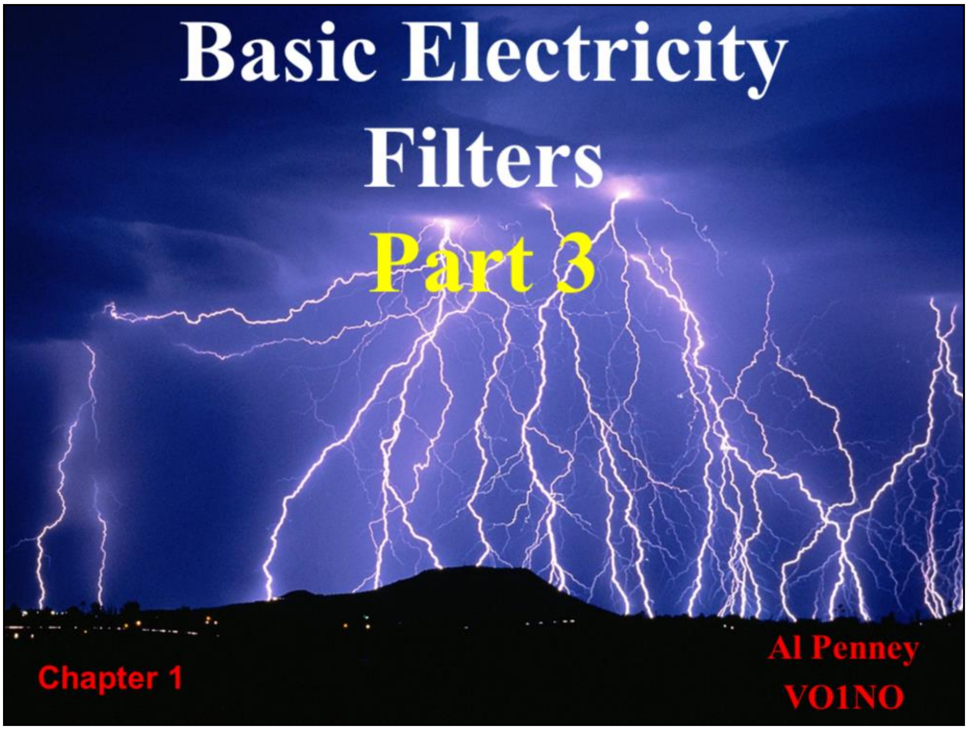
Basic Electricity
Filters
Part 3
Chapter 1
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Filters

- By the proper selection of capacitors and inductors, it is possible to design **Filters** that can **pass desired frequencies**, and **reject unwanted frequencies.**
- **General groupings** of filters include:
  - **Low Pass**
  - **High Pass**
  - **Band Pass**
  - Band Stop (Notch)

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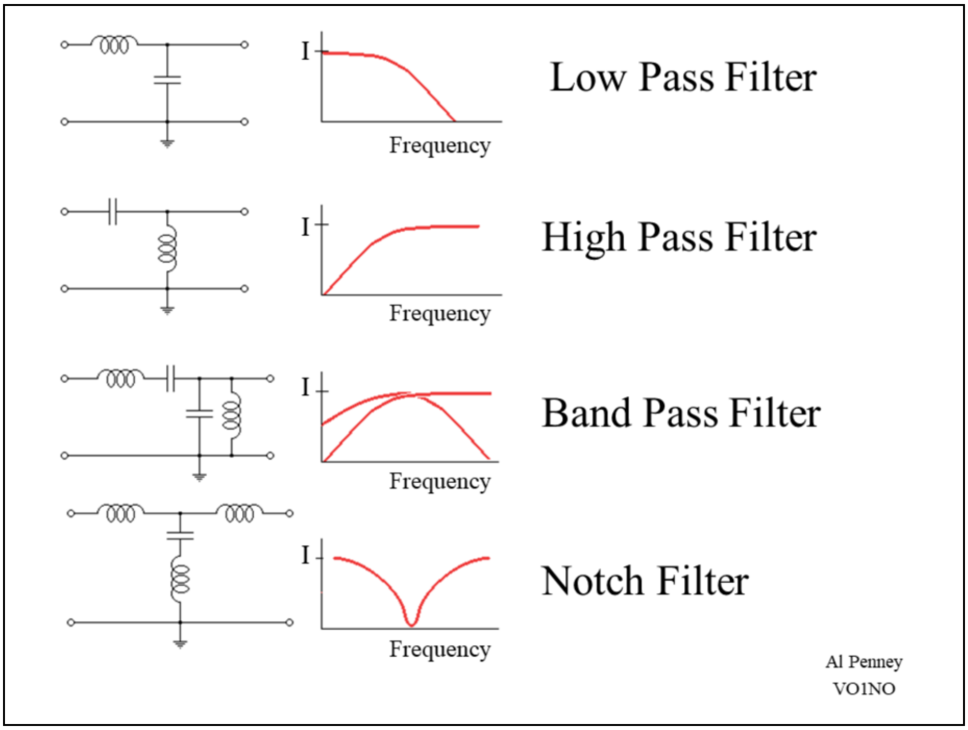
I
Frequency
Low Pass Filter
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High Pass Filter
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Band Pass Filter
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Notch Filter
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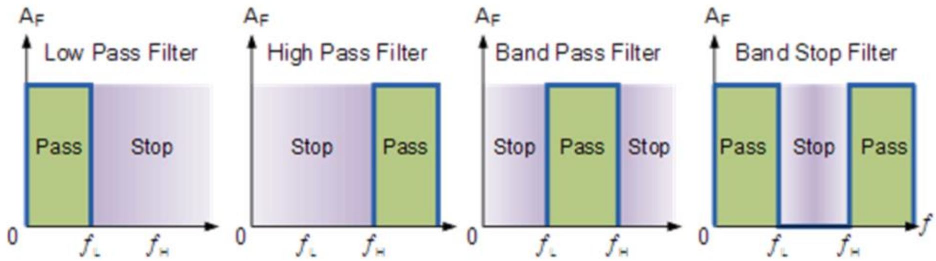

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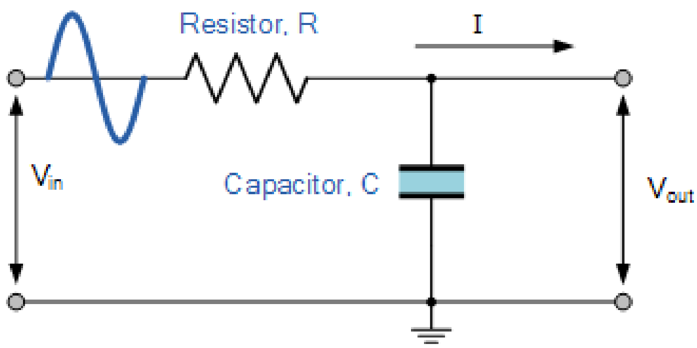
Low Pass Filter Circuit



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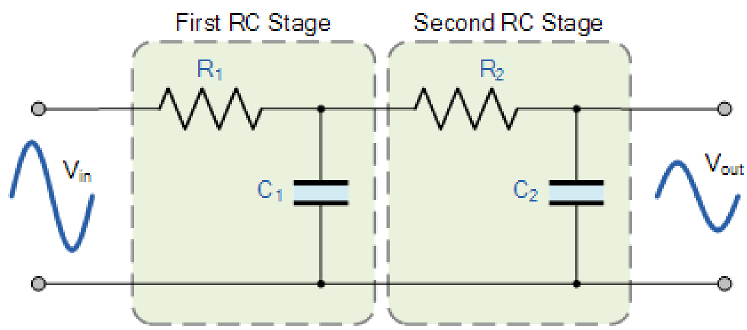
As mentioned previously in the Capacitive Reactance tutorial, the reactance of a capacitor varies inversely with frequency, while the value of the resistor remains constant as the frequency changes. At low frequencies the capacitive reactance, (X_C) of the capacitor will be very large compared to the resistive value of the resistor, R.

