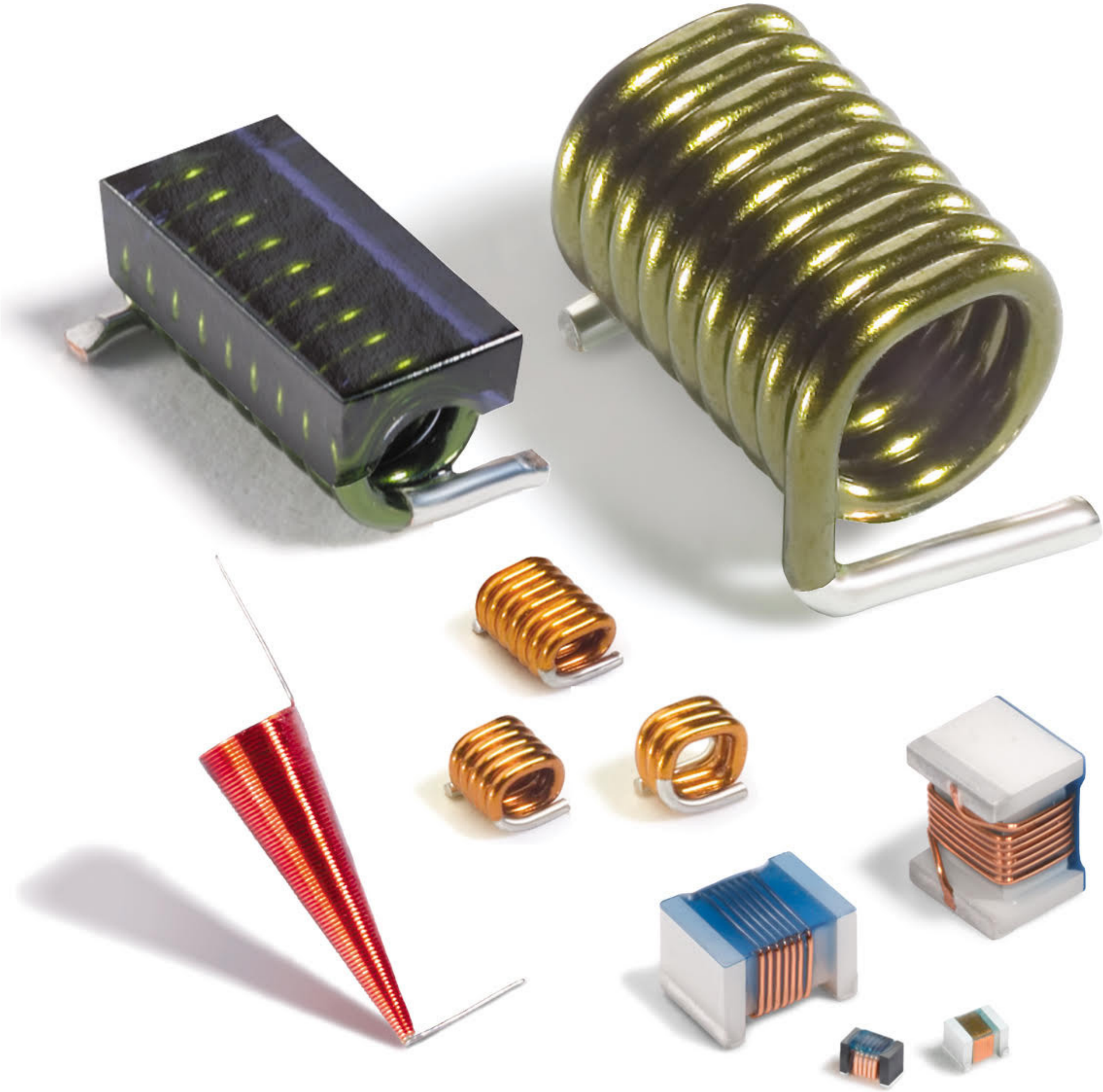


The Fundamentals of RF Inductors

The Fundamentals of RF Inductors

CONTENTS

TECHNICAL ARTICLE

What is an Inductor?

Inductors, Coils and Chokes

An inductor is a passive electrical component that opposes sudden changes in current. Inductors are also known as coils or chokes. The electrical symbol for an inductor is L.

What is an inductor used for?

Inductors slow down current surges or spikes by temporarily storing energy in an electro-magnetic field and then releasing it back into the circuit.

How are inductors attached to circuit boards?

Surface mount (SM) inductors are placed on the top of a printed circuit board (PCB) on pads with solder paste, and then reflow soldered. Through-hole (TH) inductors are mounted to the top of a PCB with the leads fed through via holes in the board, and then wave soldered on the backside.

Air or ceramic core inductor

Ferrite or iron core inductor

In what applications are inductors used?

Inductors are primarily used in electrical power and electronic devices for these major purposes:

1. Choking, blocking, attenuating, or filtering/smoothing high frequency noise in electrical circuits
2. Storing and transferring energy in power converters (dc-dc or ac-dc)
3. Creating tuned oscillators or LC (inductor / capacitor) "tank" circuits
4. Impedance matching

What is a choke?

