is a design parameter and should never be used as a specification element. Rather, that requirement should be defined as a set of passband frequencies and levels.

Next define the stopbands by specifying the amount of attenuation required and the range over which it must be held. Be sure to specify the complete region over which you need the attenuation (Figure 8).

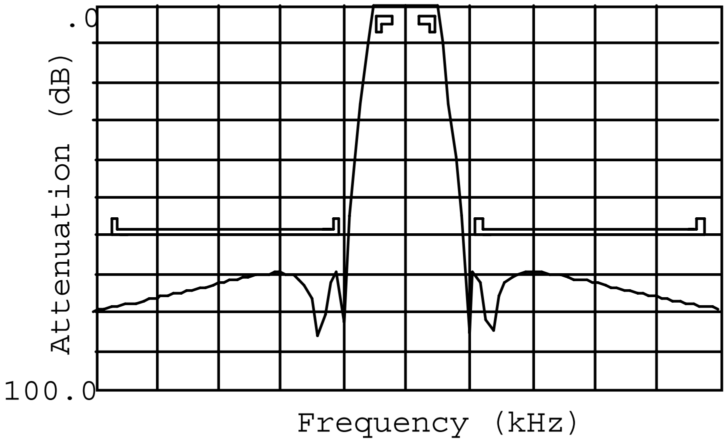

Figure 8. Stopband Specifications

Avoid the use of ultimate attenuation to describe the desired stopband performance. When ultimate attenuation is specified as 60 dB (or some other number) it is only half a definition, since the frequency range isn't specified.

On some filters the spurious responses (Figures 5 and 6) can be a problem that are very difficult to control. If they can be tolerated, your specification should allow for them (Figure 9). Contact your filter supplier for his estimate of where they will be located and how far they will return.

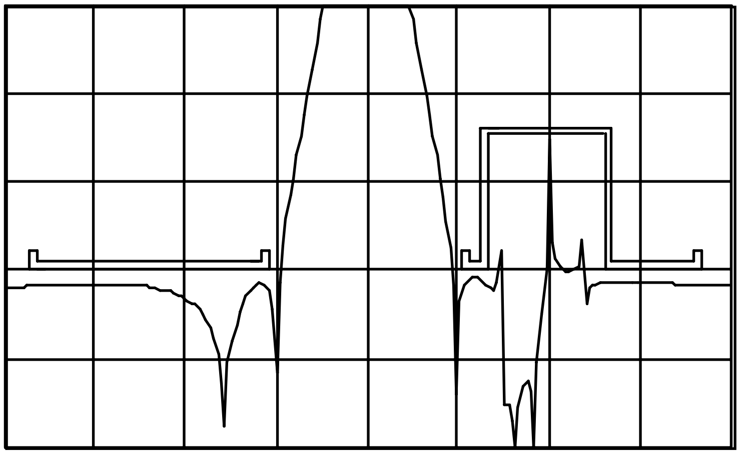

Figure 9. Stopband with Spurious Allowance.

Next it is necessary to describe the impedance of the circuit that is driving the filter (the source impedance) and the impedance that the filter must work into (the load). These two values are the ones your circuit will present to the filter, they are *not* the input and output impedances of the filter. Always be careful to observe the difference between source/load, and input/output impedances.

The last item can consist of a very complicated set of items that describe the environment that the filter will operate in.   It could be simply defined as "Laboratory Environment," or "Airborne Environment". While this type of definition is not complete, it will tell the designer what to expect and how to proceed in the review of the requirements.

These four items are all that are necessary to specify a filter. So, what about all the other parameters, shouldn't t they be specified too?   Only if they're important.   Don't put requirements on anything that you are flexible on. Let the designer make the preliminary design and then define any other needed parameters. Once the design is complete other items such as, insertion loss, delay, package size, return loss, etc., will be available and can be added to the specification as required. However, if the particular item isn't important to the performance of the system, it should not be specified because there will always be some cost connected to every parameter specified.

