Brass Tacks

An in-depth look at a radio-related topic

Filters

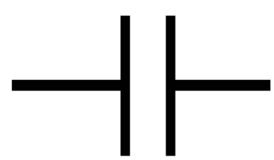
Last summer my wife and I were walking on the sand at Newport Beach, California, a few dozen miles southeast of Los Angeles. It was a terrific, sunny, summer day, so I was wearing my sunglasses, even wading in the water with them. But in a moment of weakness, when I was distracted by my beautiful wife, an unsuspecting wave came up and knocked the shades off my face, and I lost my eyewear to the ocean forever. Not a problem; we strolled to the nearest bungalow and purchased a $3 replacement for $45, and we were back to beach-combing in no time.

Once back outside, I noticed right away that everything around me had developed a deep shade of amber. I began to wonder how it was that a couple of pieces of plastic could make everything appear yellow. Then I realized that the yellow lenses on my shades didn't add anything to the light, but instead subtracted from the light. Objects within sight emitted or reflected white and other light waves into my sunglasses, but my sunglasses *filtered out* all the light, except that with the color yellow. Fascinating.

We ham radio operators might come to discover that our radios contain one or more electronic circuits or components that do something similar, but with electrical current (which I'll call a *signal*) rather than light waves. And because these circuits ***attenuate*** (reduce the amount of) certain signals passing through them, we refer to them by ***filters*** as well. But how do they work, and why should you care?

Truthfully, most of the electronic filtering you'll ever need to have done, will likely already be built into your radio or other equipment. Sure, there are those who build their own equipment, and so filter design becomes important them. Still, others just want to know. Filtering is a non-trivial subject in electrical engineering education, meaning it can be relatively simple, to overwhelmingly complex. In the interest of brevity, the scope of this article will be confined to passive, simple filtering, a small sliver of the pie, but the foundation presented here will help you grasp the basics.

The building blocks



capacitor symbol

The schematic symbol for a capacitor is drawn appropriately, as an open circuit. Without going through a complete explanation of capacitor theory, it indicates that no current can truly flow through one unless the direction of current flow constantly changes direction, which we call AC (alternating current.) When this current changes direction slowly, almost no current appears to flow through the capacitor, but the faster the current changes direction (increases in frequency), the more current appears to flow through the capacitor.

So, it seems that a capacitor can attenuate the amount of electrical current going through it, or allow a lot to seemingly go through it, simply because of the current's frequency. In this way, a

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simple capacitor is a filter of sorts, all by itself, by allowing high frequency signals to pass through it, while attenuating low frequency signals. In nearly the reverse behavior, an inductor is pretty much a short circuit at low frequencies, but will oppose changes in current at higher frequencies. Because of this, a simple inductor by itself is also a filter, allowing low frequency signals to pass through it, while attenuating high frequency signals. But, how high is *high*, and how low is *low*?

Just like sunglasses, filters don't stop *all* undesired signals from passing through, so engineers agree upon a –3 dB, or *half-power* design limitation. This means a successful filter permits less than 50% of the signal to pass through, at the design frequency. This frequency is

$$P_C/P_I = ½ = Z_I/Z_C \Rightarrow f_C = 1/2\pi RC$$

known as the ***cutoff frequency*** f_C (also called the *corner frequency*) for a series capacitor filter, resulting in signals of frequencies greater than f_C being *able* to pass through the filter, while those of lower frequencies are effectively attenuated. For a series circuit using an inductor, a similar calculation results in

$$f_L = R/2\pi L$$

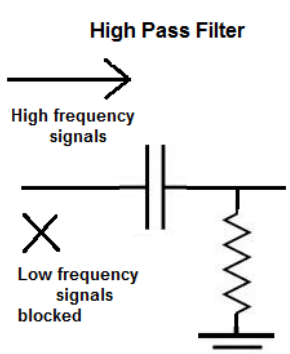
inductor symbol

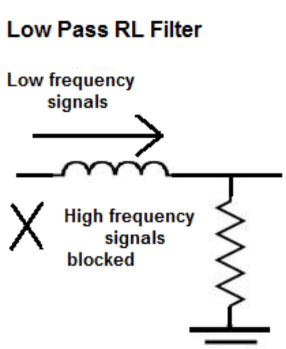
Which in turn is the cutoff frequency f_L for the series inductor filter, resulting in signals of frequencies lower than f_L being *able* to pass through the filter, while those of higher frequencies are effectively attenuated.

High-pass, low-pass, shunt filters

In the crude capacitor example above, we call the component a ***high-pass filter*** because it essentially permits the current of the higher-frequency signals to pass through it, and attenuates lower-frequency signals (and so also called a ***low-cut filter*** because it cuts off the lower frequencies). Similarly in the inductor example above, we call the component a ***low-pass filter*** because it essentially permits the current of the lower-frequency signals to pass through it, and attenuates higher-frequency signals (and so also called a ***high-cut filter***).