An inductor placed in series (in line) with a conductor, such as a wire or circuit board trace, blocks or impedes changes in current and functions as a low pass filter. Because inductors restrict or choke changes in current, they are also called "chokes". For example, a broadband (wideband) bias choke in line with the DC bias of an amplifier blocks a wide range of high frequencies while allowing pass-through of the dc current. In this way, a bias choke isolates the DC bias from the RF signal to the amplifier.

The Federal Communications Commission (FCC) has created standards and certifies electronic devices sold or manufactured in the United States for meeting electromagnetic interference (EMI) requirements. Worldwide electromagnetic compatibility (EMC) standards organizations include CISPR, IEC, ISO, and EN. FCC regulations are mandatory and apply to devices such as computer, switched-mode power supplies, television receivers, transmitters, and industrial, scientific, and medical (ISM) devices that emit RF radiation. Inductors are employed in electrical circuits to reduce EMI by attenuating high-frequency noise in order to meet EMC emission and immunity requirements.

How can I improve the filtering performance in a circuit?

Generally, high inductance values are needed to filter out low frequency noise, and vice versa: lower inductance values are used to filter out higher frequency noise. High inductance values effectively slow down the current rise time of transient events, such as closing a switch. The graphs in **Figure 1** demonstrate how a 10 µH inductor "smooths" the rise time more than a 1 µH inductor.

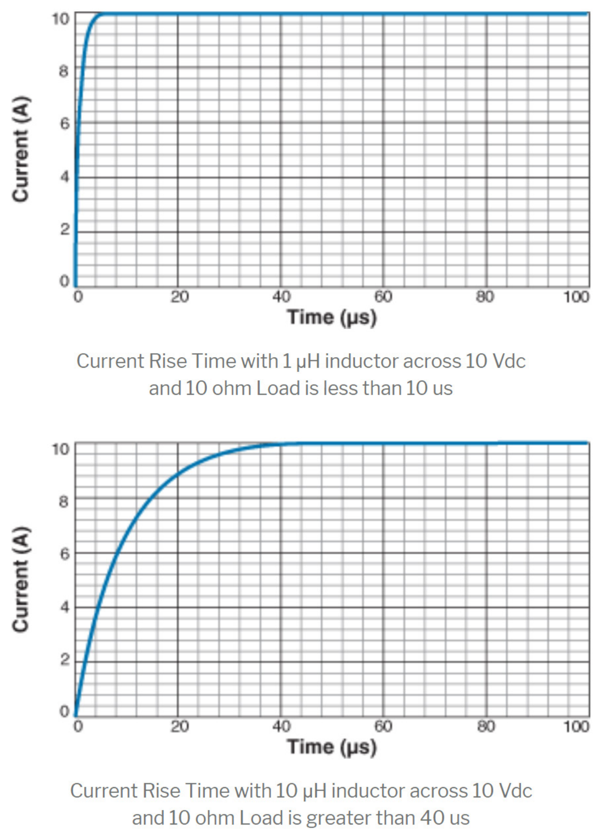


Figure 1

Inductors can also be combined with capacitors to create even more effective LC filters. Several possible LC filter alignments exist, each involving trade-offs in flatness of the attenuation vs frequency behavior and the sharpness of the filter roll-off.

This [Coilcraft reference design document]() provides 3rd order Butterworth and 7th order Elliptic LC filter reference designs that use off-the-shelf inductors to achieve cutoff frequencies in the 0.3 MHz to 3000 MHz range.

Although using high inductance values or creating LC filters improves filtering, doing so requires more board space. Because lower inductance values can be used for filtering higher frequencies, switching to operation at a higher frequency may allow the use of smaller inductors.

How are inductors used in power converters?

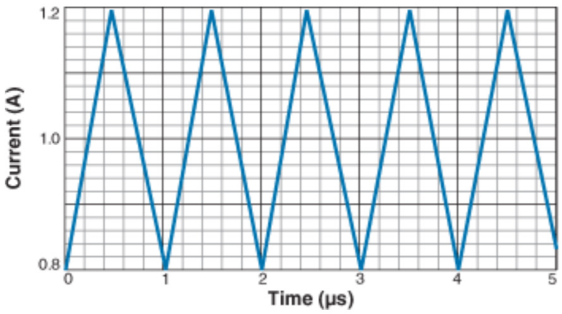
In switched mode power supplies, inductors are used to store energy and transfer the energy to an ouput load or capacitor. Inductors in power converters serve to filter the "ripple" current at the output. High inductance values result in lower ripple current, which improves efficiency and reduces EMI. **See Figure 2.**

How are inductors used in tuned circuits?

