Lumped Element (LC) Filters

The LC, or lumped element, filter (Figure 1) is perhaps the most common of all electromagnetic filter types. It takes its name from the inductors and capacitors upon which it is based. The resonant frequency of an LC filter circuit is given by:

$$\frac{1}{2\pi\sqrt{LC}}$$

LC filters can be specified in lowpass, bandpass, bandstop, or highpass configurations and in diplexers and duplexers as well. Their task, like all types of electrical filters, is to modify the frequency- or time-domain characteristics of a transmission path to reject interference arising from various external sources. LC filters are useful over a frequency range of below 100 kHz to slightly above 3 GHz.

Capacitors and inductors arranged in either series or parallel resonant circuits result in filters ranging in size from about 0.5 in. at high frequencies to 26 in. at low frequencies. The actual size of a particular LC filter is dictated by the size of these capacitors, inductors, as well as the level of RF power it must withstand.

Their frequency limit of 3 GHz results from the fact that parasitic capacitance and lead length inductance issues make them impractical to fabricate at higher frequencies. In addition, at very low frequencies capacitance and inductance values of tuned circuits become so large that they become problematic from a packaging perspective.

The performance of LC filters has increased over the years thanks to the development of ferrite materials used to manufacture inductors and the dielectric materials used in capacitors. As a result, high inductor Q factors can be achieved in smaller sizes than with earlier designs.

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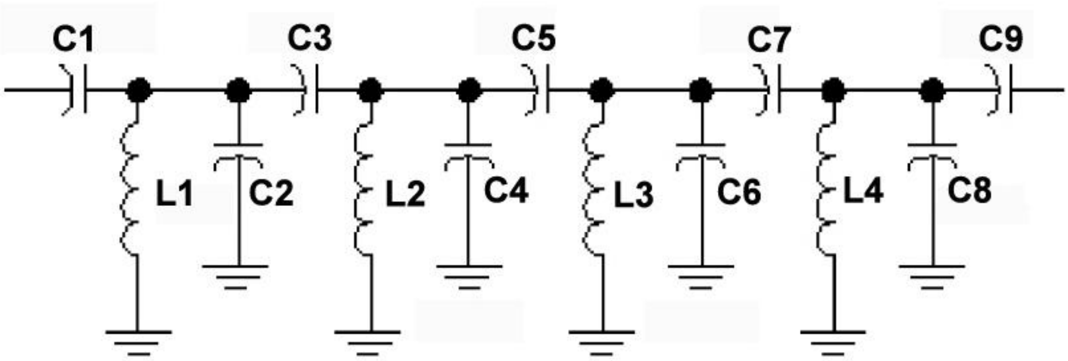

Figure 1 Typical LC bandpass filter

Table 1 provides the inherent advantages and disadvantages of LC filters. Their advantages vary depending on the application for which they are being considered. For example, they are a good choice at frequencies between 500 MHz and 1 GHz because their size remains reasonable compared to other filter types. They are also an excellent choice for very low frequencies at which they can achieve high performance when cavity filters would be too large.

For example, an LC filter with a center frequency of 500 MHz would typically be one third the size of a cavity filter (Figure 2). They can be made to provide the widest range of filter responses, including Bessel, Butterworth, Chebyshev, elliptical, constant-impedance, and constant group delay, and deliver a steep transition from passband to the rejection points. It is also relatively easy to shift the center frequency of LC filters, since it is achieved by changing the inductance of the coil and requires no machining.

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Advantages	Disadvantages
- Reasonable size at intermediate frequencies (500 MHz to 1 GHz) - Supports many topologies - Steep transition from passband to rejection - Connectorized, PC mount, surface mount, drop-in configurations - Multiple case styles - Reasonable insertion loss - Power handling acceptable for most needs - Relatively easy to shift frequencies	- Cannot achieve narrow bandwidths - Elements become impractical to fabricate at high frequencies - Limited power handling - Bulky at low frequencies - Lossy when large number of sections must be used - Moderate to high cost

Table 1 Characteristics of LC Filters

LC filters are versatile from a mechanical standpoint and can support many types of connectors in various combinations, as well as drop-in, printed circuit board, and surface mounting. Many case styles can be accommodated to meet the needs of specific physical and environment conditions as well. They inherently have low insertion loss and can handle RF power levels as high as 500 W, and in special cases even more.