This means that the voltage potential, V_C across the capacitor will be much larger than the voltage drop, V_R developed across the resistor. At high frequencies the reverse is true with V_C being small and V_R being large due to the change in the capacitive reactance value.

Second-order Low Pass Filter



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The above circuit uses two passive first-order low pass filters connected or "cascaded" together to form a second-order or two-pole filter network. Therefore we can see that a first-order low pass filter can be converted into a second-order type by simply adding an additional RC network to it and the more RC stages we add the higher becomes the order of the filter.

If a number (n) of such RC stages are cascaded together, the resulting RC filter circuit would be known as an "n^{th}-order" filter with a roll-off slope of "n x -20dB/decade".

Low Pass Filter Summary

So to summarize, the **Low Pass Filter** has a constant output voltage from D.C. (0Hz), up to a specified Cut-off frequency, (f_C) point. This cut-off frequency point is 0.707 or **-3dB**(dB = –20log*$V_{OUT/IN}$) of the voltage gain allowed to pass.

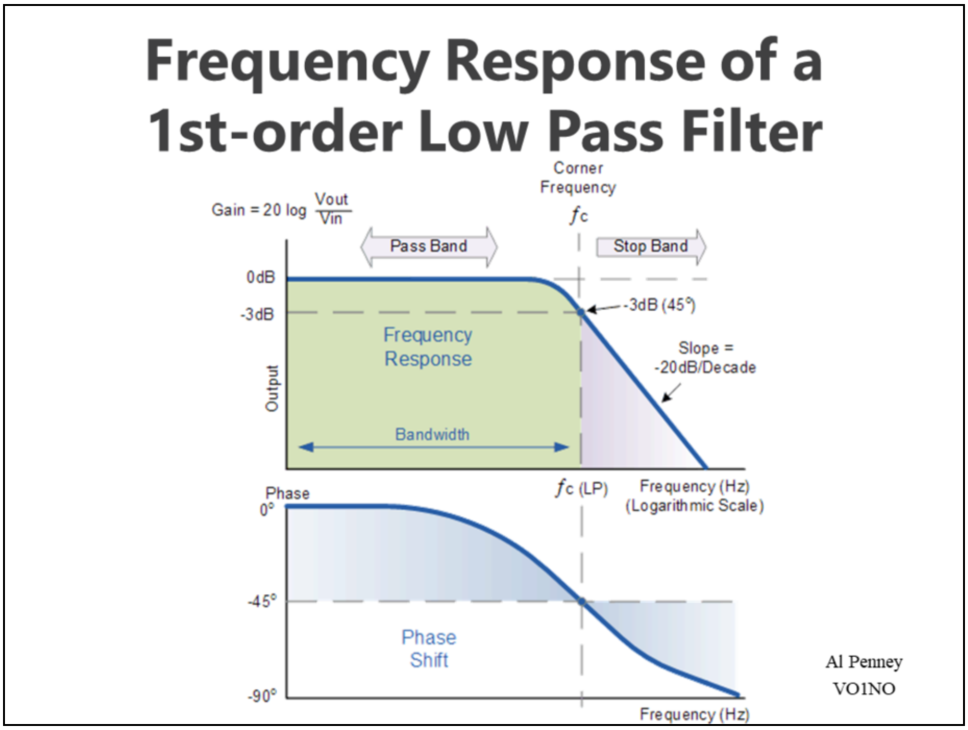
The frequency range "below" this cut-off point f_C is generally known as the **Pass Band** as the input signal is allowed to pass through the filter. The frequency range "above" this cut-off point is generally known as the **Stop Band** as the input signal is blocked or stopped from passing through.

A simple 1st order low pass filter can be made using a single resistor in series with a single non-polarized capacitor (or any single reactive component) across an input signal Vin, whilst the output signal Vout is taken from across the capacitor.

The cut-off frequency or -3dB point, can be found using the standard formula, $f c = 1/(2\pi RC)$. The phase angle of the output signal at $f c$ and is -45° for a Low Pass Filter.

The gain of the filter or any filter for that matter, is generally expressed in **Decibels** and is a function of the output value divided by its corresponding input value and is given as:

Applications of passive Low Pass Filters are in audio amplifiers and speaker systems to direct the lower frequency bass signals to the larger bass speakers or to reduce any high frequency noise or "hiss" type distortion. When used like this in audio applications the low pass filter is sometimes called a "high-cut", or "treble cut" filter.



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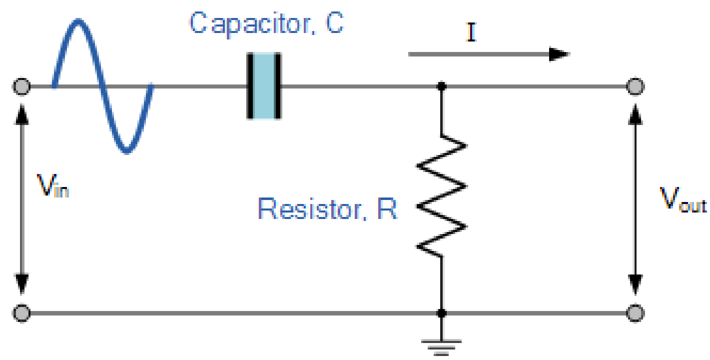
The High Pass Filter Circuit



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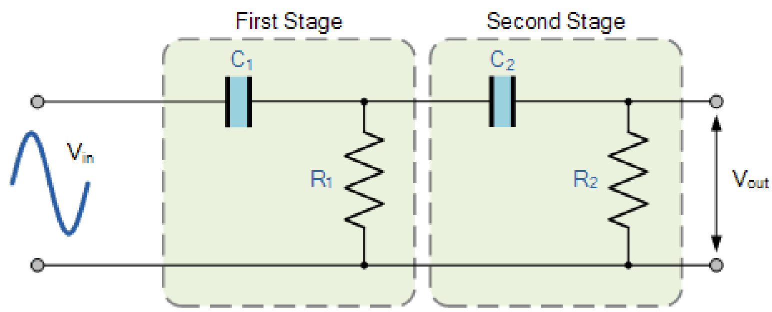
In this circuit arrangement, the reactance of the capacitor is very high at low frequencies so the capacitor acts like an open circuit and blocks any input signals at V_{IN} until the cut-off frequency point (f_C) is reached. Above this cut-off frequency point the reactance of the capacitor has reduced sufficiently as to now act more like a short circuit allowing all of the input signal to pass directly to the output as shown below in the filters response curve.