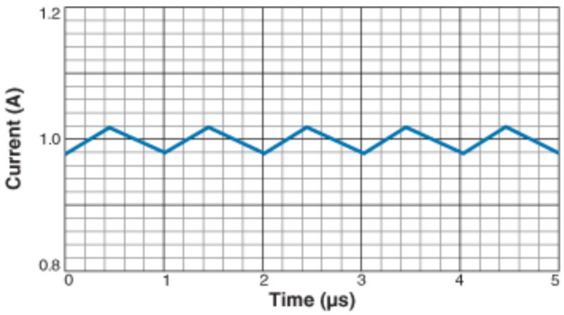
Tuned circuits are used for transmitting or receiving radio or microwave frequency signals. Inductors can be combined with capacitors to create tuned LC circuits such as oscillators.

How does Q factor affect the bandwidth of LC circuits?

Q factor (Q) is a measure of the dissipative characteristic of an inductor. High Q inductors have low dissipation and are used to make finely-tuned, narrow-band circuits. Low Q inductors have higher dissipation that results in wideband performance.



Low ripple current DC-DC converter with 7.5 µH Inductor



Low ripple current DC-DC converter with 75 µH Inductor

Figure 2

What is the Self Resonant Frequency of an inductor?

Real inductors have turn-to-turn winding capacitance that acts as if it were a parallel circuit element. The self-resonant frequency (SRF) of an inductor is the frequency at which the inductive reactance is equal in magnitude to the capacitive reactance of the windings. At the SRF, the inductive and capacitive phase angles cancel and the impedance is effectively purely resistive. Impedance magnitude increases with frequency up to the self-resonant frequency (SRF), where the impedance of an inductor is at its maximum value. At frequencies above the SRF, impedance decreases with increasing frequency.

Impedance (Z) is a characteristic of electrical components that involves a vector combination of resistance and phase. Resistance has a dissipative quality: energy is used and not recovered. Phase is the delay between an applied voltage across a component and the current flowing through it, most often expressed as an angle in degrees (°) or radians. Both the AC resistance and phase of inductors vary with frequency.

How are inductors used for impedance matching?

Impedance matching typically involves matching the impedance of a power source to the impedance of an electrical load. Maximum power is transferred from the source to the load when the impedance of the load is matched to the impedance of the source, improving the efficiency of the circuit. If the load is capacitive compared to the source, inductors can be used to counter the capacitance of the load and thus match the impedance.

What types of inductors does Coilcraft manufacture?

Coilcraft designs and manufactures off-the-shelf inductors in multiple sizes and constructions to meet a variety of filtering, tuning, and impedance matching requirements.

- RF chip inductors Compact size, high frequency, high Q, RF chokes
- Air core inductors / Springs High frequency, very high Q, narrowband bias chokes
- Power inductors High inductance, wideband filtering
- Broadband bias inductors and chokes High inductance, wideband filtering

TECHNICAL ARTICLE

What is a Conical Inductor?

What are broadband conical inductors and how do they function?

Off-the-shelf “flying lead” and surface mount broadband conical inductors, **Figure 1 and Figure 2**, are a special type of broadband RF choke that are used to filter radio frequency (RF) and microwave frequency interference from electronic circuits. At high frequency, the RF choke becomes a high impedance element used to isolate noise or DC from desired signals.

How does a conical inductor function?

An inductor placed in series (in line) with a wire or circuit board trace will impede changes in current, such as AC noise current, by temporarily storing energy in a magnetic field and then releasing it back into the circuit. As current through the inductor changes over time (di/dt) the energy stored in the magnetic field of the inductor creates a voltage ($V = L \times di/dt$) that opposes (impedes) a further change in the current. Regardless of whether the current through the inductor is increasing or decreasing, the magnetic field slows the current’s rate of change. Similar to mechanical energy being damped by a shock absorber, the electrical energy of a noise current “spike” in an RF choke is dispersed over time to reduce its impact. Conical inductors provide high impedance over a very wide range of frequencies.

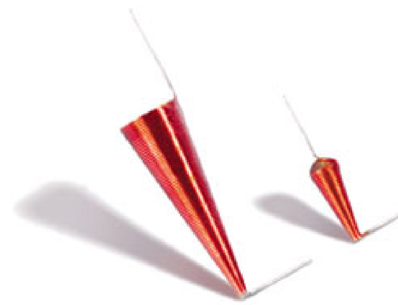


Figure 1
"Flying lead" conical inductor

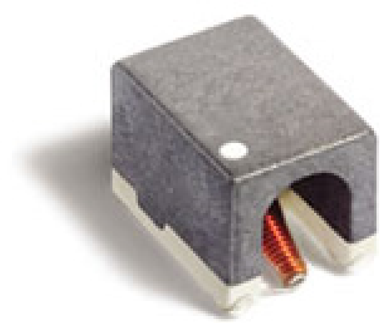


Figure 2
Surface mount broadband conical inductor

Why does the inductor have a conical shape?

The conical shape limits the effects of stray capacitance and effectively creates a series of narrow band inductors, resulting in high impedance over a very wide bandwidth. A single conical inductor can replace a series of many narrow band inductors.

What applications are appropriate for conical inductors?