Cost Drivers: The costs associated with crystal filters are the same as those associated with any component. That is, material, labor, overhead, G and A, profit, etc.   Since everything except material and labor are unique to individual manufactures, the only items that will be examined are the labor and material and what causes them to affect the price.

A bill of material for a typical filter might look like this:

Item	Qty /Fltr	Price	Total
Crystals	6	$2.50	$15.00
Cores	3	0.35	1.05
Capacitors	7	0.25	1.75
Variable Caps	3	1.19	3.57
Resistor	1	0.15	0.15
Circuit Board	1	1.20	1.20
Enclosure	1	5.75	5.75
TOTAL			$28.47

The crystals, as expected, have the highest costs because there are six of them required. Thus, the first cost driver is the number of crystals that are required to meet the specified requirements. This is determined by finding the shape factor required and then finding the number of poles required to meet it. In general, the number of poles equals the number of crystals required. The shape factor is found by dividing the bandwidth of the stopband by the bandwidth of the passband. For example if the 3 dB bandwidth must be at least 20 kHz wide and the 60 dB bandwidth must be less than 40 kHz then the shape factor is 40/20 or 2.0:1. Table 1 gives the shape factor that can be achieved for a given number of poles.

Table 1. Shape Factors for N Pole Monotonic Filters

No. of Poles	Shape Factor (60/3 dB)
2	30.0
3	10.0
4	5.0
6	2.5
7	2.1
8	1.9
10	1.5

Table 1 shows that the steeper the filter is, the more crystals will be required and, the higher the crystal costs.

The center frequency also influences the cost of the crystals because there are some regions where it is easier, and less costly, to manufacture crystals. Figure 10 gives a rough estimate of the relative costs of a crystal as a function of its frequency.

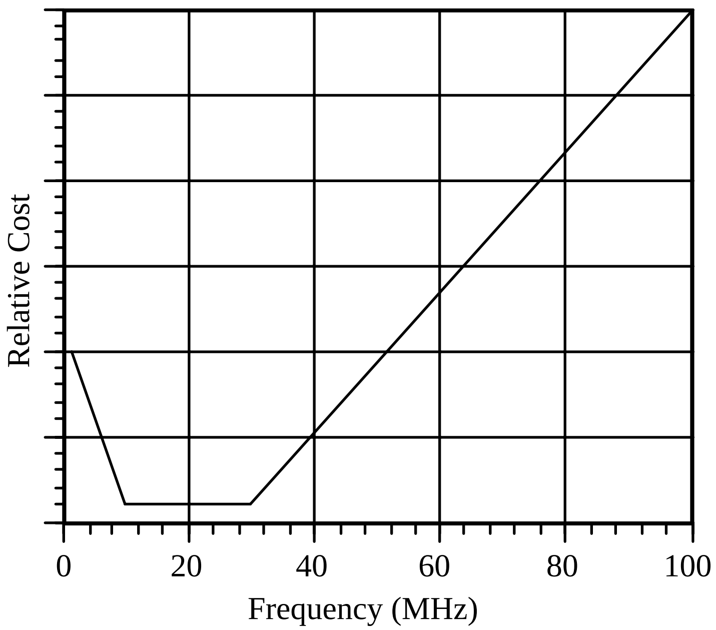

Figure 10. Relative Crystal Cost vs. Frequency

This graph shows only fundamental mode crystals and it indicates that the lowest cost crystals will fall from about 5 MHz up to about 35 MHz. To minimize the crystal costs reduce the number of crystals required by increasing the shape factor and select the center frequency to fall between 5 and 35 MHz.

As the bandwidth of the filter increases above 100 kHz the spurious responses of the crystals become a problem. To control them it is sometimes necessary to add more filter sections and include more crystals.

Another way the bandwidth of the filter can affect the crystal costs is if the bandwidth becomes quite narrow. The crystals will have to meet very tight Q and temperature stability requirements and their yield will drop. The best way to minimize costs due to the bandwidth associated problem is to keep the percentage bandwidth between .05 and 1.5% and the maximum bandwidth below 200 kHz.