Second-order High Pass Filter



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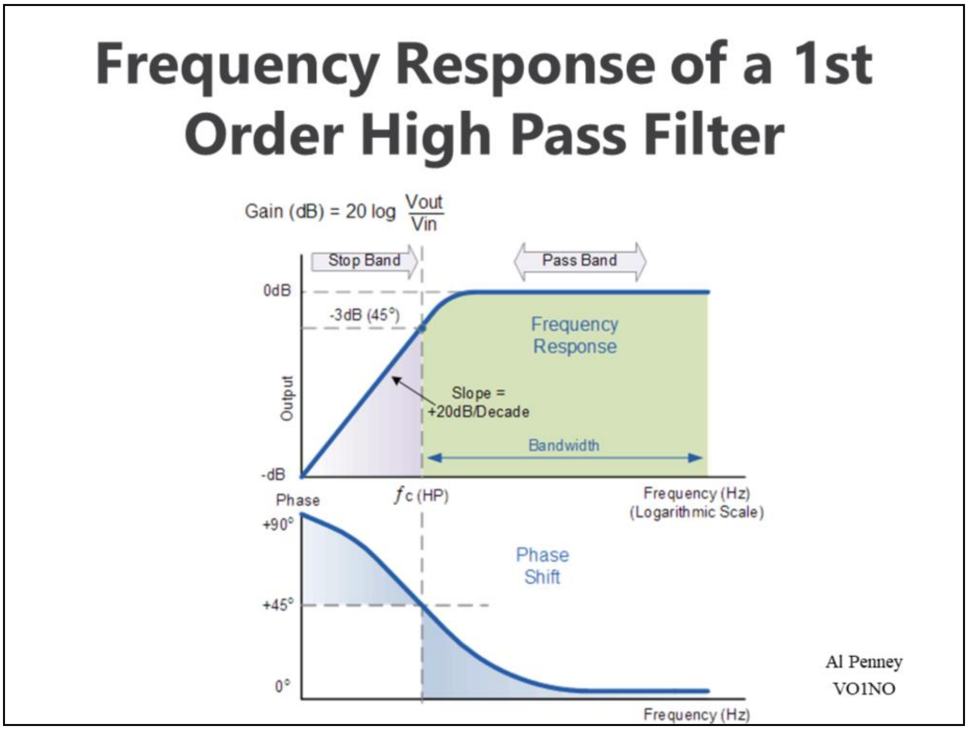
The above circuit uses two first-order filters connected or cascaded together to form a second-order or two-pole high pass network. Then a first-order filter stage can be converted into a second-order type by simply using an additional RC network, the same as for the 2^{nd}-order low pass filter. The resulting second-order high pass filter circuit will have a slope of 40dB/decade (12dB/octave).

High Pass Filter Summary

We have seen that the **Passive High Pass Filter** is the exact opposite to the low pass filter. This filter has no output voltage from DC (0Hz), up to a specified cut-off frequency ($ƒc$) point. This lower cut-off frequency point is 70.7% or **-3dB** (dB = -20log V_{OUT}/V_{IN}) of the voltage gain allowed to pass.

The frequency range "below" this cut-off point $ƒc$ is generally known as the **Stop Band**while the frequency range "above" this cut-off point is generally known as the **Pass Band**

A very common application of this type of passive filter, is in audio amplifiers as a coupling capacitor between two audio amplifier stages and in speaker systems to direct the higher frequency signals to the smaller "tweeter" type speakers while blocking the lower bass signals or are also used as filters to reduce any low frequency noise or "rumble" type distortion. When used like this in audio applications the high pass filter is sometimes called a “low-cut”, or “bass cut” filter.



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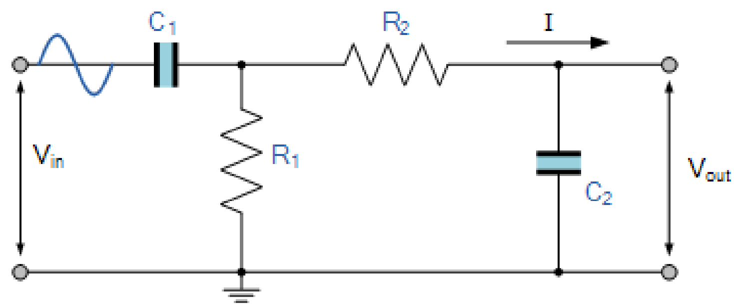
Band Pass Filter Circuit



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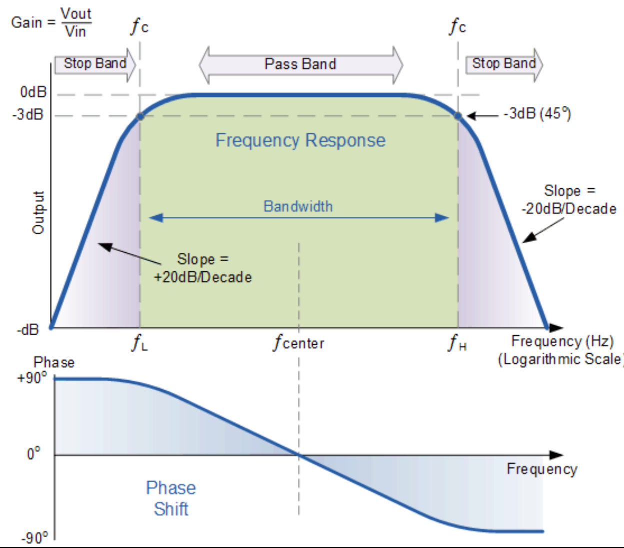
Unlike the low pass filter which only pass signals of a low frequency range or the high pass filter which pass signals of a higher frequency range, a **Band Pass Filters** passes signals within a certain "band" or "spread" of frequencies without distorting the input signal or introducing extra noise. This band of frequencies can be any width and is commonly known as the filters **Bandwidth**.

Bandwidth is commonly defined as the frequency range that exists between two specified frequency cut-off points ($ƒc$), that are 3dB below the maximum centre or resonant peak while attenuating or weakening the others outside of these two points.

Then for widely spread frequencies, we can simply define the term "bandwidth", BW as being the difference between the lower cut-off frequency ($ƒc_{LOWER}$) and the higher cut-off frequency ($ƒc_{HIGHER}$) points. In other words, BW = $ƒ_H - ƒ_L$. Clearly for a pass band filter to function correctly, the cut-off frequency of the low pass filter must be higher than the cut-off frequency for the high pass filter.

The "ideal" **Band Pass Filter** can also be used to isolate or filter out certain frequencies that lie within a particular band of frequencies, for example, noise cancellation. Band pass filters are known generally as second-order filters, (two-pole) because they have "two" reactive component, the capacitors, within their circuit design. One capacitor in the low pass circuit and another capacitor in the high pass circuit.

Frequency Response of a 2nd Order Band Pass Filter



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Band Pass Filter Summary

A simple passive **Band Pass Filter** can be made by cascading together a single **Low Pass Filter** with a **High Pass Filter**. The frequency range, in Hertz, between the lower and upper -3dB cut-off points of the RC combination is know as the filters "Bandwidth".

The width or frequency range of the filters bandwidth can be very small and selective, or very wide and non-selective depending upon the values of R and C used.

The centre or resonant frequency point is the geometric mean of the lower and upper cut-off points. At this centre frequency the output signal is at its maximum and the phase shift of the output signal is the same as the input signal.

The amplitude of the output signal from a band pass filter or any passive RC filter for that matter, will always be less than that of the input signal. In other words a passive filter is also an attenuator giving a voltage gain of less than 1 (Unity). To provide an output signal with a voltage gain greater than unity, some form of amplification is required within the design of the circuit.

A **Passive Band Pass Filter** is classed as a second-order type filter because it has two reactive components within its design, the capacitors. It is made up from two single RC filter circuits that are each first-order filters themselves.

If more filters are cascaded together the resulting circuit will be known as an "n^{th}-order" filter where the "n" stands for the number of individual reactive components and therefore poles within the filter circuit. For example, filters can be a 2^{nd}-order, 4^{th}-order, 10^{th}-order, etc.

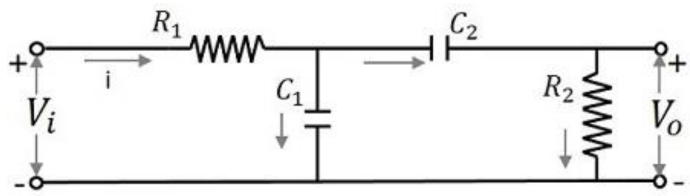
The higher the filters order the steeper will be the slope at n times -20dB/decade. However, a single capacitor value made by combining together two or more individual capacitors is still one capacitor.

We can see from the amplitude and phase curves above for the band pass circuit, that the quantities f_L, f_H and f_C are the same as those used to describe the behaviour of the band-pass filter. This is because the band stop filter is simply an inverted or complimented form of the standard band-pass filter. In fact the definitions used for bandwidth, pass band, stop band and center frequency are the same as before, and we can use the same formulas to calculate bandwidth, BW, center frequency, f_C, and quality factor, Q.