Blocking "noise" in RF circuits

The Federal Communications Commission (FCC) has created standards and certifies electronic devices sold or manufactured in the United States meet the electromagnetic interference (EMI) requirements. Worldwide electromagnetic compatibility (EMC) standards organizations include CISPR, IEC, ISO, and EN. FCC regulations are mandatory and apply to devices such as computer, switched-mode power supplies, television receivers, transmitters, and industrial, scientific, and medical (ISM) devices that emit RF radiation. RF chokes, such as conical inductors, are employed in electrical circuits to reduce EMI by attenuating high-frequency noise in order to meet EMC emission and immunity requirements.

Isolating RF signals from a DC bias / broadband filtering

A broadband (wideband) conical bias choke placed in line with the DC bias of an amplifier blocks a wide range of high frequencies from reaching the DC source. In this way, the bias choke injects the DC bias while isolating the AC signal from distortion by any stray AC noise. The critical determination when choosing an RF choke for a bias tee is the frequency range that needs to be blocked. Other key parameters are DC resistance, current requirements, size and cost. This application note from Coilcraft explains how to successfully apply a DC bias onto the RF line of a Bias Tee using broadband chokes.

What Types of RF Chokes Does Coilcraft Manufacture?

Coilcraft has designed and manufactured off-the-shelf surface mount (BCR Series) and “flying lead” thru-hole mount (BCL Series) broadband conical inductors for ultra-wideband Bias Tee applications up to 40 GHz:

- The surface mount BCR versions can be automatically pick-and-placed onto a PCB.
- The “flying lead” BCL style allows precise positioning of the mounting angle. The optimal mounting angle is application-specific. Generally, larger angles result in better higher-frequency performance.
- Both the BCR and BCL series have a flat bandwidth with high impedance up to 40 GHz and are ideal for bias tees.

For higher current, lower frequency applications, the 4310LC series of wideband bias chokes are available off-the-shelf. The **4310LC Wideband Bias Chokes** are used in high current Bias Tee applications up to 6 GHz.

TECHNICAL ARTICLE

Inductors as RF Chokes:

Solving RF Isolation Issues with RF Inductors

Introduction

Many consumer products communicate with each other over broadband networks. From television to fiber transmission networks, the bandwidth of data communication is increasing, and the integrity of RF signals has become a major design concern. This paper provides examples of how different inductors can be used for RF isolation in a range of circuits from relatively narrow band applications like portable devices up to broadband networks for data distribution. The different types of inductors used in these applications are identified and discussed.

Why an Inductor?

By its nature, an inductor is a low pass filter ($XL = \omega L$). At high frequency the inductor becomes a high impedance element that can be used for RF isolation. High frequency cannot pass through the inductor, but dc current and very low frequency signals are allowed to pass. Without this type of isolation, antenna efficiency can diminish, signal loss can occur and RF noise can interfere with other parts of the circuit.

The peak of inductor impedance occurs at the natural self resonant frequency.

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

The magnitude of the peak impedance is related to the quality factor (Q-factor) of the inductor. Low loss inductors with high Q (i.e. Coilcraft 0402DC) have a very high peak impedance, while a lossy inductor (i.e. Coilcraft 0402DF), has a lower peak impedance (**See Figure 1**).

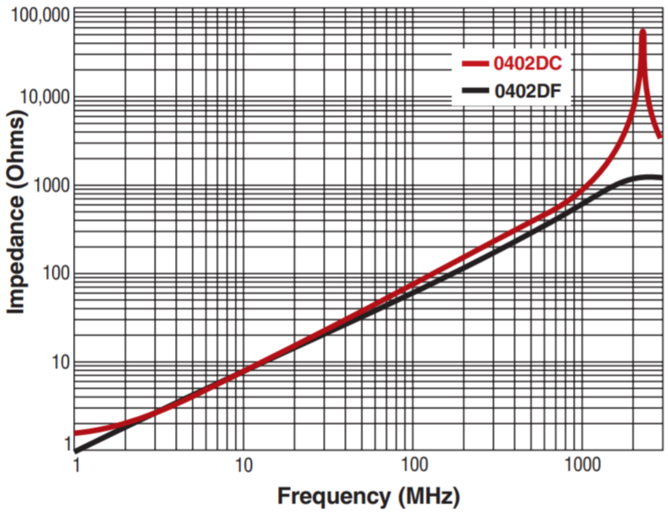


Figure 1. Coilcraft 0402DC & 0402DF 120 nH Impedance

By changing the way a coil is wound or the materials used in the construction, multiple resonances can be aligned to provide high impedance over a wide bandwidth. This is what occurs in Coilcraft Conical Inductors.

Applications

High Q ceramic inductors, like the 0402DC shown in **Figure 1**, or air (core) inductors can be used when a narrow frequency band needs to be blocked, like small-signal, high-frequency communication lines on handsets.

On the other hand, for an audio line inside a handset where it is important to limit low frequency losses, using a ferrite part like the 0402DF is ideal. While the peak impedance is lower, the dc resistance is only a third or less than that of the ceramic core counterpart.