Either the enclosure costs or the variable capacitor costs are the second most expensive costs in the filter. In the example shown, the enclosure comes in second. The enclosure costs can vary dramatically depending on the requirements. For example, standard drawn cans are cheaper than fabricated enclosures and fabricated enclosures are much cheaper than machined housings. Glass feed-through terminals generally cost less than 50 cents but hermetically sealed connectors can cost $10.00 or more. Small filters that don't need any provision for mounting (other than their input, output and ground pins) will cost less than filters with studs. Filters requiring inserts will cost more than ones with studs, and filters that require a hole completely through the package will be even more costly. Special paint or marking inks will always cost more than using the manufactures standard plated finish and marking methods.

Another factor that affects the costs is the environmental requirement. It is fairly obvious and so it won t be discussed here except to say that a laboratory environment" will cost less than designing to operate the same filter in a missile environment.

The labor content can be the major cost of the filter. The factors that drive up the labor costs are such things as: difficult specifications that require a large amount of alignment time; phase and/or amplitude matching requirements; special screening and quality requirements. Most engineers understand the effect that stringent quality requirements place on a program and so it won t be covered. It is also nearly impossible to discuss difficult specifications in a general sense since each filter will have its own unique tuning procedure. However, there are some general comments that can be made about phase and amplitude matching.

Phase and amplitude matching requirements mean that the matched filters all have identical (or nearly identical) shapes and responses. To achieve this, all the crystals and coils have to be tuned properly to the same (correct) frequencies. This is especially difficult on very narrow and very wide bandwidths. The more filters that have to match each other the more difficult it is. Therefore, to keep the cost down, require matching on the smallest number of filters possible. That is, it is cheaper to require matched pairs rather than matched trios, trios rather than quads, etc.

The largest changes in both the phase and amplitude occur as the edge of the passband is approached. Therefore, it is more difficult to match all the way to the 3 dB point than it is to match to only 80% of the bandwidth. If it is necessary to match all the way out to the edge of the passband then it would be better if a looser specification could be used in the last 20 % of the bandwidth.

The most expensive type of matching is matching both phase and amplitude on two or more filters at the same time.

Very narrow and very wide matched filters will always be more costly than filters with a bandwidth that falls between 0.05 and 1.5 %.

Testing: All filter testing must be conducted in a well constructed, well grounded test fixture. Such a fixture must provide a shield between input and output terminals and should be placed on a ground plate (Figure 11).

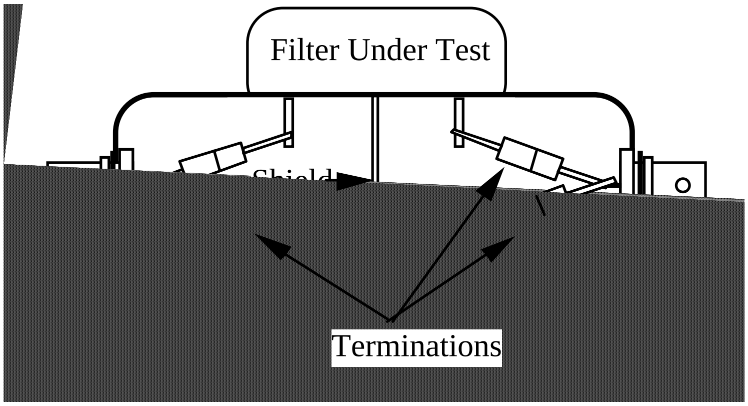

Figure 11. Approved Test Fixture

The filter is connected to the fixture using normal mounting means, whenever possible, or by clamping it to the fixture to make sure that a good ground connection is established. In some cases it may be necessary to use finger stock between the filter and the fixture. The terminations provided inside the fixture are adjusted to properly terminate both the filter and the network analyzer and the associated cables. The circuit shown in Figure 12 will provide the proper terminations for a 50Ω system.