The ideal band stop filter would have infinite attenuation in its stop band and zero attenuation in either pass band. The transition between the two pass bands and the stop band would be vertical (brick wall). There are several ways we can design a "Band Stop Filter", and they all accomplish the same purpose.

Generally band-pass filters are constructed by combining a low pass filter (LPF) in series with a high pass filter (HPF). Band stop filters are created by combining together the low pass and high pass filter sections in a "parallel" type configuration as shown.

Band Stop Filter



Circuit diagram for Band Stop Filter

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By combining a basic RC low-pass filter with a RC high-pass filter we can form a simple band-pass filter that will pass a range or band of frequencies either side of two cut-off frequency points. But we can also combine these low and high pass filter sections to produce another kind of RC filter network called a band stop filter that can block or at least severely attenuate a band of frequencies within these two cut-off frequency points.

The **Band Stop Filter**, (BSF) is another type of frequency selective circuit that functions in exactly the opposite way to the Band Pass Filter we looked at before. The band stop filter, also known as a *band reject filter*, passes all frequencies with the exception of those within a specified stop band which are greatly attenuated.

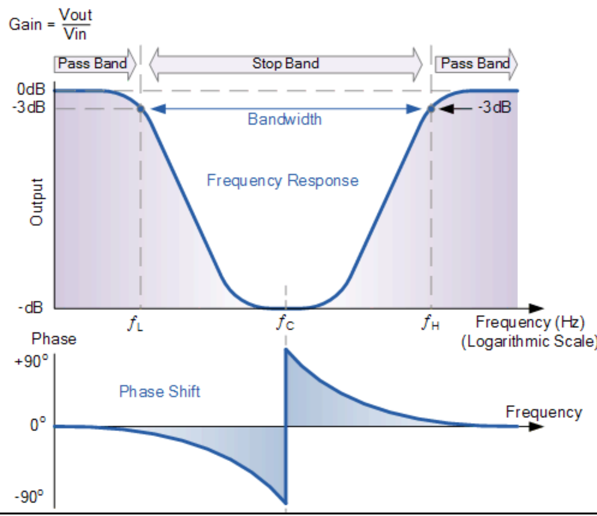
If this stop band is very narrow and highly attenuated over a few hertz, then the band stop filter is more commonly referred to as a *notch filter*, as its frequency response shows that of a deep notch with high selectivity (a steep-side curve) rather than a flattened wider band.

Also, just like the band pass filter, the band stop (band reject or notch) filter is a second-order (two-pole) filter having two cut-off frequencies, commonly known as the -3dB or half-power points producing a wide stop band bandwidth between these two -3dB points.

Then the function of a band stop filter is too pass all those frequencies from zero (DC) up to its first (lower) cut-off frequency point f_L, and pass all those frequencies above its second (upper) cut-off frequency f_H, but block or reject all those frequencies in-between. Then the filters bandwidth, BW is defined as: $(f_H - f_L)$.

So for a wide-band band stop filter, the filters actual stop band lies between its lower and upper -3dB points as it attenuates, or rejects any frequency between these two cut-off frequencies.

Band Stop Filter Response



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Crystal Filters

- Filters that uses Quartz Crystals as resonators.
- Very high Q (10,000 to 100,000).
- Crystals' stability and high Q permit precise center frequencies, narrow bandwidth, and steep skirts.
- Often used in IF stages of receivers.
- Bandwidth and response shape determined by frequency of individual crystals.
- Typically 2 – 3 dB insertion loss.

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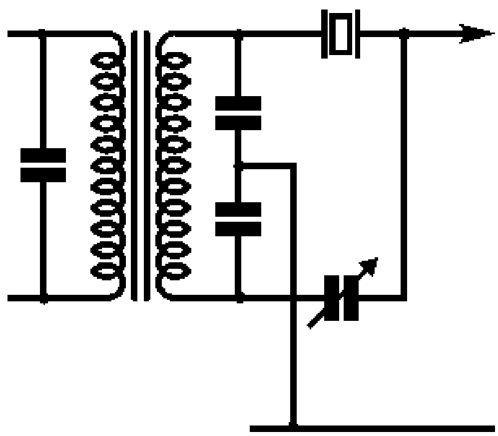
Single Crystal Filter



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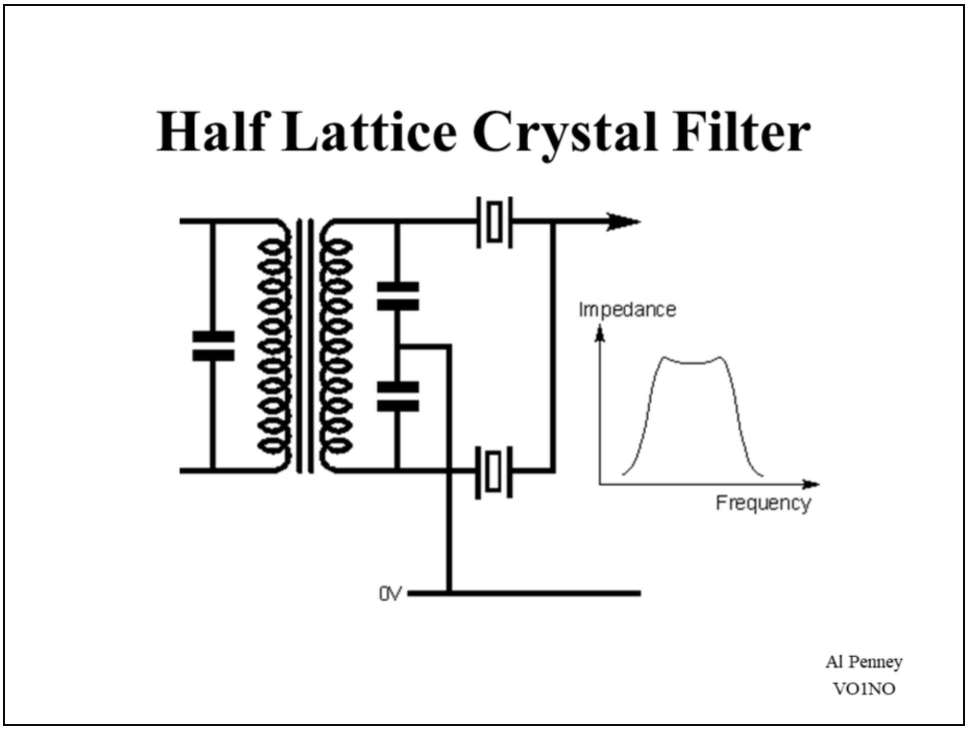
The simplest crystal filter employs a single crystal. This type of RF filter was developed in the 1930s and was used in early receivers dating from before the 1960s but is rarely used today. Although it employs the very high Q of the crystal, its response is asymmetric and it is too narrow for most applications, having a bandwidth of a hundred Hz or less.