One application driving demand for this type of product is the integration of the antenna into the case of the phone. In the past an external antenna would be used to ensure the antenna remained isolated from the rest of the phone components. Recently the integrated antenna is often placed near a speaker, microphone or keyboard, which needs to be isolated from the antenna frequencies to prevent coupling to the antenna.

In broadband applications, most inductors do not cover enough bandwidth. By putting three or four inductors in series, a broader band can be covered, but dc loss increases. Since size is not as critical in many broadband applications, there is often room to keep the broadband portion of the circuit isolated with ground planes, shields, etc. There are also instances where DC current is injected onto RF lines. For these applications, RF inductors provide the isolation function, blocking the RF signal from the DC bias source.

For an example requiring RF isolation, a television antenna may need up to 500 mA injected onto the RF line, while blocking frequencies from 20 MHz to 2 GHz. Consider the isolation that can be achieved with a Coilcraft 4310LC wideband inductor.

As shown, the impedance of the 4310LC remains greater than 100 Ohms from 20 MHz to above 3 GHz. The insertion loss measurement shown is for the coil connected in shunt

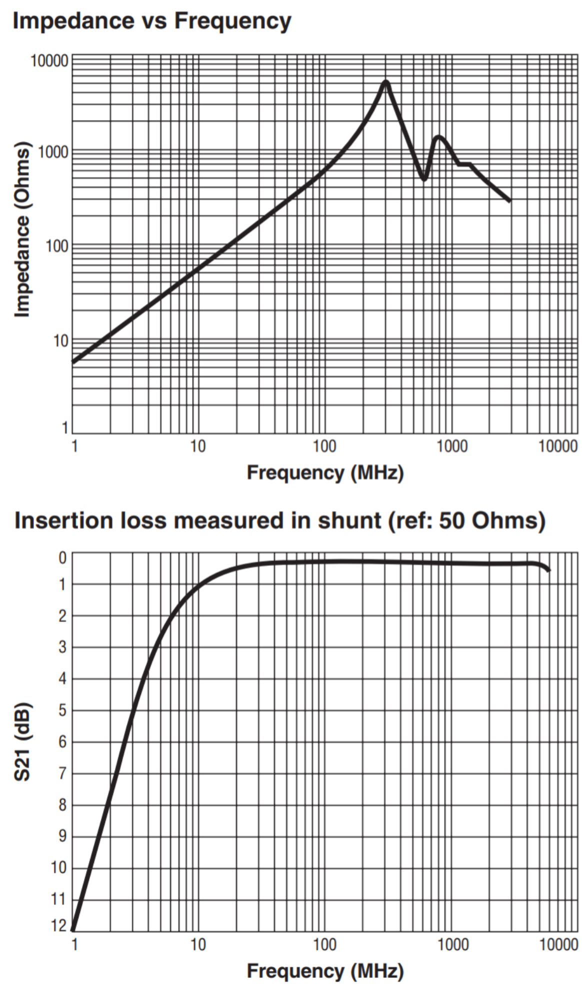


Figure 2. 4310LC Characteristics

from a transmission line to ground. This curve illustrates how frequencies below 10 MHz are lost to the ground plane (pass through the component) and that frequencies between 10 MHz and 6 GHz are rejected by the coil and pass along the transmission line.

Another application requiring RF isolation is the biasing of a pin diode for use in fiber networks. Here, a 200 mA dc injection is needed on an RF line that carries frequencies from 100 MHz to 30 GHz. To meet this requirement, any Coilcraft BCR Conical Inductor can be used.

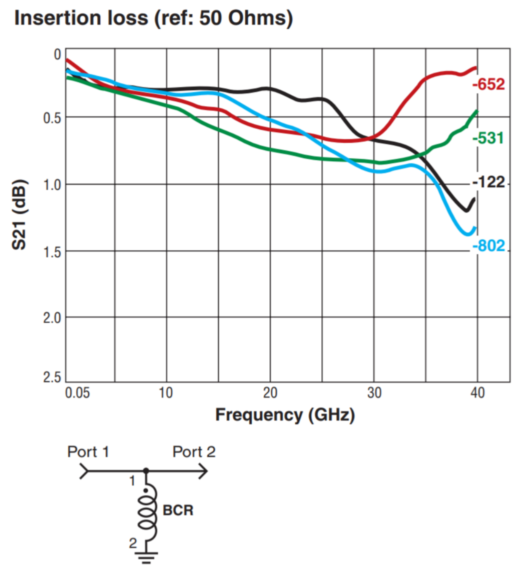


Figure 3. Broadband Conical Inductors

Figure 3 shows that the insertion loss using BCR inductors from 50 MHz to 35 GHz is less than 1.0 dB when the component is measured in shunt from a transmission line to ground.

The critical determination when choosing RF chokes is the frequency range that needs to be blocked. Other key parameters are dc resistance, current requirements, size and cost. From that, online tools like the Highest Impedance Finder or RF Inductor Comparison tool from Coilcraft can help identify the right RF choke for narrow band applications. Tools are still in development for larger bandwidths.