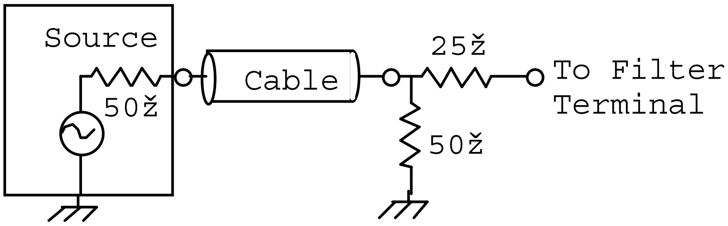

Figure 12. Terminating Circuit

In all cases, the test fixture must be calibrated at the center frequency of the filter.

If the circuit is not properly terminated the filter will be mismatched and the passband response will be distorted. Figure 13 shows a filter response when the source and load impedance have been set low by 20 and 50 %.

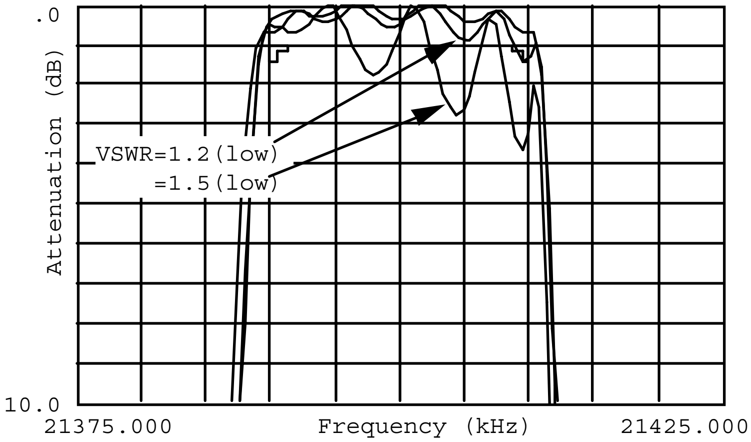

Figure 13. Response of a Mismatched Filter

When mismatched by 20% the upper 1 dB point now falls out of spec, however when the terminations are 50% low the passband response is totally unacceptable with the deep holes in the passband exceeding 3 dB.

If the filter is not properly grounded the stopband will fail to reach the desired attenuation level. The circuit shown in Figure 14 has a small resistor between the filter and actual ground.

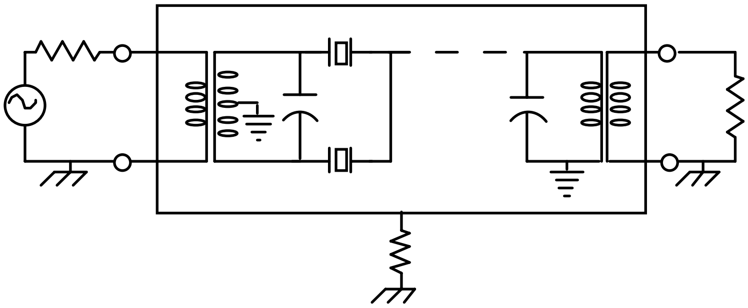

Figure 14. Grounding Problems

Figure 15 shows the responses for the filter when the value of this resistor is changed from 0 to 5, 10 and 50 milli Ohms.

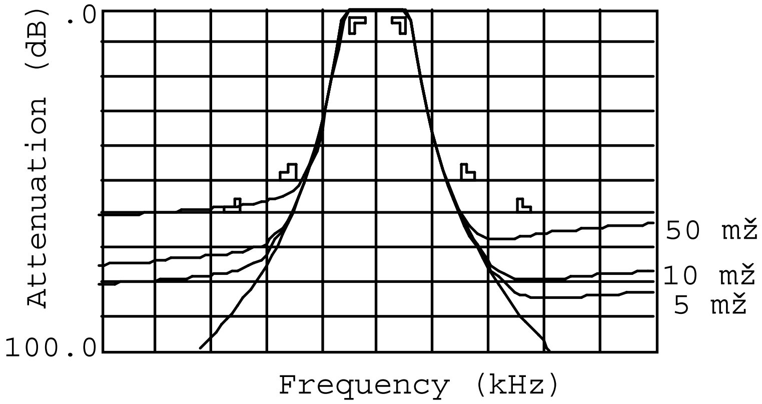

Figure 15. Filter Response with Poor Grounding

The other common problem occurs when there is some feed-through either through the filter or around it. It is shown schematically in Figure 16 with the feed-through shown as a reactance X.