LC filters can maintain a highly stable stopband response, and the stability of attenuation poles depends greatly on the resonance frequency of the filter’s tuned circuits. Such desirable passband and stopband properties in combination with small size and low cost, have made LC filters extremely popular for many years.

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However, LC filters inherently have higher loss at the edges of the passband because of finite element Q. Their loss is proportional to increases in attenuation, and is most pronounced in networks that have sharp rejection characteristics. In addition, LC filters cannot achieve extremely narrow bandwidths because of the coupling between elements.

Figure 2 Cavity filter and smaller LC filter

Since their power handling ability is defined by the physical characteristics of their elements it is somewhat limited, and although they can be made with up to 14 sections, their insertion loss increases significantly when many sections are needed. They can also be complex to design and fabricate when steep rejection skirts are required. Finally, LC filters can be expensive depending on the specific design because they require a considerable amount of touch labor.

Lumped Element (LC) Filters

Response Types

There are four types of filter response curves that are important to consider when specifying an LC filter.

The Butterworth response is a medium-Q type that is desirable for use in designs that require the filter's amplitude response to be as flat as possible. It offers the flattest possible response and contains no ripple. A typical response is shown in Figure 3. Attenuation is about 6 dB per octave per section.

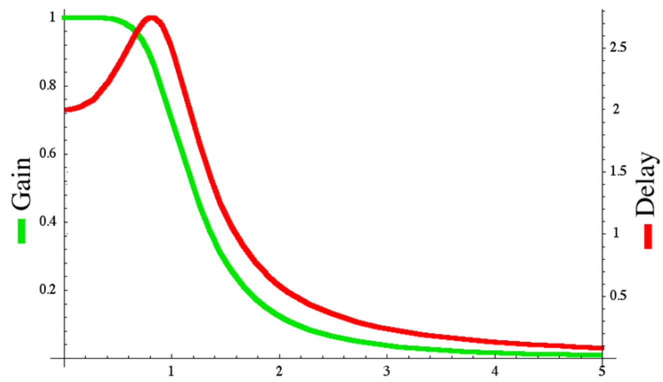

Figure 3 Butterworth filter response

Butterworth filters are usually normalized for an attenuation of 3 dB at the cutoff frequency. Because of its medium Q, initial attenuation steepness of a Butterworth filter is not as great as some types of filters. However, its element values are more practical to achieve and less critical. The rounding of its frequency response near the cutoff frequency can make this type of filter less desirable when a sharp cutoff is required, but its overall favorable characteristics make it widely useful.

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A Chebyshev response Figure 4) produces a high-Q filter that is desirable when steeper initial descent into the stopband is required and passband response is not required to be flat. It provides the greatest theoretical rate of roll-off of any pole-type transfer function for a given order.

The Chebyshev filter has ripple in the passband but not in the stopband, and the amount of ripple can be controlled and is directly proportional to standing wave ratio and reflection coefficient. The cutoff frequency is specified at an attenuation equal to the passband ripple.