Summary

It is critical for designers to maintain RF integrity without sacrificing overall circuit size or cost. In handset applications, the integration of the antenna to the case of the phone increases the demand for RF isolation inductors on transmission lines. The need to provide bias on RF lines requires “bias chokes,” which perform the same function as an RF isolation choke.

For any of these applications, an inductor is the key to success. Start with identifying the frequency range of the application, and then determine what the other parameters need to be. If one coil is not able to provide the solution, a network of inductors may be required. That will be the subject of another application note.

TECHNICAL ARTICLE

Wirewound Ferrite Beads: Outperforming Traditional Chip Ferrite Beads

What is a Ferrite Bead?

Ferrite beads, or ferrite chokes, are used as low pass filters to eliminate high frequency noise while allowing low frequency signals or DC current to pass through a circuit. The noise may come from any number of sources including high-frequency switching noise from a power-supply circuit or RF noise in an RF signal-isolation circuit that must be minimized to ensure both signal integrity and antenna efficiency.

Ferrite beads, whether chip or wirewound, are used to filter electromagnetic interference (EMI). You may be surprised to discover that wirewound ferrite beads provide a high magnitude of attenuation over a wide frequency range, whereas traditional thick-film chip ferrite beads have limited options for both attenuation and frequency range.

Wirewound Versus Traditional Chip

In addition to offering better attenuation and frequency performance than their chip counterparts, wirewound ferrite beads also provide lower DC resistance (DCR) and higher current ratings without core saturation, resulting in the highest possible performance in the smallest size.

Coilcraft wirewound ferrite beads come in standard package sizes from 0201 (0603) to 1812 (4532), all providing extremely low DCR while maintaining high filtering impedance over the broadband frequency range. These features enhance the performance of the choke circuit while potentially reducing board space by replacing a larger chip ferrite bead with an equivalent, or higher-performing wirewound ferrite bead.

Figure 1 and **Figure 2** demonstrate how Coilcraft wirewound ferrite beads provide superior broadband performance compared to both low- and high-DCR chip ferrite beads. **Figure 1** compares the Coilcraft 0402DF-121 wirewound ferrite bead to the lowest-DCR 0402-sized chip ferrite bead. The 0402DF offers higher impedance across the frequency range, providing a greater measure of filtering from 100 MHz and above. Compared to typical high-DCR chip ferrite beads, the Coilcraft wirewound ferrite bead maintains the same high frequency attenuation while providing higher current ratings and 40 percent better DCR.

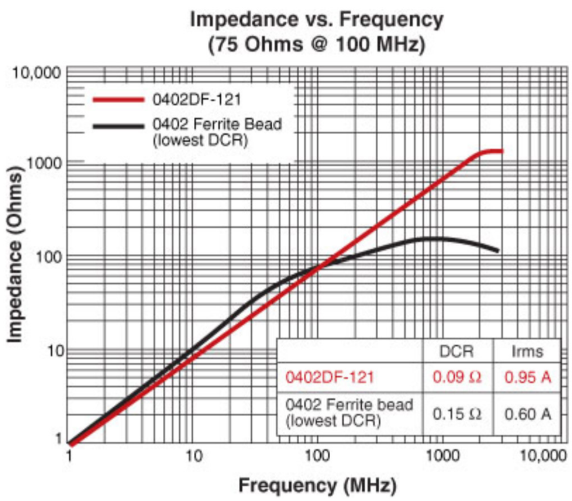


Figure 1

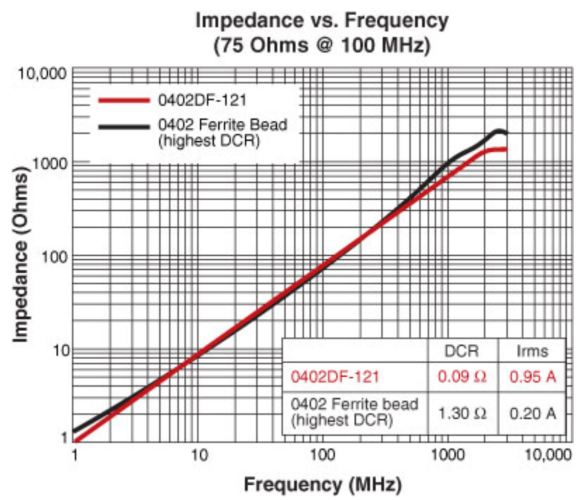


Figure 2

What Types of Ferrite Beads does Coilcraft Manufacture?

