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Waveguide Filters You Can Build—*and* Tune Part 1 A Tour of Filters

In this first of a 3 part series, the author reviews basic filter design parameters and terminology

Let's take a short tour of filters, skipping the deep math. Before we can talk about filters, though, we must start with resonators, the building blocks for filters. Common resonators include LC circuits, transmission line sections, waveguide cavities, and quartz crystals.

There are also mechanical resonators, which may be easier to visualize than the invisible workings of an electrical resonator. Pluck a guitar string, or tap a suspended pot lid, and an audible tone will be produced for a few seconds. The mechanical resonator has been excited with mechanical energy; the energy is stored as a resonance and slowly released as sound. Good resonators will produce a pure tone for a longer time.

Another example of a mechanical resonator is a pendulum. A good pendulum will swing for a very long time with a constant period, or time to complete one swing back and forth. The period of the pendulum swing is determined by the length or the pendulum. The amplitude of the swing will decay slowly, due to friction and air resistance, but the period does not change — the frequency is constant (frequency is the inverse of period). The stored energy is dissipated very slowly. In electrical terms, a pendulum is a high-Q resonator, where Q is defined as the ratio of stored energy to energy dissipated.

To produce something useful, some energy must be extracted from a resonator. The guitar string produces sound to make music, while a pendulum may be coupled to a clock mechanism to tell time. When energy is extracted, the resonator decays faster — the Q has been reduced.

If we add energy to the resonator as fast as it is being extracted and dissipated, it can continue indefinitely. We could blow gently on the pendulum each time it starts a downward swing, but we must time it correctly — energy at the wrong frequency may be counterproductive. Of course, we could use a mechanical or electrical signal to time the addition of energy — I have a clock whose pendulum will run for eight days just by winding up a spring and allowing the mechanism to extract a tiny bit of energy from the spring for each tick.

The electrical equivalent of the clock mechanism is called feedback, adding energy to a resonator to make an oscillator.

Microwave Resonators

Typical microwave resonators are sections of transmission line: odd multiples of an electrical quarter-wavelength shorted at one end and open at the other, or multiples of an electrical half-wavelength either shorted at both ends or open at both ends. The transmission line may be coaxial, with an inner and outer conductor of various shapes, or waveguide formed by a conductor. These transmission line structures are often called cavities. Planar structures on dielectrics are also used. The shapes need not be regular or symmetrical, but odd shapes will complicate calculations.

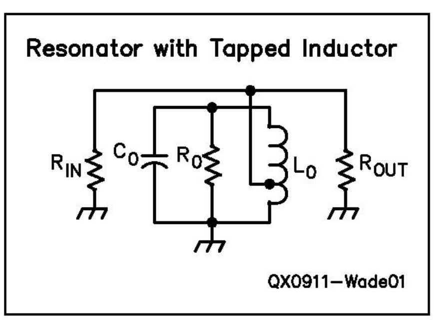

Figure 1 —This is the schematic diagram of a single L-C resonator with tapped inductor.

Whatever the configuration, a single resonator is equivalent to a parallel LC circuit (often called a tank circuit for reasons lost in antiquity) like Figure 1. At some frequency, the reactance of the capacitor, X_C, will be equal to the reactance of the inductor, X_L, and at that frequency the circuit is resonant. It will "ring" at this frequency if excited by an impulse.

Any real resonator has some intrinsic loss, shown as the R_o in the circuit. This loss determines the intrinsic Q, or unloaded Q, of the resonator: $Q_U = R_o / X$. Since the reactances are equal, either X_L or X_C may be used.