Now, rather than rely on the resistance inherent in a component or its leads (wires), place a resistor of a known value to set the cutoff frequency of the high-pass or low-pass filter. Using both the resistance (R) and capacitance (C) values, you can design a simple RC circuit to meet your filtering needs. Use the same approach to design a simple RL circuit filter.





If you swap the resistor and capacitor with each other, then the higher frequency signals actually get "shorted to ground" instead of being passed to the circuit output. This is known as a ***shunt filter***. Connecting the two leads between the signal and ground will effectively *ground* the signals whose frequencies are greater than the cutoff frequency, and therefore is another way to create a low-pass filter, but with a capacitor. Of course, the high-

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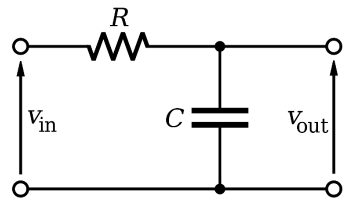
pass shunt can be created by swapping the inductor and resistor in the second circuit example.



capacitor shunt filter

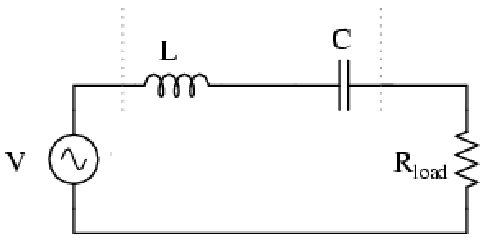
Let's say you have a smoke alarm or detector that keeps chirping every time you key up your 2-meter transceiver. The wires inside the device might be picking up your 2-meter transmissions like a small antenna. It's possible to create a small shunt filter to redirect the VHF signals to ground, while permitting all other lower-frequency (DC, in this case) signals to pass into the device. Let's assume that we need no more resistance than is provided by the wires in your series shunt filter, maybe 0.1 ohms. The idea is to filter out all signals of frequencies greater than 144 MHz, which means

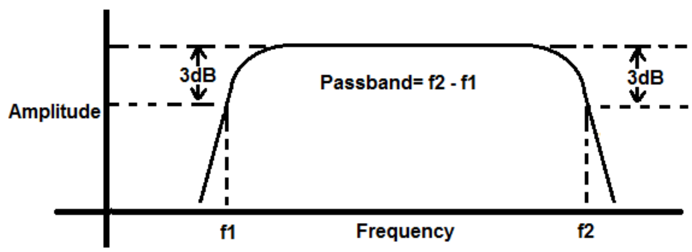
$$C = 1/2\pi Rf_c = 1/[2\pi(0.1 \text{ ohms})(144 \text{ MHz})] = 0.011\ \mu F$$

Install a 0.01 μF capacitor between a receiving wire (often, the DC power plus side) and the DC power minus side. Voila...no more chirping false alarms!

Band-pass and band-reject filters

Now that you're armed with the foundational knowledge you need to create the building blocks of passive filters, let's make something a little more complex with that information. Apply what we know, to create what's known as a ***band-pass filter***. Simply, allow to pass the signals of a band of frequencies you want, and attenuate the signals you don't want passing through. Consider the following circuit and its ***frequency response*** graph:





This series circuit contains both an inductor and a capacitor, which share the same current with the load resistor. In this case, high-frequency signals are attenuated by the inductor and low-frequency signals are attenuated by the capacitor. So, the only electrical signals effectively reaching the load resistor are those in between the low (f_1) and high (f_2) frequencies.

The effect of a band-pass filter is the result of combining a low-pass filter and a high-pass filter. The band of frequencies that the circuit allows to pass is known as the ***passband***, and the difference between the two cutoff frequencies ($f_2 - f_1$) is known as the ***bandwidth*** of the circuit. And if the bandwidth of such a filter is sufficiently narrow, we often refer to it as a ***peak filter***.

It's often useful to allow for a *variable* passband, so that only the desired signals of particular frequencies can be heard, for example, while signals from nearby frequencies and noise sources can be *tuned out*, a function known as ***passband tuning***.