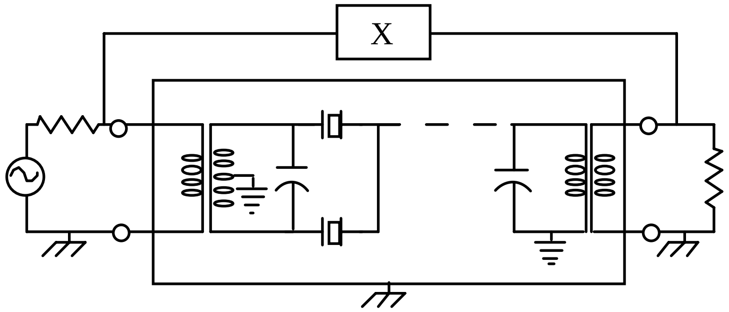

Figure 16. Filter with Reactive Feed-Through

A small amount of signal coupled around the filter can cause a noticeable problem. Figure 17 shows the results when small capacitors are used for X.

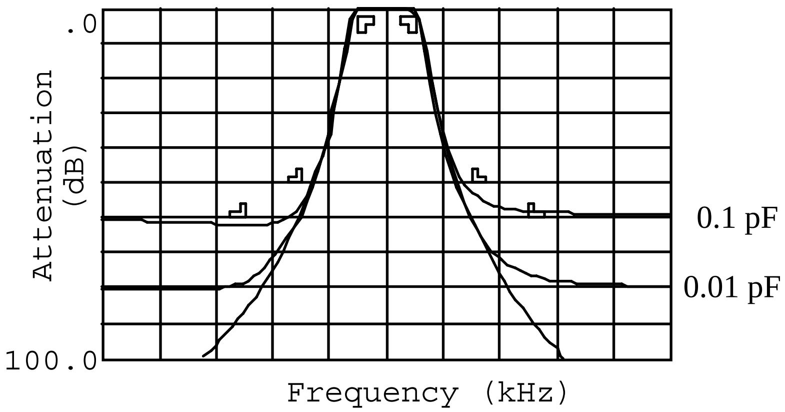

Figure 17. Feed-Through Levels

Computer Aided Testing: Computer aided testing is not new. It has been used to conduct automatic testing of circuits for over 20 years. But today, because of the availability of powerful personal computers, it can be extended to perform even more complicated measurements.

Many filter manufactures use standard testing programs in their PC s that control the test equipment. These programs test the part, record the data and plot the passband and stopband responses. Because of their prevalent use throughout the industry nothing more will be said about them. Rather, we will concentrate on the use of the computer to make it possible to phase match any number of filters to each other, and to make time domain responses without the inaccuracies caused by associated test equipment.

Phase matched filters have always required that a standard, or a group of standard filters be kept and used to match to the other filters. However, because there was always the chance that one or more of the standards would age and change its phase response, it was deemed impractical and so filters were matched into pairs, trios or quads. This could cause logistic problems because anytime one of the filters failed the entire set had to be replaced. Now a polynomial can be fit to the average phase change on a group of filters. This produces a standard phase polynomial that is kept in the testing program and used to match all the filters. A second standard polynomial is created to provide the match over the temperature range. The stability of this measurement is controlled by the calibration of the network analyzer and test fixture that is used to make the measurements. Both need to be carefully controlled but the stability is not dependent on the stability of a standard filter but rather the calibration of the equipment.

The PC can also be used to simplify time response measurements and to make them less dependent upon the test equipment and therefore the measurements are more accurate. Figure 18 shows the test equipment set-up that was previously necessary to test the time response of a filter. The pulse generator feeds the mixer which 100% modulates the RF signal. This produces a CW pulse that is sent into the filter and then to the spectrum analyzer. The spectrum analyzer is used as a broad band log amplifier and detector. The detected signal is measured on the oscilloscope. Unfortunately, often parts of the test equipment weren't good enough to allow resolution to the required level. Several schemes were used to fix the problem but often these attempts yielded less than satisfactory results.