When the resonator is connected to a circuit, the resistance added by the circuit appears in parallel with the intrinsic R_o, so the total R must be lower than R_o, reducing the Q to the loaded Q, Q_L. For example, suppose that we make the connection by tapping down on the inductor ¼ of the turns from the bottom. You might recall that the impedance

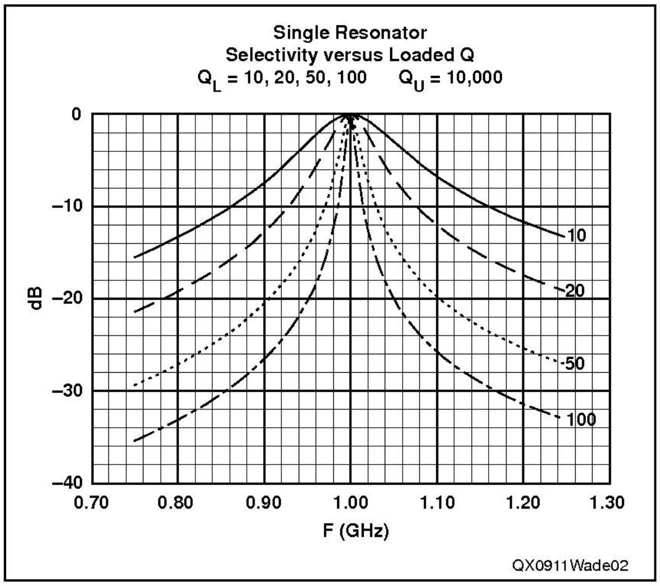

Figure 2 — This graph shows the selectivity of a single resonator versus loaded *Q*.

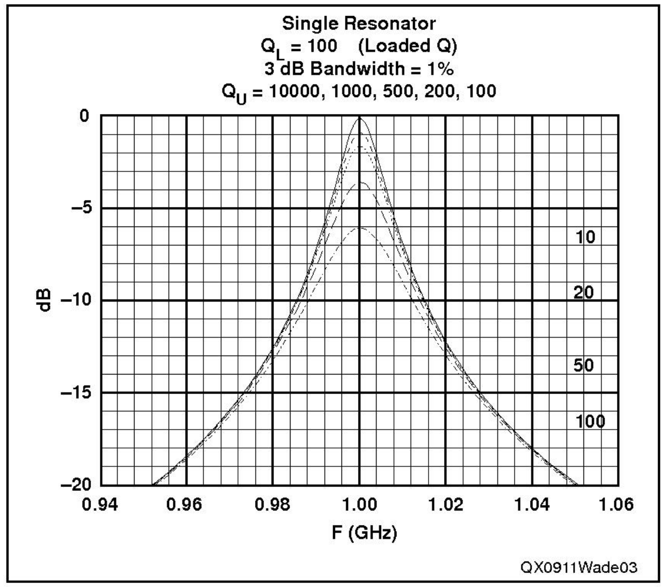

Figure 3 — A graph of the selectivity of a single resonator with loaded *Q* = 100 and varying unloaded *Q*.

ratio is the square of the inductor turns ratio; the turns ratio is 4, so the impedance ratio is 16. If we connect a 50 Ω circuit to the resonator, then the added resistance is 16 × 50 Ω = 800 Ω. If the intrinsic R_o were 10,000 Ω, then the resultant R would be 740 Ω. For an arbitrarily chosen reactance X = 200 Ω, Q_U = 10000 Ω / 200 Ω = 500, while the loaded Q_L = 740 Ω / 200 Ω = 3.7, a significant reduction.

Selectivity

The selectivity of a resonator is determined by its loaded Q_L. The 3 dB bandwidth — the difference between the frequencies at which the response is reduced by 3 dB — is simply stated by Equation 1.

$$BW_{3\,dB} = \frac{Frequency}{Q_L} \qquad \text{[Eq 1]}$$

Figure 2 makes the effect clear — low Q_L resonators are not very selective, while high- Q_L resonators are quite sharp. The graph is centered at 1 GHz to make it easily scalable to any frequency — for example, the response at 0.8 times the desired frequency is exactly that shown at 0.8 GHz.

Why not just use high-Q_L resonators? Unless the unloaded Q_U is much higher than Q_L, losses will be high, since R_o would be a significant part of the circuit. Some examples are shown in Figure 3 for a Q_L = 100, so that the bandwidth is only 1% of the operating frequency.