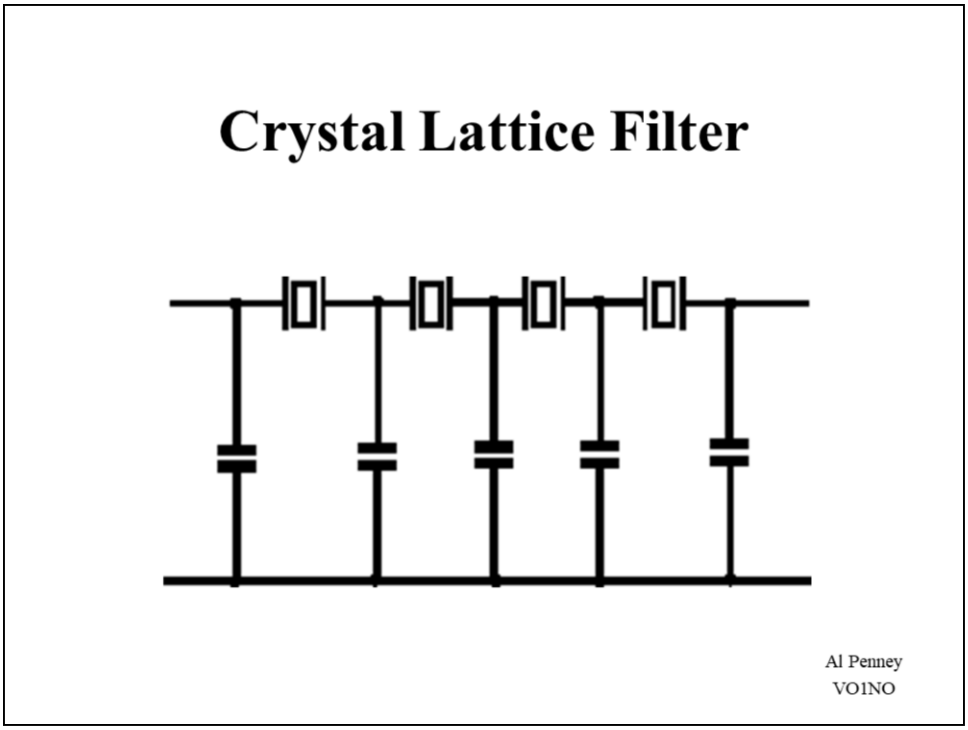
In the circuit there is a variable capacitor that is used to compensate for the parasitic capacitance in the crystal. This capacitor was normally included as a front panel control.



This form of band pass RF filter provided a significant improvement in performance over the single. In this configuration the parasitic capacitances of each of the crystals cancel each other out and enable the circuit to operate satisfactorily. By adopting a slightly different frequency for the crystals, a wider bandwidth is obtained. However the slope response outside the required pass band falls away quickly, enabling high levels of out of band rejection to be obtained. Typically the parallel resonant frequency of one crystal is designed to be equal to the series resonant frequency of the other.

Despite the fact that the half lattice crystal filter can offer a much flatter in-band response there is still some ripple. This results from the fact that the two crystals have different resonant frequencies. The response has a small peak at either side of the centre frequency and a small dip in the middle. As a rough rule of thumb it is found that the 3 dB bandwidth of the RF filter is about 1.5 times the frequency difference between the two resonant frequencies. It is also found that for optimum performance the matching of the filter is very important. To achieve this, matching resistors are often placed on the input and output. If the filter is not properly matched then it is found that there will be more in-band ripple and the ultimate rejection may not be as good.

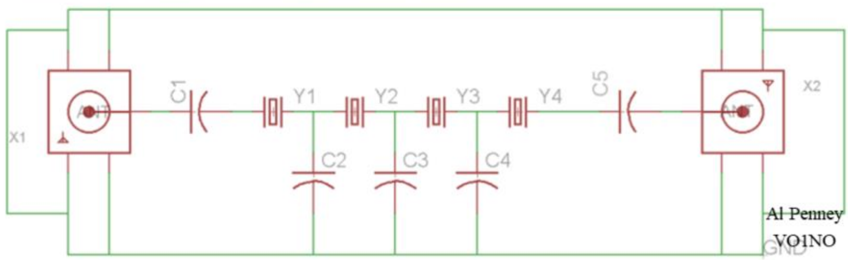
A two pole filter (i.e. one with two crystals) is not normally adequate to meet many requirements. The shape factor can be greatly improved by adding further sections. Typically ultimate rejections of 70 dB and more are required in a receiver. As a rough guide a two pole filter will generally give a rejection of around 20 dB; a four pole filter, 50 dB; a six pole filter, 70 dB; and an eight pole one 90 dB.



For many years the half lattice filter was possibly the most popular format used for crystal filters. More recently the ladder topology has gained considerable acceptance. In this form of crystal pass band filter all the resonators have the same frequency, and the inter-resonator coupling is provided by the capacitors placed between the resonators with the other termination connected to earth.

Crystal filters are widely used in many radio communications receiver applications. Here these filters are able to provide very high levels of performance and at a cost which is very reasonable for the performance that is given. These RF filters may be made in a variety of formats according to the applications and the performance needed. While these RF filters can be made from discrete components, ready manufactured crystal filters are normally bought, either off the shelf, of made to a given specification.

Crystal Lattice Filter



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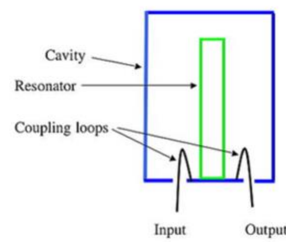
Cavity Filters

- High Q, stable filters used at VHF and up.
- Very common for repeaters systems.
- Consists of 2 coupling loops in a resonant cavity.
- Tuned by adjusting resonator.
- Sharp tuning.



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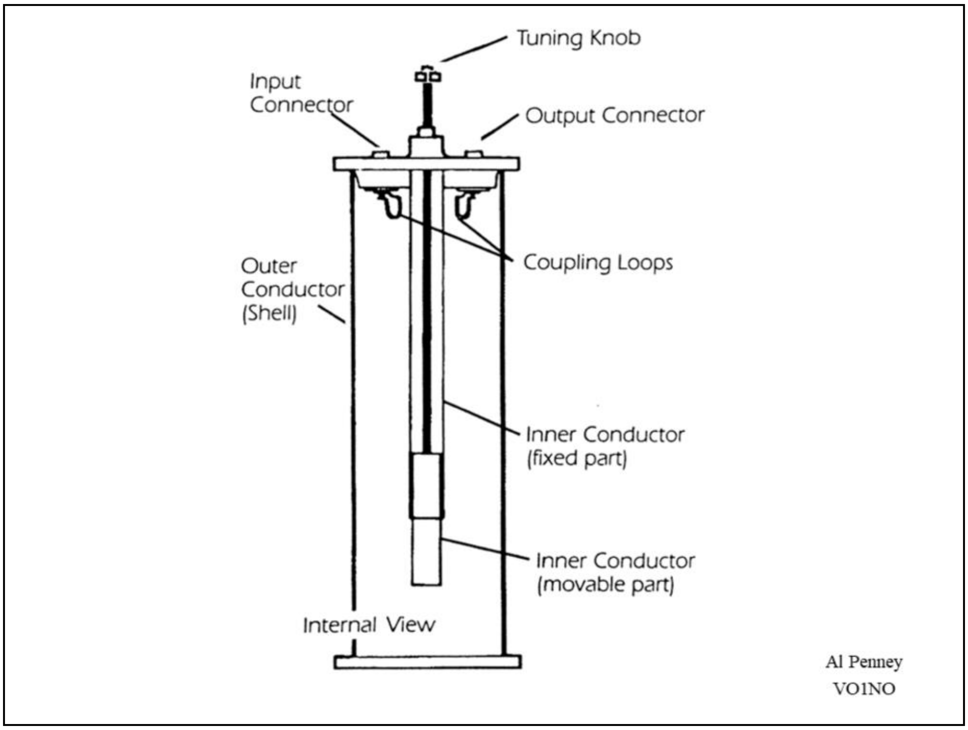
Tuning Knob
Input
Connector
Output Connector
Coupling Loops
Outer
Conductor
(Shell)
Inner Conductor
(fixed part)
Inner Conductor
(movable part)
Internal View
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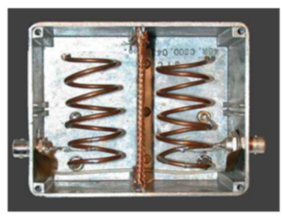
Helical Resonator

- High Q filter consisting of wire helix surrounded by conductive shield.
- Often silver-plated due to Surface Effect.
- Used primarily at VHF and higher in RX front ends to prevent overload and spurious signals.