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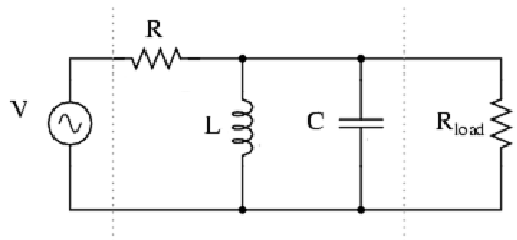
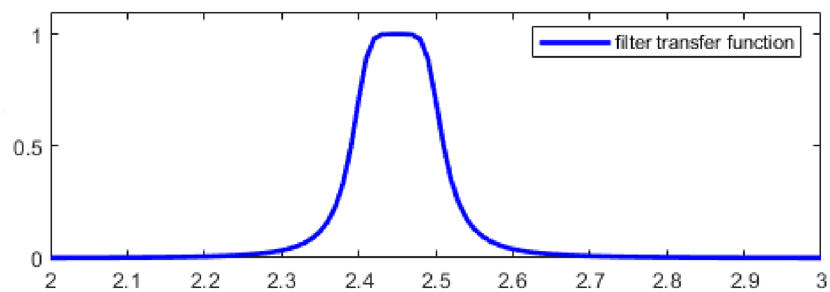
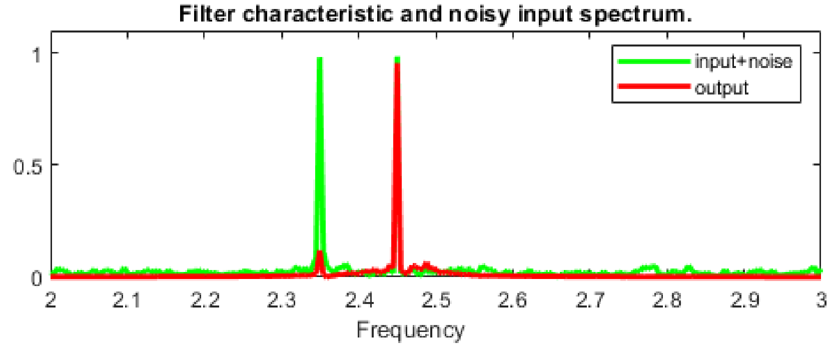
The parallel LC band-pass circuit, such as the following, has a similar frequency response graph to that for the series circuit:



In this case, the unwanted signals are shunted to ground, the low frequencies by the inductor and the high frequencies by the capacitor, instead of being prevented from passing through. This version of the band-pass filter is known as a ***tuned circuit***, and has formed the basis for tuning radio receivers for many years. Using a tuned circuit allows your receiver to focus on a particular subset of frequencies for amplification and further processing, presenting you with audio modulated (encoded and carried) only within a small frequency range.

The following two graphs demonstrate a practical application for passband tuning, in which a strong noise source is present near the desired frequency of operation:





By adjusting the passband such that the frequency of the noise source is attenuated in one of the stopbands, it might be possible to filter much of the noise out of processing range, leaving only the desired signal.

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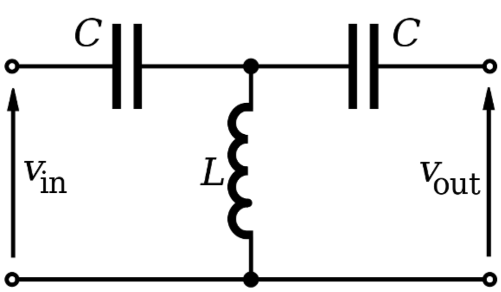
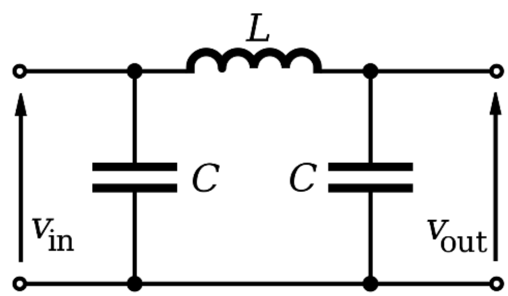
It's often useful to create a filter that performs the opposite function; that is, allows to pass all signals of frequencies except those within a particular range. This is known as a ***band-reject filter***, with the region of frequencies being rejected known as the ***stopband***. And if the stopband of such a filter is sufficiently narrow, we often refer to it as a ***notch filter***.

Other common passive filter types include those we often use for impedance-matching, such as the T-filter (also called T-network) and the Pi-filter (also called Pi-network), so-named because the shapes of the circuit schematics for them resemble the letters "T" and "π", respectively:

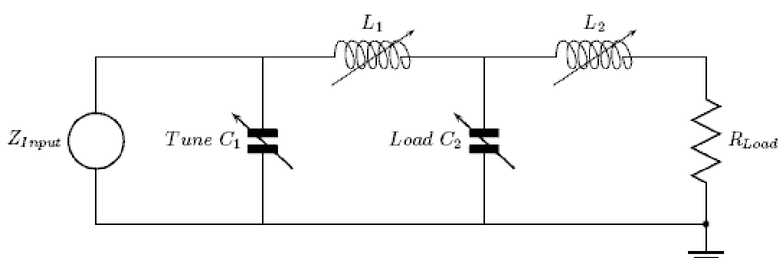


high-pass T-filter



low-pass Pi-filter

You can add more components to existing filters, to further shape the frequency response to your needs. The following schematic shows a general diagram of a tuner circuit, employing a Pi-L network, the output inductor L_2 added to the low-pass Pi-filter to help suppress harmonics:



The arrows through the capacitors and inductors indicate that they're variable, to allow adjustment of the filter impedance for matching at desired frequencies.