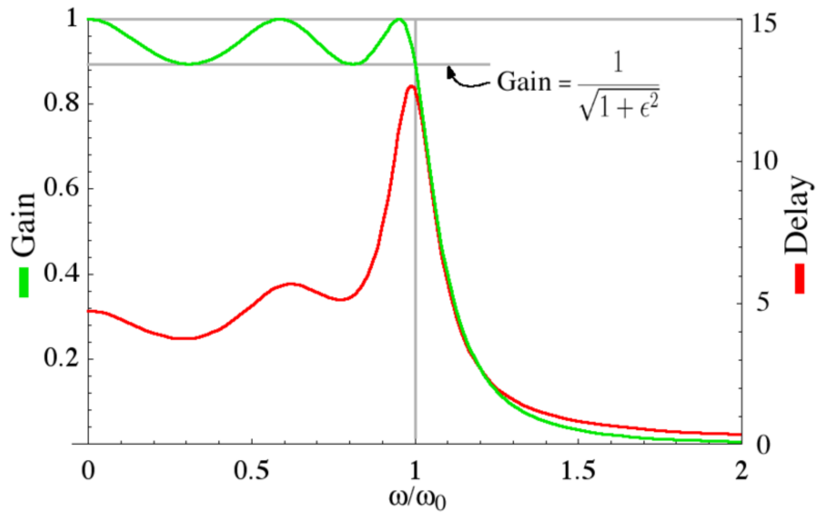

Figure 4 Chebshev filter response

The Chebyshev response is more selective than the Butterworth response at the expense of greater insertion loss and group delay. As more ripple is introduced, the initial slope at the beginning of the stopband is increased, producing a more rectangular attenuation curve when compared to a Butterworth response. In addition, as passband ripple increases, the rate of roll-off increases as well, and transient properties rapidly degrade.

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If no ripple is allowed, the responses transition to a Butterworth type. The Chebyshev response shown has 3 dB of passband ripple and produces a 10 dB improvement in stopband attenuation over the Butterworth response. Filters with a Chebyshev response have a narrower transition region between the passband and stopband than Butterworth filters but have more delay variation in their passband.

The Bessel filter has fairly good amplitude and transient characteristics, although very poor stopband attenuation, and less selective frequency response than other types of filters (Figure 5). The Butterworth, in contrast, provides better selectivity but poor transient behavior.

The Bessel response has a characteristic that makes it very appealing, which is that it is optimized to obtain “maximally flat” group delay or linear phase characteristics in the filter’s stopband.

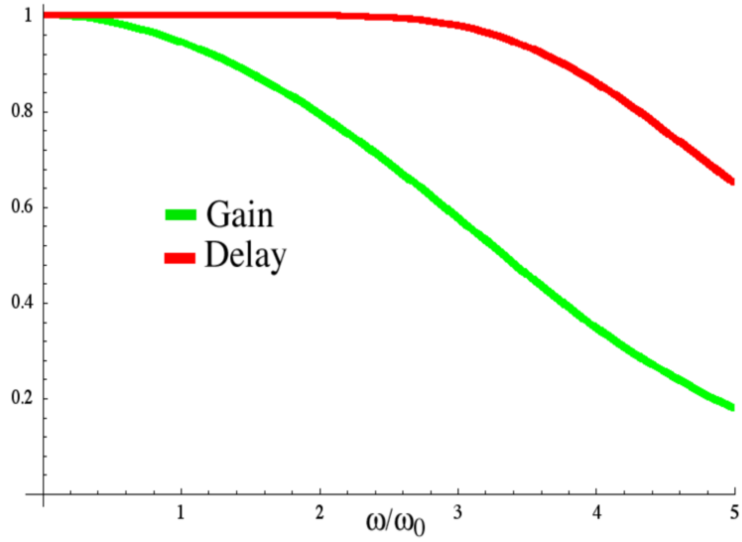

Figure 5 Bessel filter response

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Its step response has essentially no overshoot or ringing and the impulse response has no oscillator-like behavior. In medium-Q and high-Q filters such as the Chebyshev and Butterworth, the phase response is highly nonlinear through the filter's passband, which results in distortion of wideband signals because of the widely-varying time delays associated with the signal's different spectral components. Conversely, Bessel filters, which have constant (flat) group delay, can pass wideband signals with a minimum of distortion while still providing some selectivity. A similar type of filter, called the Gaussian type, is not as linear as the Bessel filter with the same number of poles, and its selectively is not as sharp.

The elliptic filter (Figure 6) is not an all-pole network, as are the filter response types just discussed. It has infinite rejection only at the extremes of the stopband, and has zeros as well as poles at finite frequencies. The elliptic filter has ripple in the passband and in the stopband, the amount of which can be controlled, and as with the Chebyshev response is proportional to standing wave ratio and reflection coefficient. The location of the poles creates equiripple behavior in the passband, much like that of the Chebyshev type. Elliptic filters are more selective than the Chebyshev types but exhibit more group delay variation in the passband.

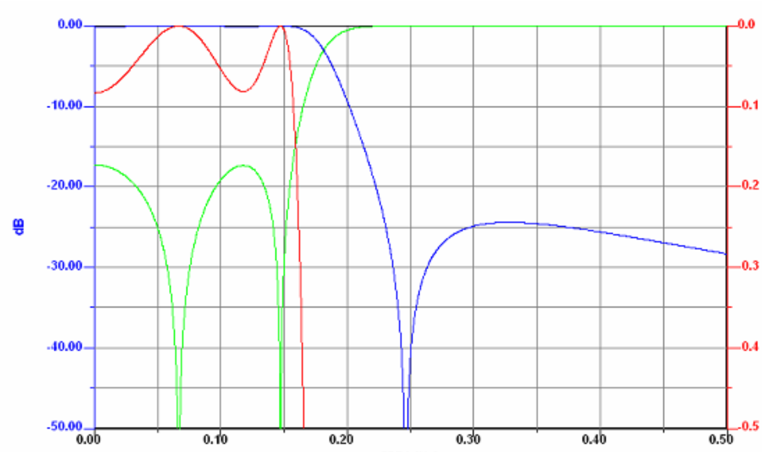


Figure 6 Elliptic filter response

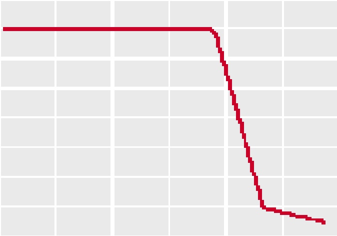
Lumped Element (LC) Filters

Finite transmission zeros in the stopband reduce the transition region so that very sharp roll-off characteristics can be achieved. The result is the steepest rate of descent possible in the transition region for a given number of poles, but this performance is obtained at the expense of return lobes in the stopband. Elliptic filters are more complex than all-pole networks, although fewer sections are required.

LC Filter Types

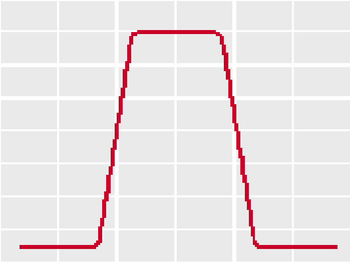
LC filters are extremely versatile in their ability to be configured to achieve lowpass, bandpass, bandstop, and highpass characteristics.

• A **lowpass** filter allows energy from DC to a specified (cutoff) frequency to pass with little or no attenuation while energy above this frequency is rejected.



Lowpass response

• A **bandpass** filter passes energy within a certain bandwidth and rejects frequencies below and above this bandwidth.



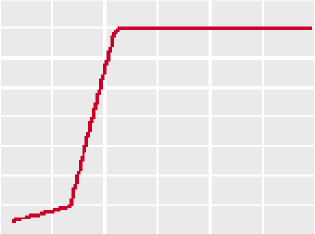
Bandpass response

• A **bandstop** filter or band-rejection filter passes most frequencies without disrupting them but significantly attenuates frequencies over a specific region.

A bandstop filter is essentially the opposite of a bandpass filter. A notch filter is a specific type of bandstop filter that has a narrow stopband.

Bandstop response

• A **highpass** filter passes energy above a specified cutoff frequency, and rejects signals at frequencies lower than the cutoff frequency.



Highpass response

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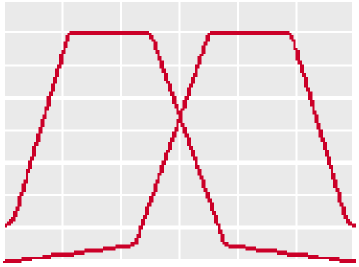
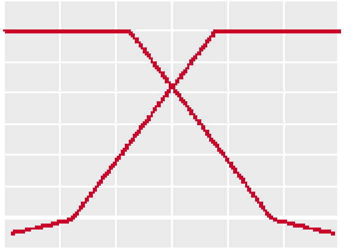

Diplexer

• A **diplexer** is a dual bandpass filter that combines two bands (usually one transmit and one receive) into a common port. It can be constructed using LC filters.

• A **duplexer** is a lowpass and highpass “dual-band” filter that combines two bands into a common port. One of the bands is usually the transmit port and the other the receive port. It too can be constructed using LC filters.


Duplexer

The stopband is the range of frequencies over which a filter rejects signals. The amount of attenuation can range from 20 to 120 dB. The lower and upper limiting frequencies, also called lower and upper stopband corner frequencies, are where the stopband and the transition bands meet. For example, the stopband of a lowpass filter is the frequency band from the stopband corner frequency (slightly higher than the passband 3 dB cut-off frequency) to the infinite frequency.

The stopband of a highpass filter, for example, consists of the frequencies from DC to a stopband corner frequency (slightly lower than the passband cut-off frequency). A bandstop filter has one stopband, specified by two non-zero and non-infinite corner frequencies. The difference between the limits in the bandstop filter is the stopband bandwidth expressed in Hertz. A bandpass filter has two stopbands. The shape factor of a bandpass filter is the relationship between the 3-dB bandwidth and the difference between the stopband limits.

Key LC Filter Specifications

There are several key specifications that are essential when specifying any LC filter, since all will affect not just the filter’s performance, but how it is designed and fabricated. When taken together, they can even determine whether or not a specific problem can be solved using an LC filter or if another filter type is best suited for the task.

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• **Insertion loss** is the ratio of signal amplitude before the filter to the amplitude at its output. Insertion loss is almost invariably an important factor and should be as low as possible. It is equally important with low or high signal input levels. For example, heat dissipation increases at higher power levels, and lower insertion loss can help reduce it. When signal levels are low, high insertion loss could reduce the output after the filter to an unacceptable level.

• **Stopband rejection** is the ratio of the unwanted frequency components at the input of the filter to those after it. It can be considered the key filter performance specification, since it equates to the filter's rejection capability. Typical values can range from 20 to 100 dB, and will vary to some degree over the stopband frequency.

• **Center frequency** is the region equidistant between the filter's upper and lower cutoff frequencies.

• **Cut-off frequency,** also called corner frequency, is the point at which energy begins to be attenuated by the filter rather than passing through it. More specifically, it is the boundary between the passband and a stopband and is often specified as the point in the filter response at which a transition band and passband meet, such as a "3 dB corner frequency" at which the output deviates 3 dB from the passband value.

• **Bandwidth** is the frequency range between the 3-dB cutoff frequencies in a bandpass filter. In the case of a lowpass filter, it is the same as the band between DC and the cut-off frequency (or simply the cutoff frequency).

• **Q factor** is the ratio of the center frequency to the bandwidth when applied to bandpass filters, where the center frequency is the region between the 3-dB cutoff frequencies. For a bandpass filter, Q factor is actually the loaded Q factor since the driving and terminating load impedances are connected to the filter when it is inserted into a network. In contrast, unloaded Q factor represents the performance of the components used to make the filter. As a result, Q_L/Q_U is the value of the insertion loss of the filter and the degradation of the skirt slope or selectivity that can be achieved within the 3-dB transition zone. Unloaded Q is generally not a key element of filter specification because it is adequately represented by the filter's other characteristics.

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• **Shape factor**, when applied to bandpass filters, is the ratio of the bandwidth at the 60-dB points below insertion loss to the bandwidth at the 6-dB points below insertion loss. Owing to the way filters are generally specified, it is generally more useful to simply refer to the filter's stopband rejection and bandwidth.

• **Impedance** is the value in ohms of the driving load impedance and terminating impedances, which are generally the same -- typically 50, 75, or 300 ohms.

• **Power handling ability** is the power in watts beyond which the filter's performance degrades or it is destroyed. It can be specified as either average power or peak power. While this specification is fundamental in specifying any filter, it takes on increased importance when power levels significantly increase.

Summary

As one of the most fundamental filter types, LC filters are also some of the most useful, since they are extremely versatile in the responses they can achieve, the types (such as lowpass, highpass, etc.) they can accommodate, and their potential performance. Like all filters however, the best choice for a specific application results from trade-offs that can only be determined if the designer has considerable experience in filter design.

All too often a filter specification is not factored into the design until late in the development cycle. When this happens, unexpected (and unpleasant) surprises can reveal themselves that could otherwise have been avoided had the filter been considered at the beginning of the design. However, in other cases a filter is used to solve a problem in an installed existing system, so its specifications are determined by an existing condition.

In either case, the route to the best results by simply contacting Anatech Electronics, which has more than 20 years of experience solving even the most complex filtering problems. Call Anatech at (973) 772-4242, send an e-mail to sales@anatechelectronics.com, or visit Anatech's Web site at www.anatechelectronics.com.

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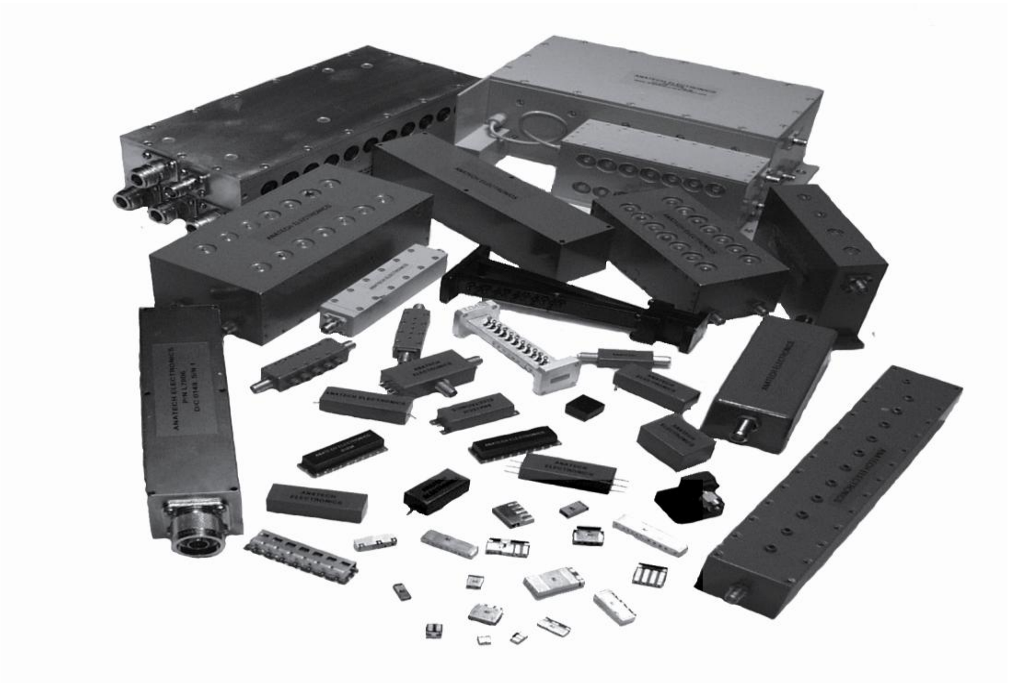
Second in a series



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