The loss increases rapidly as Q_U decreases. The loss may be calculated using Equation 2:[1]

$$\text{Insertion Loss} = 20\log\left(\frac{Q_U}{Q_U - Q_L}\right)\text{dB} \qquad \text{[Eq 2]}$$

Figure 4 shows this relationship graphically: when the ratio of Q_U to Q_L is about 10, the loss is about 1 dB. The loss is lower with higher ratios, but loss increases rapidly with lower ratios: when $Q_L = Q_U$, the loss is 6 dB. Trying to make a sharp filter with low Q_U resonators will result in most of the power heating the filter.

At lower frequencies, unloaded Q_U may be improved by increasing physical size, like the large quarter-wave "cavities" used for repeater duplexers. At microwave frequencies, however, when large dimensions are a significant part of a wavelength, additional unwanted resonances will be created in the cavity.

[1]Notes appear on page 43.

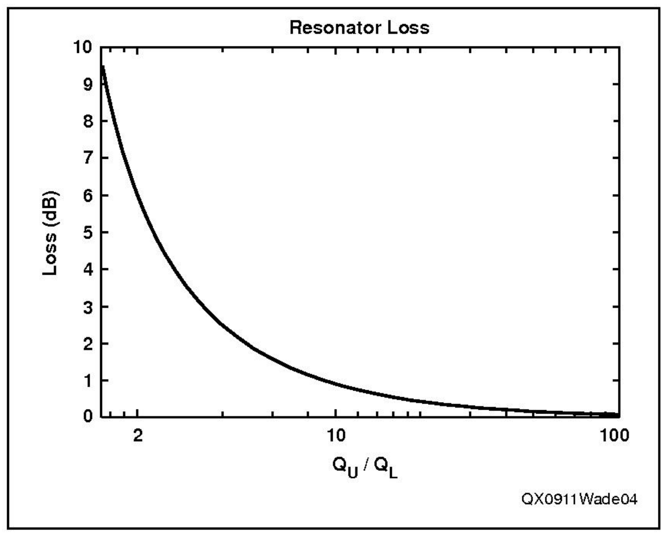

Figure 4 — Here is a graph showing resonator loss versus ratio of loaded *Q* to unloaded *Q*.

Multiple Resonators

A common rule of thumb is that a single capacitor or inductor in a circuit creates a 6 dB / octave rolloff. A simple resonator, with one C and one L, should roll off at 12 dB / octave, where an octave is doubling or halving the frequency relative to the bandwidth. To get faster rolloff, for better out-of-band rejection, therefore, you will need additional resonators.

Simply connecting resonators together produces interactions that distort the response. A traditional technique — dating back to tuned radio frequency (TRF) receivers, before the superheterodyne — is to separate resonators with amplifiers to limit interaction between the resonators. At the lower microwave frequencies, where MMIC amplifiers provide cheap gain, we often use two or three simple "pipe-cap" resonators separated by MMIC amplifiers. This com-

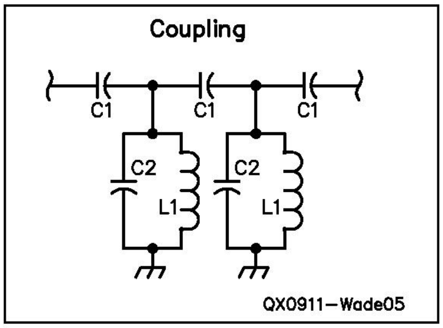

Figure 5 — This schematic diagram shows a simple double-tuned filter with coupled resonators.

bination can provide enough selectivity for good local oscillator (LO) and image rejection. The resonators may be synchronously tuned, all at the same frequency, for narrowest bandwidth. Alternately, they may be stagger-tuned, to slightly different frequencies, for a wider passband while still providing fast rolloff.

Modern filter design techniques use multiple resonators, or sections, coupled to control the interactions and achieve a desired response. By varying the coupling between resonators, the response may be controlled. A simple double-tuned circuit, Figure 5, with two coupled resonators, is a good example. Figure 6 shows the effect of coupling: the optimum coupling achieves a flat response; over coupling increases the bandwidth but creates some ripple in the passband, while under coupling decreases the bandwidth at the cost of increased loss. Note that all the responses roll off at the same rate outside the passband — only additional resonators will improve the rolloff.