Finally, electronic filters can be designed using many components that we haven't explored, such as crystals, op amps (operational amplifiers), and discrete tubes and transistors. Also, many special-purpose and special-property filters have been designed, such as Chebyshev, Butterworth, crystal-ladder (often, crystal-lattice), roofing, elliptic, Jones, antennas (yes, antennas are filters too!), and many more. Designers of electronic equipment such as analyzers, oscilloscopes, and receivers, have used many of these complex filters to accomplish the magic their instruments are known for.

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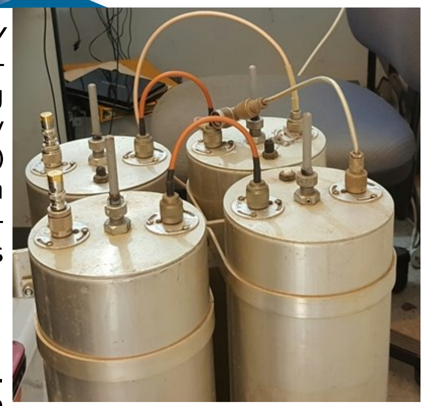
One such special-purpose and special-property filter is a ***cavity filter***, designed primarily to keep the *repeater duplexer* transmit and receive signals on the same antenna from interfering with each other, and to prevent interference from other, nearby repeaters. It's a band-pass filter (in some cases, a notch filter) with an extremely small bandwidth, to reject signals close in frequency to that of the repeater signals. This narrow bandwidth is represented by a quantity called ***circuit Q***, which is calculated by

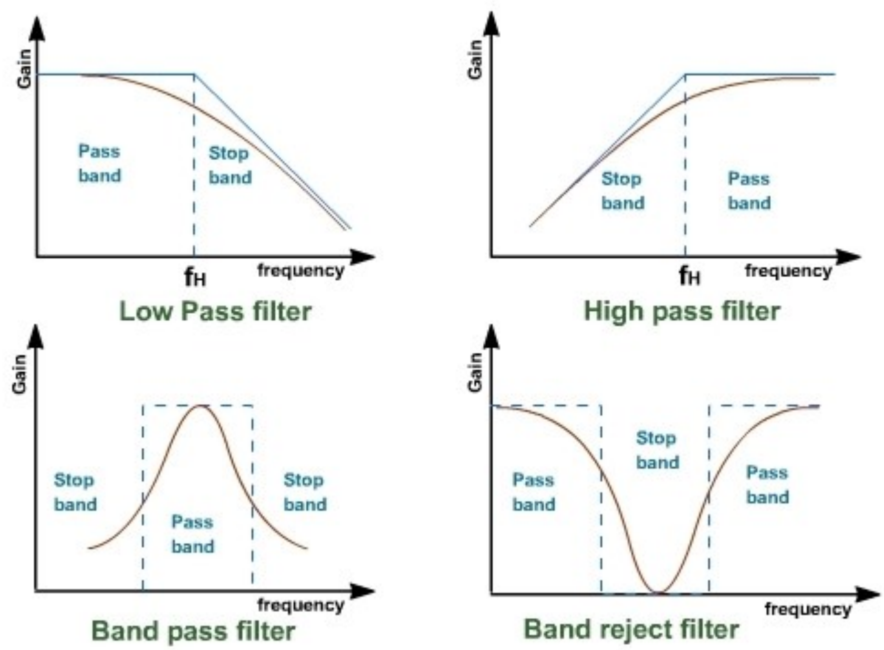
$$Q = f_c / (f_2 - f_1)$$

in which f_c is the center frequency, or the frequency of focus. As the difference between the cutoff frequencies decrease (bandwidth decreases), the Q increases.



repeater cavity filters

The following summarizes the different frequency responses of the filters we've discussed:



As mentioned previously, the information I've presented here is very simplistic, and is missing quite a lot of depth. For example, I've not mentioned anything about the introduction of phase shifts or nonlinearities as a result of filtering. My hope is to help you understand what a passive electronic filter is, without clouding the topic by complex side-tracks. But I believe I've provided some basics on which you can build your knowledge of filters, to at least begin removing some of the mystery behind these fundamental tools.

Noji Ratzlaff, KNØJI (kn0ji@arrl.net)