- Ferrite construction for higher current handling
- Higher inductance values than other inductors
- Low Losses for low frequency filter applications
- RoHS Compliant, halogen free, 260°C compatible
- Samples are available in Coilcraft Designer's Kits
- Click on a table row below for detailed information about each ferrite bead series

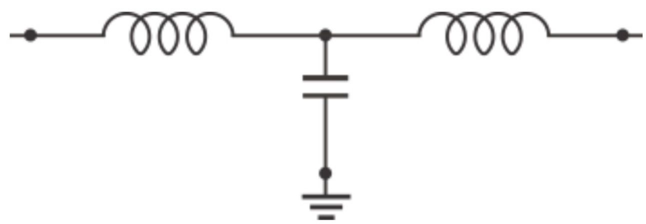
Series	Size	Max Height	Impedance Range (Ohms)
0201AF	0201 (0603)	0.46 mm	19.89 - 118.6 @ 100 MHz 159.9 - 1,089 @ 900 MHz
026011F	0201 (0603)	0.55 mm	16.60 - 320.5 @ 100 MHz 133.7 - 3,435 @ 900 MHz
0402DF	0402 (1005)	0.66 mm	11.98 - 5,270 @ 100 MHz 93.76 - 7,628 @ 900 MHz
0402AF	0402 (1005)	0.66 mm	11.23 - 331.3 @ 100 MHz 82.23 - 3,593 @ 900 MHz
0603AF	0603 (1608)	0.91 mm	8.83 - 3,807.7 @ 100 MHz 48.14 - 7,687 @ 900 MHz
0603LS	0603 (1608)	1.12 mm	28.21 - 5,760 @ 100 MHz 27.89 - 3,815 @ 900 MHz
0805AF	0805 (2012)	1.52 mm	65.61 - 7,069 @ 100 MHz 26.14 - 2,451 @ 900 MHz
0805LS	0805 (2012)	1.60 mm	48.54 - 7,765 @ 100 MHz 28.82 - 2,265 @ 900 MHz
1008AF	1008 (2520)	1.91 mm	6.09 - 66.51 @ 1 MHz 59.29 - 721.8 @ 10 MHz
1008LS	1008 (2520)	2.03 mm	6.56 - 682.9 @ 1 MHz 63.95 - 7,511 @ 10 MHz
1812LS	1812 (4532)	3.43 mm	77.85 - 7,167 @ 1 MHz 770.7 - 191,219 @ 10 MHz

TECHNICAL ARTICLE

What is an LC Filter?

What is an LC Filter?

An LC filter combines inductors (L) and capacitors (C) to form low-pass, high-pass, multiplexer, band-pass, or band-reject filtering in radio frequency (RF) and many other applications. Passive electronic LC filters block, or reduce, noise (EMI) from circuits and systems, and separate, or condition, desired signals.



Example:
Low-Pass LC Filter Schematic

While ideal filters would pass desired signal frequencies with no insertion loss or distortion, and completely block all signals in the stop-band, real filters have DC and AC resistances that contribute to insertion loss, requiring careful component selection. Selecting the exact values of the parts for a particular application requires high quality components as well as complete specifications and performance models. The simplest to design and implement are the low-pass and high-pass types.

Coilcraft high-Q, tight-tolerance, surface-mount RF chip inductors and air-core inductors help you achieve top performance in all of these LC filter categories.

How do you design LC filters?

The alignment (type) of the filter determines the flatness of frequency behavior and the sharpness of the cut-off. There are many types of alignments, including those with the most commonly desired characteristics such as Butterworth, Bessel, Chebyshev, and elliptic.

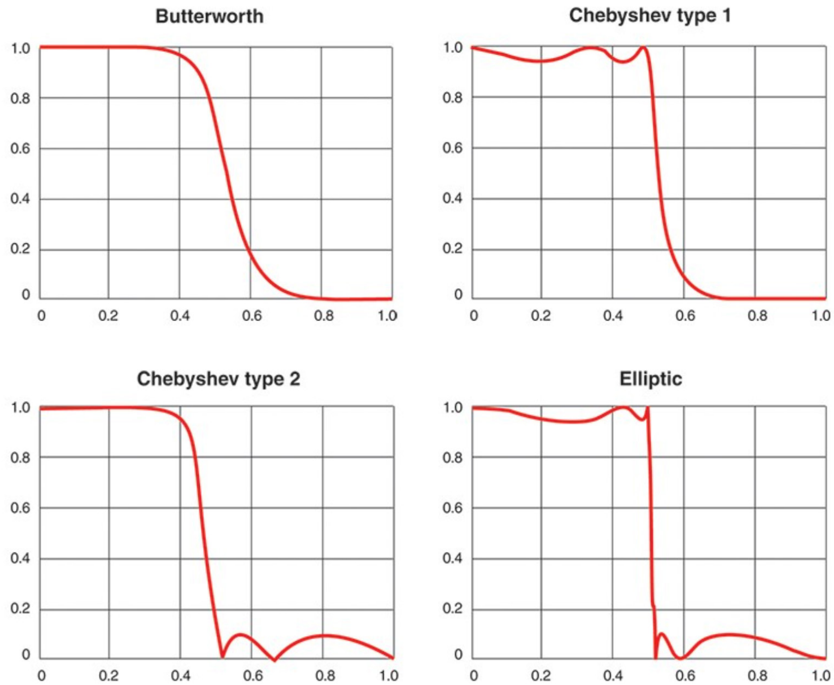
The simplest LC filter consists of one inductor and one capacitor. Higher-order filter alignments use more components to give a sharper, more defined roll-off in attenuation of unwanted noise. For example, Elliptic (Cauer) filters give the sharpest roll-off and are the least sensitive to component variation. As a trade-off, there is more pass-band ripple and stop-band ripple in Elliptic LC filters.