The coupling between resonators may be capacitive, as shown in Figure 5, or inductive, or magnetic, with no physical connection. The input and output connections may also be capacitive, as shown, or inductive, either tapped down on the coils like Figure 1 or as a separate winding.

Adding additional resonator sections makes the filtering action much sharper, as shown in Figure 7. A filter may be designed for narrow or wide bandwidth with skirts as sharp as desired. The dimensions and tolerances become more critical, however, and tuning the filter can be much more difficult. I have a six-resonator filter that looks great in the computer design but has proven impossible to tune.

Many commercial applications have stringent filter requirements, to separate channels or to block adjacent bands. These may require a broad passband with low insertion loss, steep skirts that roll off quickly, and high stopband rejection. Figure 8 illustrates these terms. This surplus filter has close to 0 dB loss over a broad passband and more

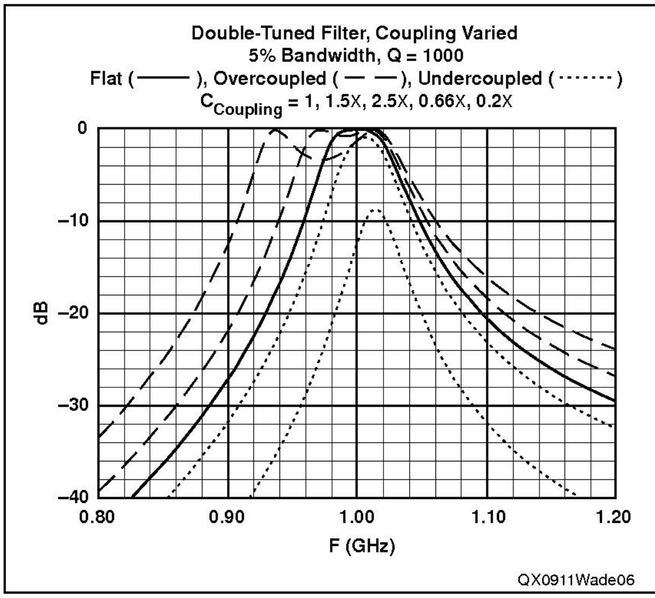

Figure 6 — The responses of a double-tuned filter with under-coupling, critical coupling, and over-coupling are shown in this graph.

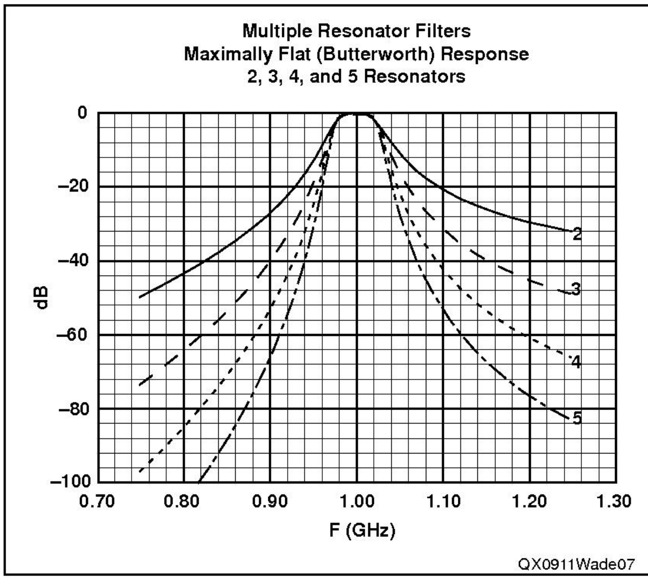

Figure 7 — This graph shows the response of filters with 2, 3, 4, and 5 coupled resonators.