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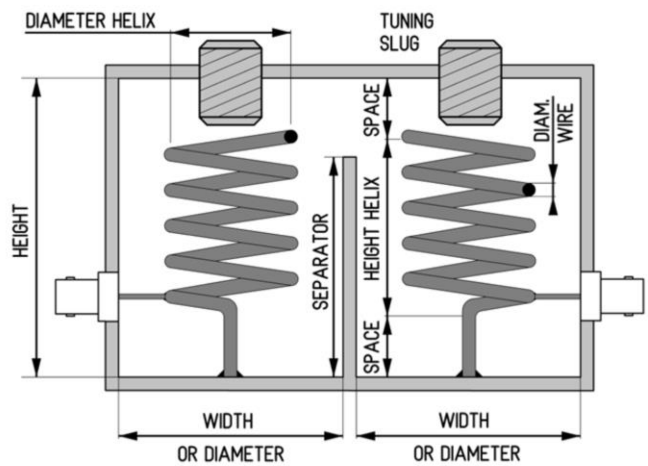
Helical Filter



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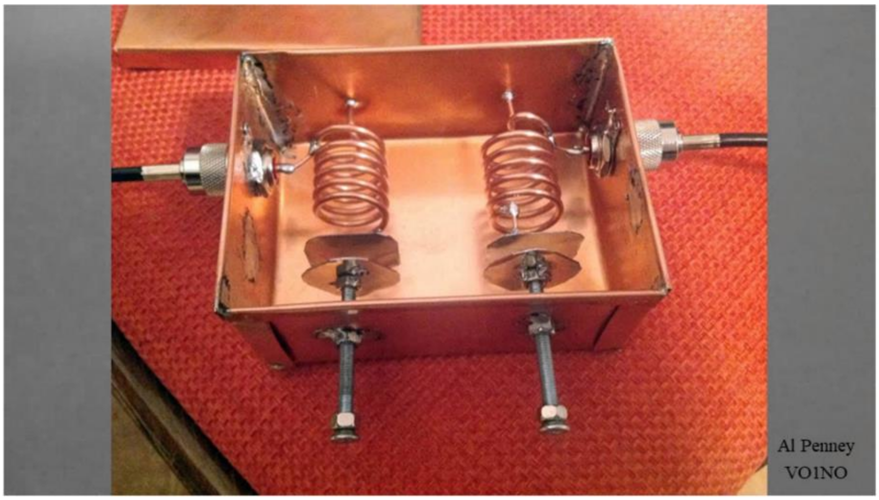
Homebrew 145 MHz Bandpass Filter



Comb Filter

- Similar to Cavity and Helical Filter.
- Sections not tuned to the exact same frequency, but over the desired passband.
- Tuned using capacitors at open end of rods.
- Input and Output use coupling link.
- Intermediate stages coupled using holes through partitions.
- 4 MHz bandwidth possible.

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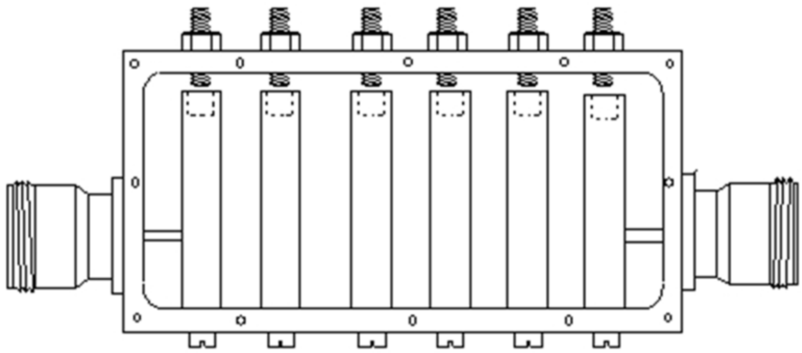

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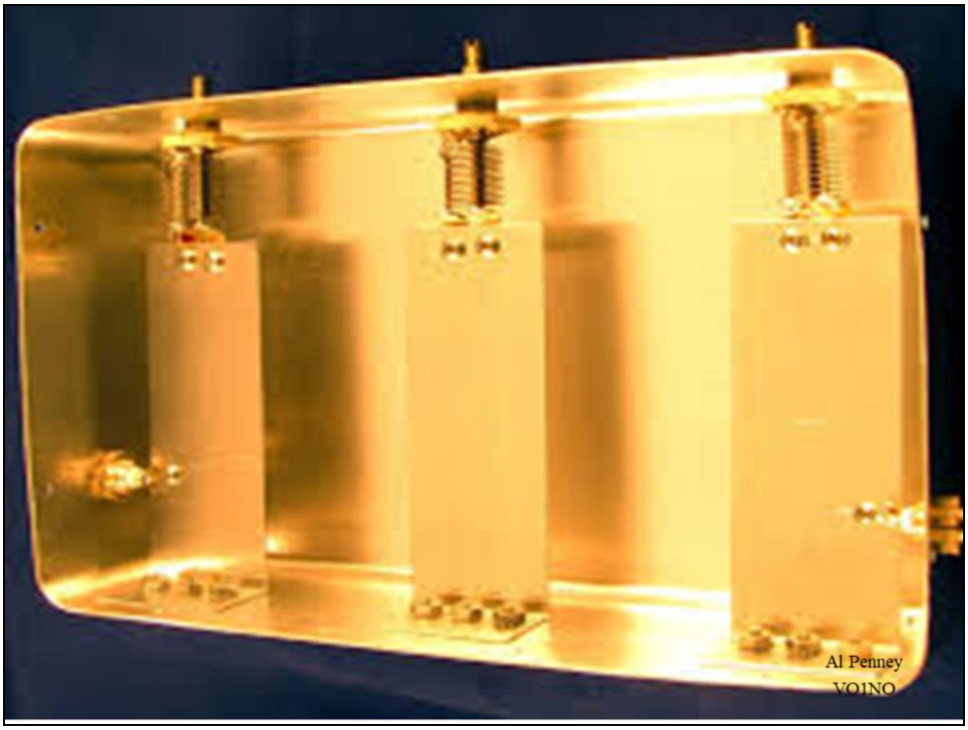
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Butterworth Filter

- A filter design having a frequency response as flat as possible in the passband, and small phase shift.
- The more stages, the steeper the rolloff.
- Lots of math involved in the design of such filters!
- Pre-calculated design info tables exist.

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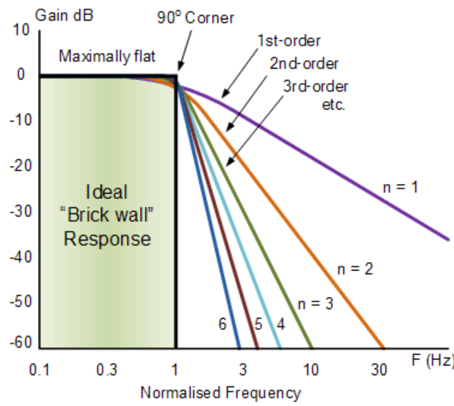
Butterworth Filter



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The **Butterworth filter** is a type of signal processing filter designed to have a frequency response as flat as possible in the passband. It is also referred to as a **maximally flat magnitude filter**. It was first described in 1930 by the British engineer and physicist Stephen Butterworth in his paper entitled "On the Theory of Filter Amplifiers".

Chebyshev Filters

- Analog or digital filters having a steeper roll-off and more ripple in passband than Butterworth filters.
- Also have more phase shift than Butterworth.
- The more stages, the steeper the rolloff, though there is still ripple in passband.
- Lots of math involved in the design of such filters!
- Pre-calculated design info tables exist.