Today, using the Network Analyzers and the personal computers the transfer function can be measured and recorded. Then the PC is used to compute the time response of the filter. In a 1984 paper Pond[1] described

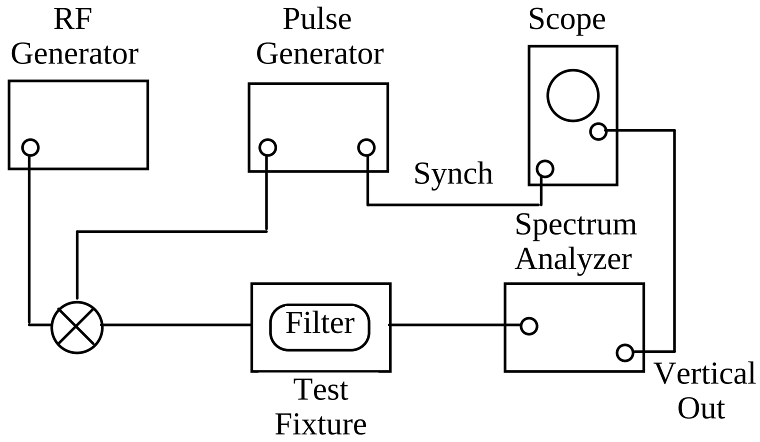

Figure 18. Old Transient Analysis Test Set-Up

how the transient behavior of a filter is calculated from its transfer function and the Fourier transform of the input pulse. The method that was set forth in that paper is modified to utilize the equipment available today and it is summarized as follows:

1. Measure and record the filter transfer function ($H(j\omega_i$) in a series of i frequency steps (ΔF) across a frequency range that is wide enough to at least cover the attenuation level desired. (That is, if the ringing response must show 60 dB of attenuation then the filters frequency response must also show **at least** 60 dB attenuation.)
2. Select the pulse width τ and its frequency ω_c.
3. Compute the Fourier transform $E(j\omega_i)$ of the input pulse at each frequency point ω_i.

   $$E(j\omega) = \frac{\sin(\omega_i - \omega_c)\tau + j(\cos(\omega_i - \omega_c) - 1}{\omega_i - \omega_c}$$
4. Select the starting and ending times and select the number of steps to be taken,
5. Compute the response from:

   $$|r(t_i)| = \left| \sum_{i=1}^{n} H(j\omega_i) E(j\omega_i) e^{j(\omega_i - \omega_c)t} \Delta F \right|$$

This procedure requires some programming to find the transform of the input pulse and compute the sum but it need only be done once and it eliminates the inaccuracies of the test equipment.

Summary: Crystal filters can be built with center frequencies from below 1 kHz up to several hundred MHz and bandwidths that vary from a few Hz to a MHz. Very selective filters can be built with shape factors as small as 1.10:1 however, if cost is a consideration it is best to stay with shape factors of 2.0:1 or higher. The most cost effective center frequency range runs from around 5 to about 35 MHz. While the filter pass bandwidths should range from 0.05% to 1.5%. Filters can be built outside these limits, but these values will provide the most cost effective units.

When specifying filters it is necessary to clearly define what you want to pass and the region you want to reject. Avoid the use of the words ripple and ultimate attenuation . Carefully specify the source and the load impedances that will be presented to the filter.

When testing filters pay careful attention to the test fixture. The calibration of the equipment and the test fixture must be done *at the center frequency of the filter*.

Computer controlled test equipment can aid in the measurement of standard frequency/attenuation characteristics, and the final testing of filters. In addition PC s are invaluable in phase and amplitude matching of multiple filters. Finally a test technique for using computers to help perform transient (ringing) measurements was shown.

References:

[1] C. W. Pond, Crystal Filter Transient Behavior, in Proceedings of the 6th Quartz Devices Conference, 1984, pp. 188-206.