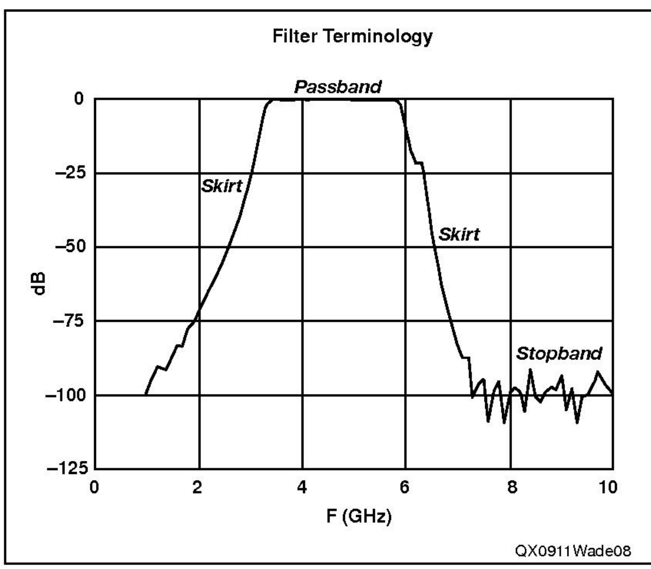

Figure 8 — This graph shows the response of a multiple-resonator surplus filter, and also illustrates the common filter terminology.

than 100 dB of stopband rejection — a good filter can be better than we can measure.

Advanced filter design techniques have been developed to meet these requirements. For instance, a Chebyshev (Чебышёв — also sometimes spelled Chebychev, Chebyshov, Tchebycheff or Tschebyscheff) filter has steeper skirts at the cost of some ripple in the passband loss; the allowable ripple is part of the design procedure.[2, 3] Figure 9 compares a five-section Chebyshev filter to the maximally-flat, or Butterworth, design from Figure 7. More advanced filter design techniques, such as Cauer, elliptic-function, and cross-coupled filters, offer high performance at the expense of more complex design procedures and tuning difficulty. Today, filter design software eases the task; traditionally, the design parameters were tabulated in books.[4, 5, 6] Either way, some engineering is still needed to design a practical filter that can actually be built. Amateurs rarely need such a fancy filter, except for the crystal filters in our transceivers.

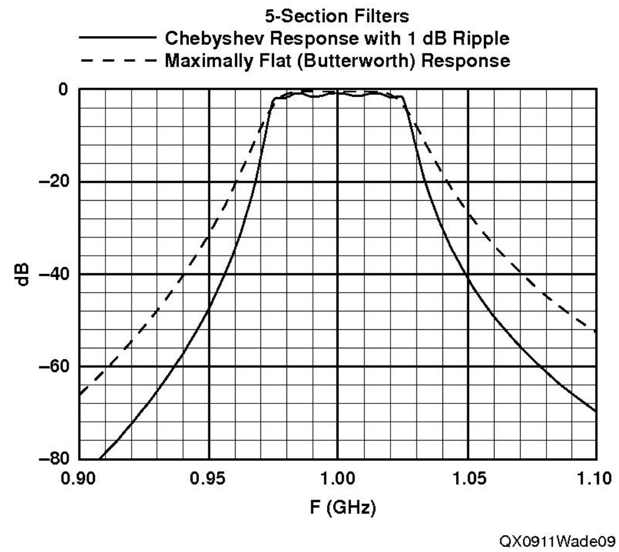

Figure 9 — This graph is for five section filters with a maximally flat Butterworth response and a Chebyshev response with 1 dB of passband ripple.

Most microwave operation is close to a standard calling frequency, so all that is required is a filter that passes the calling frequency and rejects the conversion image and any LO leakage from the mixer. For the common 144 MHz IF, the ratio of LO frequency to radio frequency is 0.89 at 1296 MHz and 0.937 at 2304 MHz. These ratios may be scaled to 0.89 GHz and 0.937 GHz on Figure 7. For at least 20 dB of LO rejection, a two section filter is adequate for 1296 MHz, while a three section filter may be needed for 2304 MHz. For higher bands, we need either a sharper filter or a higher IF, such as 432 MHz.

A sharp filter may be either very narrow or have more sections. Several factors limit how narrow a filter we can use. The first is the unloaded *Q*, or Q_U, of the resonators — we can't make a narrow, high *Q* filter with low *Q* resonators. The response curve of a lossy filter with low *Q* resonators tends to be more rounded and less sharp.[7]

A more practical limit is whether we can tune a narrow filter *and* have it stay tuned over temperature and vibration, particularly for rover operation. The alternative, adding more sections, also has problems. Unlike the ideal filters in Figures 7 and 9, each section adds additional loss, so that the filter loss is proportional to the number of sections. Also, filters with more than three or four sections are very difficult to tune properly without sophisticated test equipment.

With high *Q* resonators, like those found in waveguide filters, a narrow double-tuned circuit, or two-section filter, should be satisfactory for many amateur applications. We can see from Figure 5 that the skirt selectivity is not affected by the coupling, so the maximally flat, or Butterworth type of filter is a good choice. The bandwidth of a two section Butterworth filter is $\sqrt{2}$, or 1.414 times the bandwidth of a each single resonator. Thus, to find the desired Q_0, the loaded *Q* of each resonator, we simply calculate the value using Equation 3.

$$Q_0 = \frac{Frequency}{BW_3} \times \sqrt{2} \quad \text{[Eq 3]}$$

For circuits with discrete L and C values, the coupling components are easily calculated.[8] For direct-coupled resonators like those in waveguide filters, however, we must rely on tables (such as those given in Note 6) or programs like *WGFIL*.[9] More importantly, we can estimate loss using Figure 4 if we have an idea of the unloaded *Q*, Q_U, of the resonators.

Different types of filter construction are available, each with advantages and disadvantages. Waveguide filters can have extremely high *Q*, so that narrow filters are possible with very low loss. At lower frequencies, however, they become very large. Printed circuit filters have low *Q* resonators, but are cheap and repeatable, requiring no tuning, so they may be preferred at lower frequencies where gain is cheap. Other possible choices include helical, interdigital, and combline filters.[10] Each type offers different tradeoffs in loss, size, and difficulty in design and construction. It is a matter of choosing an adequate filter for each application.

Part 2 of this series will describe practical "Waveguide Post Filters," and Part 3 will present "Evanescent Mode Waveguide Filters."

Notes

[1]Harlan H. Howe, *Stripline Circuit Design*, Artech, 1974, p 215.

[2]See the Wikipedia entry at **http://en.wikipedia.org/wiki/Pafnuty_Chebyshev**.

[3]See the Wikipedia entry at **http://en.wikipedia.org/wiki/Chebyshev_filter**.

[4]Anatol I. Zverev, *Handbook of Filter Synthesis,* Wiley-Interscience, 2005, available from **Amazon.com** and other book sellers.

[5]Philip R. Geffe, *Simplified Modern Filter Design,* Rider, 1964.

[6]G. Matthaei, L. Young, and E.M.T. Jones, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, McGraw-Hill, 1964.

[7]Hong, Jia-Sheng, and Lancaster, M.J., *Microstrip Filters for RF/Microwave Applications*, Wiley, 2001, p 71.

[8]Wes Hayward, W7ZOI, Rick Campbell, KK7B, and Bob Larkin, W7PUA, *Experimental Methods in RF Design,* ARRL, 2009, p 3.14. ARRL Order No. 9239, $49.95. ARRL publications are available from your local ARRL dealer or from the ARRL Bookstore. Telephone toll free in the US 888-277-5289, or call 860-594-0355, fax 860-594-0303; **www.arrl.org/shop**; **pubsales@arrl.org**.

[9]Dennis G. Sweeney, WA4LPR, "Design and Construction of Waveguide Bandpass Filters," *Proceedings of Microwave Update 1989*, ARRL, 1989, pp 124-132. The *WGFIL* program may be downloaded from **www.w1ghz.org/filter/WGFIL.COM**.

[10]Paul Wade, W1GHZ, "Waveguide Interdigital Filters," *QEX*, January 1999, p 3. A PDF file of this article is available at **www.w1ghz.org/10g/QEX_articles.htm**.