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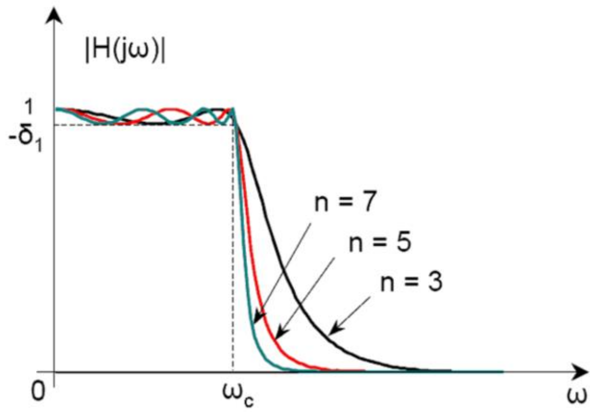
Chebyshev Filters



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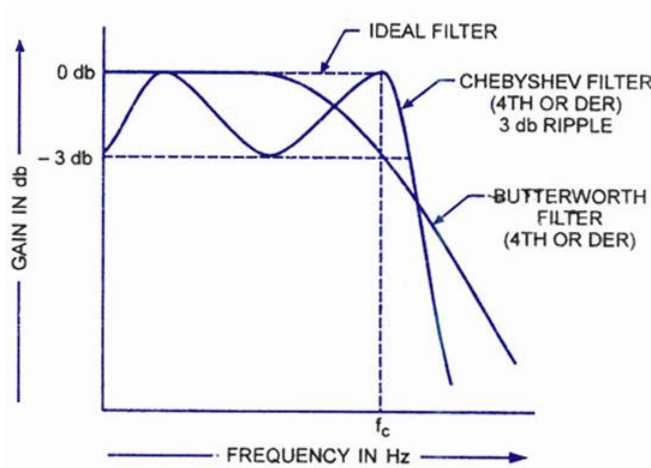
Chebyshev vs Butterworth



Chebyshev and Butterworth Filter

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Chebyshev and Butterworth filters are designed for totally different applications.

Butterworth filters are used in applications where maximum pass band flatness is required.

Chebyshev filters are optimized to give a steeper roll off.

As you can see, the pass band of a Butterworth filter is quite flat. This means a signal of frequency, say (1/2)*fc and (1/3)*fc will both have the same amplification which is 1 (0 dB). So, they will pass through the filter without no attenuation. This is required for conditioning analog signals where you don't want to distort the signal too much. E.g. you want to hook up an sensor to an ADC to get some readings but the problem is that you have some high frequency noise. Now, you want to eliminate this noise without affecting the sensor readings too much. In this case, go with a Butterworth filter. Butterworth filters are also used for Anti-aliasing applications.

Chebyshev filters are used where the frequency content of a signal is more important than having a constant amplitude. Say, you have a digital signal where you are sending a square wave to indicate 1 and nothing for 0. Now, you would not care so much about accurately recreating a square wave when it pass through a filter. Even if the original square wave is distorted by the filter to resemble more like a sine wave it is fine because all you cared about, in the first place, was the presence of a square wave.

Active Filters

- Passive filters suffer from attenuation.
- The more stages, the greater the attenuation.
- Active filters use op-amps, transistors or FETs in their design.
- Power is provided by an external source.
- Op-amps offer high input impedance, low output impedance, and a voltage gain determined by resistors in feedback loop.

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We also noticed that the main disadvantage of passive filters is that the amplitude of the output signal is less than that of the input signal, ie, the gain is never greater than unity and that the load impedance affects the filters characteristics.

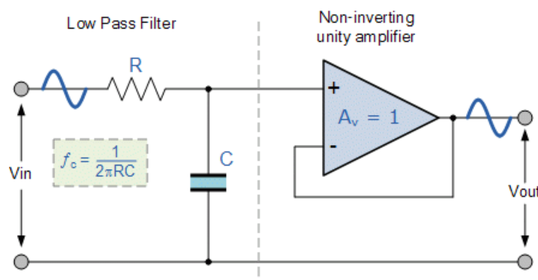
With passive filter circuits containing multiple stages, this loss in signal amplitude called "Attenuation" can become quiet severe. One way of restoring or controlling this loss of signal is by using amplification through the use of **Active Filters**.

As their name implies, **Active Filters** contain active components such as operational amplifiers, transistors or FET's within their circuit design. They draw their power from an external power source and use it to boost or amplify the output signal.

Filter amplification can also be used to either shape or alter the frequency response of the filter circuit by producing a more selective output response, making the output bandwidth of the filter more narrower or even wider. Then the main difference between a "passive filter" and an "active filter" is amplification.

An active filter generally uses an operational amplifier (op-amp) within its design and in the Operational Amplifier tutorial we saw that an Op-amp has a high input impedance, a low output impedance and a voltage gain determined by the resistor network within its feedback loop.

Active Low Pass Filter



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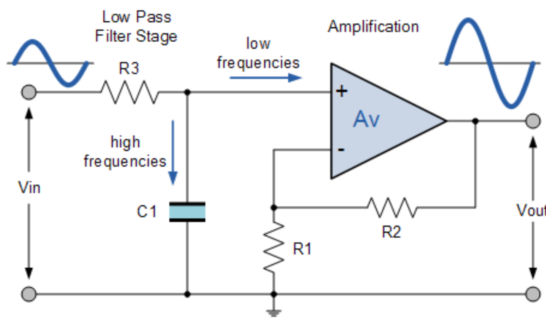
The most common and easily understood active filter is the **Active Low Pass Filter**. Its principle of operation and frequency response is exactly the same as those for the previously seen passive filter, the only difference this time is that it uses an op-amp for amplification and gain control. The simplest form of a low pass active filter is to connect an inverting or non-inverting amplifier, the same as those discussed in the Op-amp tutorial, to the basic RC low pass filter circuit as shown.

This first-order low pass active filter, consists simply of a passive RC filter stage providing a low frequency path to the input of a non-inverting operational amplifier. The amplifier is configured as a voltage-follower (Buffer) giving it a DC gain of one, Av = +1 or unity gain as opposed to the previous passive RC filter which has a DC gain of less than unity.

The advantage of this configuration is that the op-amps high input impedance prevents excessive loading on the filters output while its low output impedance prevents the filters cut-off frequency point from being affected by changes in the impedance of the load.

While this configuration provides good stability to the filter, its main disadvantage is that it has no voltage gain above one. However, although the voltage gain is unity the power gain is very high as its output impedance is much lower than its input impedance.

Active Low Pass Filter - Amplified



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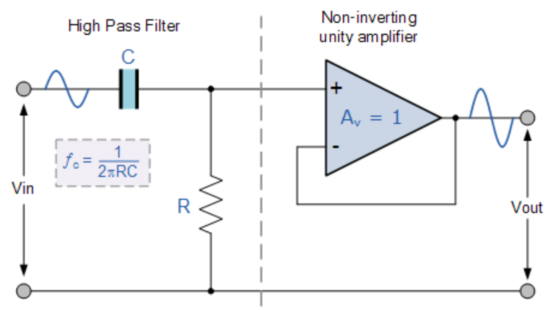
The frequency response of the circuit will be the same as that for the passive RC filter, except that the amplitude of the output is increased by the pass band gain, A_F of the amplifier. For a non-inverting amplifier circuit, the magnitude of the voltage gain for the filter is given as a function of the feedback resistor (R_2) divided by its corresponding input resistor (R_1) value and is given as:

DC Gain = (1 + R2/R1)

Active High Pass Filter



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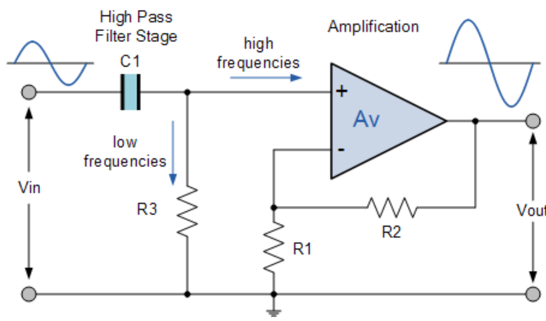
The basic operation of an **Active High Pass Filter** (HPF) is the same as for its equivalent RC passive high pass filter circuit, except this time the circuit has an operational amplifier or included within its design providing amplification and gain control.