More details on the various filter alignments are shown in Appendix A of this application note.

Modern circuit synthesis and analysis programs can quickly perform the otherwise tedious and time-consuming calculations for designing LC filters. Filter synthesis programs generate the required inductance

(L) and capacitance (C) values. Analysis programs simulate the results after the user enters the appropriate values. Once the initial ideal values have been calculated, practical solutions are created using off-the-shelf components.

Ideally, one could simply define the band of frequencies to be passed and those to be blocked, and a program would generate standard component values resulting in the actual on-board performance. Realistically, a passive LC filter design starts with calculations and then a very iterative trial-and-error process is needed to match the actual performance to the required performance. To speed design time and improve accuracy of design calculations, models of real-world inductors are available.



Appendix A: Passive LC Filter Design and Analysis Filter Alignments and Properties

For many designs, accurate inductance models based on actual component measurements are necessary, but ideal capacitors can be used for the simulation. Simulations of filters near the Gigahertz range may require non-ideal capacitor models as well.

Free programs for generating basic LC filter designs are available. Coilcraft's LC Low Pass Filter Designer software by Nuhertz uses real measurement-based s-parameter models of the inductors for improved filter simulations.

How do you design low-pass filters with Coilcraft LC filter Designer Software (Nuhertz Technologies FilterSolutions®)?

- Design low pass elliptic filters
- Select 3, 5, or 7 poles
- Uses actual Coilcraft inductor data
- S-parameter analysis
- 50 Ohms characteristic impedance
- Request Coilcraft free inductor samples directly from the software

While these simulations may be acceptable for many designs, it should be noted they do not include PCB parasitics, which have an effect on the actual cut-off frequency of the components mounted on any PCB.

Ideal component values generated by simulation programs can be used as a good starting point for filter designs, however, if all component and PCB parasitics are ignored the results may not be very close to real-world performance. This can result in a time-consuming process of tuning and adjusting, particularly for high-cutoff-frequency filters.

For high-performance design examples, including component parasitic effects and parasitic interactions of the components on a ceramic circuit board, try the following Coilcraft LC filter reference designs.

Designing low-pass and high-pass filters with Coilcraft LC Filter Reference Designs

These reference designs include 3rd-order Butterworth low-pass and high-pass, as well as 7th order-elliptic filters, and demonstrate the high performance that can be achieved using Coilcraft inductors and standard capacitors.

The 3rd-order low-pass filters reference designs provide a wide range of cut-off frequencies from 3 MHz to 3 GHz. For 3-pole high-pass filters, 15 MHz to 900 MHz cutoff frequencies are achievable.

Compared to a Butterworth filter, elliptic filters have equalized ripple in both the pass-band and the stop-band. However, for the same order level, elliptic has the fastest transition between passband and the stop-band. Coilcraft offers 7th-order elliptic reference designs with less than 0.3 dB insertion loss at 50-Ohm characteristic impedance. These include our off-the-shelf 1812LS Series ferrite chip inductors with tolerances is as low as 5%. These 7th-order-elliptic low-pass filters offer sharp roll-off rate at 80 dB/dec and a wide range of cutoff frequencies from 0.3 MHz to 500 MHz.

Coilcraft LC filter reference designs can save you time, effort and cost, allowing you to better select the right components, evaluate real performance compared to calculations, and achieve your desired results.

In what applications are LC filters used?

LC low-pass and LC high-pass filters are used in many general filtering applications to block undesired frequencies and meet EMC / EMI requirements. They are also used in the following specific applications:

Reference Design for 9th-order elliptical filter for MoCA® applications

This reference design for a 9th-order elliptical filter for MoCA® applications shows a real-world example of a high order sharp cut-off elliptical filter using Coilcraft RF air core inductors.

The Coilcraft Micro Spring™ air core inductors used in this design provide the high performance needed for MoCA filters. The combination of inductance values and performance make these off-the-shelf inductors ideal for the implementation of these filters in set top boxes and cable modems. With tolerances as tight as 1%, there is no longer a need to tune these filters.

Class-D Amplifiers

In order to achieve EMC requirements in Class-D amplifiers above 10 W of output power, an LC filter is used on the output of the amplifier to smooth out the current ripple due to switching . Dual inductors combine two Class-D inductors in a single package to achieve the smallest possible footprint. High-temperature, AEC-Q200 Grade 1 Class-D dual inductors are appropriate for the harsh conditions of automotive applications.

These Class-D inductors from Coilcraft are designed specifically for applications up to 100 W.

The Fundamentals of RF Inductors

Coilcraft