Technically, there is no such thing as an **active high pass filter**. Unlike Passive High Pass Filters which have an "infinite" frequency response, the maximum pass band frequency response of an active high pass filter is limited by the open-loop characteristics or bandwidth of the operational amplifier being used, making them appear as if they are band pass filters with a high frequency cut-off determined by the selection of op-amp and gain.

Active High Pass Filter - Amplified



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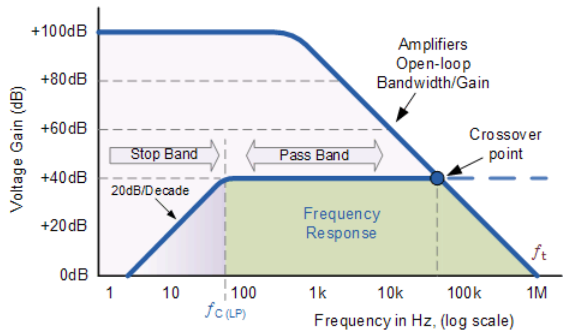
A first-order (single-pole) **Active High Pass Filter** as its name implies, attenuates low frequencies and passes high frequency signals. It consists simply of a passive filter section followed by a non-inverting operational amplifier. The frequency response of the circuit is the same as that of the passive filter, except that the amplitude of the signal is increased by the gain of the amplifier and for a non-inverting amplifier the value of the pass band voltage gain is given as 1 + R2/R1, the same as for the low pass filter circuit.

Frequency Response Curve



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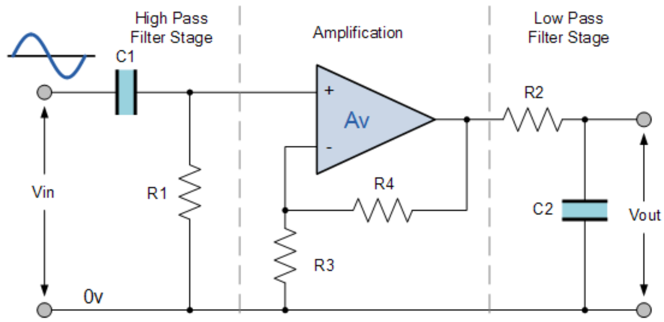
Active Band Pass Filter



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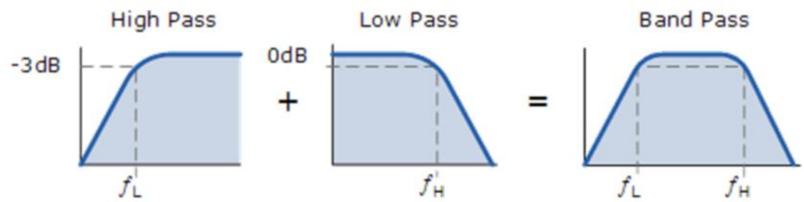
This cascading together of the individual low and high pass passive filters produces a low "Q-factor" type filter circuit which has a wide pass band. The first stage of the filter will be the high pass stage that uses the capacitor to block any DC biasing from the source. This design has the advantage of producing a relatively flat asymmetrical pass band frequency response with one half representing the low pass response and the other half representing high pass response as shown.

Active Band Pass Filter



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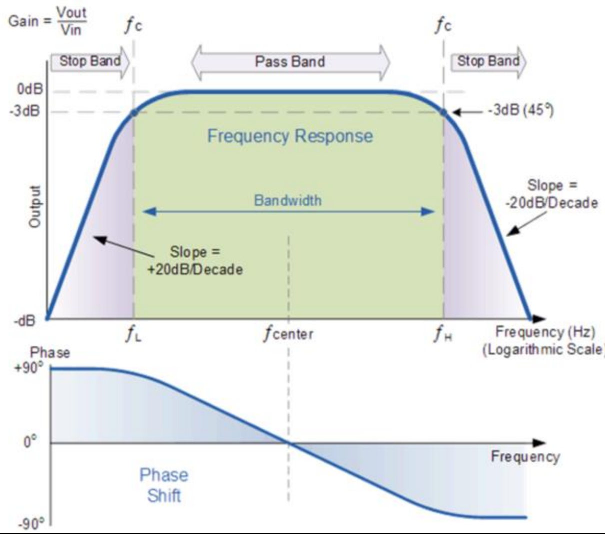
Frequency Response Curve



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Questions?

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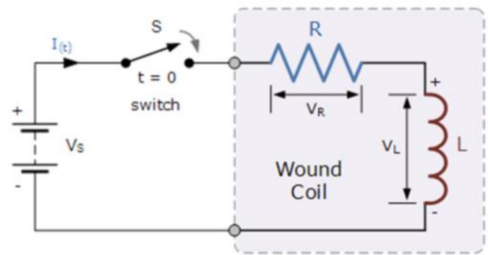

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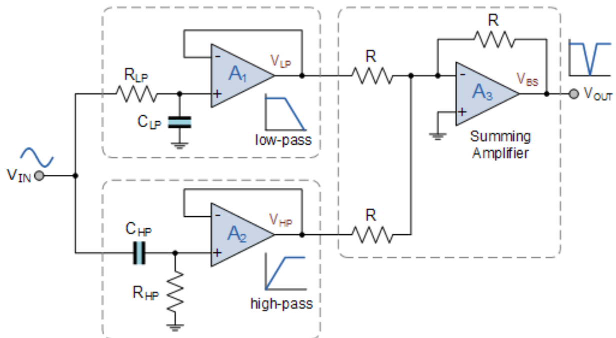
Band Stop Filter Circuit



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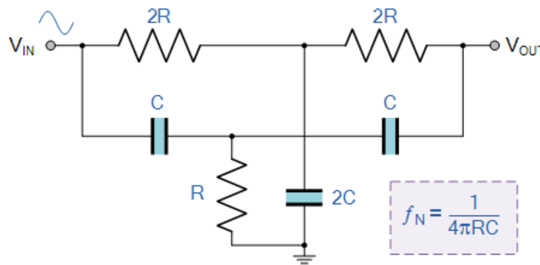
The use of operational amplifiers within the band stop filter design also allows us to introduce voltage gain into the basic filter circuit. The two non-inverting voltage followers can easily be converted into a basic non-inverting amplifier with a gain of Av = 1 + Rf/Rinby the addition of input and feedback resistors, as seen in our non-inverting op-amp tutorial.

Notch Filters



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Notch filters are a highly selective, high-Q, form of the band stop filter which can be used to reject a single or very small band of frequencies rather than a whole bandwidth of different frequencies. For example, it may be necessary to reject or attenuate a specific frequency generating electrical noise (such as mains hum) which has been induced into a circuit from inductive loads such as motors or ballast lighting, or the removal of harmonics, etc.

But as well as filtering, variable notch filters are also used by musicians in sound equipment such as graphic equalizers, synthesizers and electronic crossovers to deal with narrow peaks in the acoustic response of the music. Then we can see that notch filters are widely used in much the same way as low-pass and high-pass filters.

Notch filters by design have a very narrow and very deep stop band around their center frequency with the width of the notch being described by its selectivity Q in exactly the same way as resonance frequency peaks in RLC circuits.

The most common notch filter design is the twin-T notch filter network. In its basic form, the twin-T, also called a parallel-tee, configuration consists of two RC branches in the form of two tee sections, that use three resistors and three capacitors with opposite and opposing R and C elements in the tee part of its design as shown, creating a deeper notch.

The upper T-pad configuration of resistors 2R and capacitor 2C form the low-pass filter section of the design, while the lower T-pad configuration of capacitors C and resistor Rform the high-pass filter section. The frequency at which this basic twin-T notch filter design offers maximum attenuation is called the “notch frequency”, f_N and is given as: