

EXP9: Active Filters

OBJECTIVES

We will investigate the various characteristics of analog passive and active filters. In particular, we will design, analyze, simulate, and observe the following:

- (i) Low pass, High pass, and Band pass passive RC filters
- (ii) Low pass, High pass, and Band pass two-pole active filters.

INTRODUCTION¹

Filters are found in various types of electronic equipment and perform various functions. For example, they are used in power supplies to attenuate undesirable ripple, in audio circuits for bass and treble control, and in signal processing applications where they are often used to *band limit* a signal before it is sampled. There are four basic types of filters: high-pass, low-pass, band-pass and band-reject or notch. All filter implementations fall in one of two categories: passive or active. Passive filters consist of *only* passive elements, i.e., resistors, inductors and capacitors. On the other hand, active filters consist of passive elements along with active devices, such as transistors or op-amps. It should be noted that one can not take the output of a passive filter and amplify it using an op-amp or transistor to produce an active filter! Typically, op-amps are chosen over transistors in active filters to take advantage of their high performance characteristics and minimal cost.

The question one needs to ask is why bother with active filtering? The answer is really quite simple: an active filter uses combinations of op-amps, resistors and capacitors to obtain a response equal to or better than conventional passive filters. For example, in order to obtain a *sharp* response with a passive filter, we would need to cascade several passive stages. Each cascaded stage, however, loads the previous stages. This loading attenuates the desired part of the signal, i.e., frequencies within the filter pass-band, as well as unwanted frequency content within signal. This problem is commonly known as insertion loss. Active filtering practically eliminates insertion loss due to the *high* input impedance and the *low* output impedance of an op-amp. Furthermore, with active filtering, we can attenuate unwanted frequencies while amplifying desired frequencies! Two other advantages of active filters include simple design and ease of tuning. Lastly, active filters usually do not require the use of inductors, which are typically bulky, costly and depart further from ideal models compared to capacitors.

The Basic Types of Filters

There are five basic filter types that bear consideration (shown below in Figure 1): low pass, high pass, band pass, notch, and “all-pass”. Low pass filters (by far the most

¹ Material in this section were obtained from http://www.clarkson.edu/class/ee311/Experiment3/Lab3_F02.PDF , http://www.stanford.edu/class/ee122/Handouts/EE122_Labs_02_fall2002.pdf , and Richard Jaeger, Microelectronic Circuit Design, McGraw Hill, 1996.

common type) ideally pass all frequencies below a specific cut-off frequency. High pass filters ideally pass all frequencies above a specific cut-off frequency. Band pass filters ideally have a pass band between a low and a high cut-off frequency and reject frequencies outside of this band. Notch filters ideally reject only a specific, and often very narrow, band of frequencies, passing all others. All-pass filters ideally pass all frequencies equally in amplitude but change the phase of the input signals depending upon their frequency.

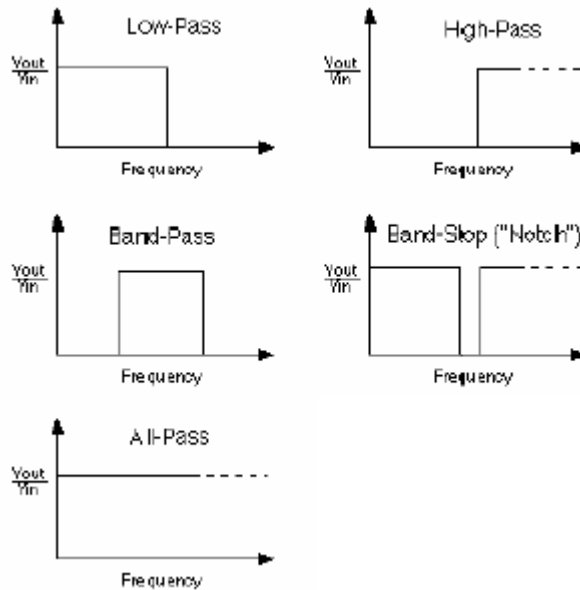


Figure 1. Basic Types of Filters

Since some designs in this experiment investigate the performance characteristics of a band-pass filter, we will need to define some important concepts related to band-pass filters. Refer to Figure 2 to obtain some physical intuition to the following terms.

Center Frequency

The center frequency, which is sometimes called the resonant frequency, is given by f_o . In second order circuits and some higher order circuits, the center frequency is easy to determine since it is the frequency at which the maximum gain of the filter occurs.

Theoretically, the center frequency is the geometric mean of the two half-power frequencies, f_L and f_H . Therefore, $f_o = \sqrt{f_L \cdot f_H}$.

Lower and Upper Cutoff Frequencies

The lower and upper cutoff (or half-power) frequencies are given by f_L and f_H , respectively. The lower cutoff frequency is the lower frequency at which the gain is 3dB less than the gain at the center frequency. Similarly, the upper cutoff frequency is the upper frequency at which the gain is 3dB less than the gain at the center frequency.

Maximum Gain

The maximum gain of a filter is given by H_o . It is the ratio of V_o to V_i at the filter's center or resonant frequency. Decibels (dB) are often used as a relative measure of filter gain in the lab, where it is common practice to uncalibrate an instrumentation channel so

that the output voltage reads 0 db at the point of maximum gain. If you do this, you still need to record the actual, i.e., unscaled, gain for a given frequency.

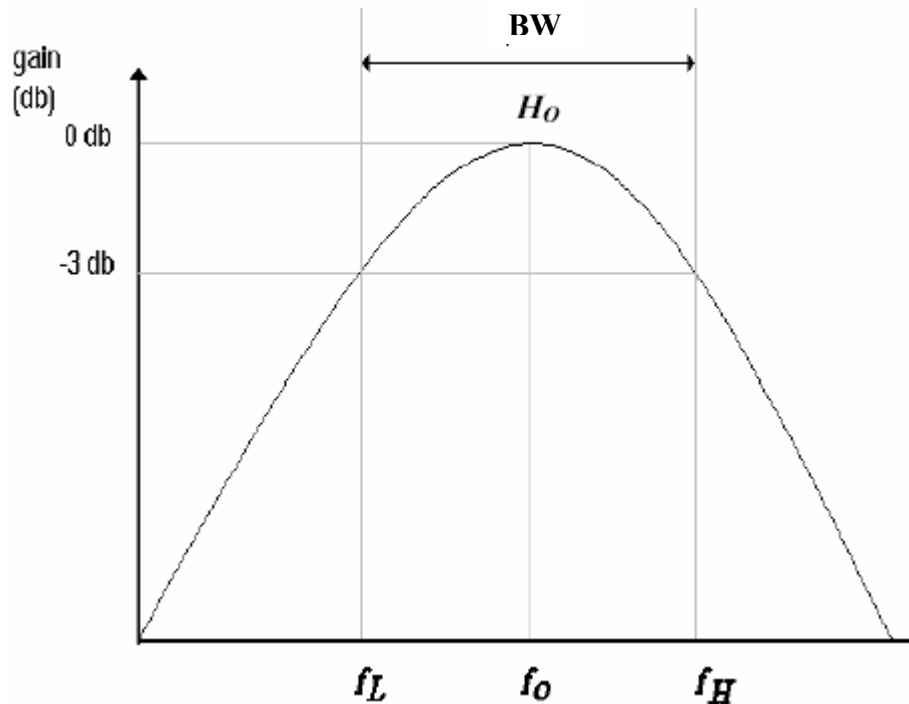


Figure 2. Typical frequency response for a band-pass filter with peak gain of 1.0.

Passband

The passband is the frequency range for the part of the signal that is *not* attenuated, i.e., the gain is within 3dB of the maximum gain. Hence, the passband frequency range lies between the lower and upper cutoff frequencies.

Bandwidth

The bandwidth, BW, is closely related to the passband, being the difference between the upper and lower filter cutoff frequencies, $BW = f_H - f_L$.

Quality Factor

The quality factor, Q , is a dimensionless figure of merit used to measure the selectivity of a filter and is expressed as the ratio of the filter's center frequency to bandwidth, $Q = f_o/BW$. For example, given a filter with a fixed center frequency, decreasing the filter's bandwidth (i.e., increasing its sharpness) increases Q .

Active Filters

Low Pass Active Filters

Figure 3 shows a two-pole low pass active filter. The voltage transfer function is specified in equation (9-1).

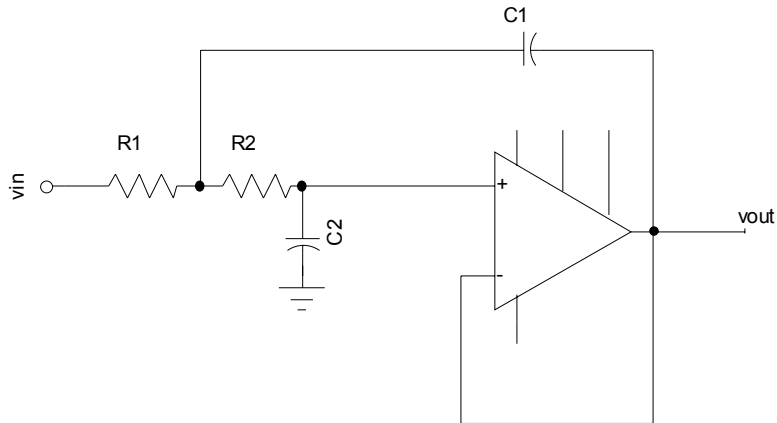


Figure 3. Two-pole Low Pass Active Filter

$$A_v(s) = \frac{\omega_0^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2} \quad (9-1)$$

where $\omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}$, ω_0 is the cutoff frequency, and $Q = \sqrt{\frac{C_1}{C_2}} * \frac{\sqrt{R_1 R_2}}{R_1 + R_2}$ (9-2)

High Pass Active Filters

Figure 4 shows a two-pole high pass active filter. The voltage transfer function is specified in equation (9-3).

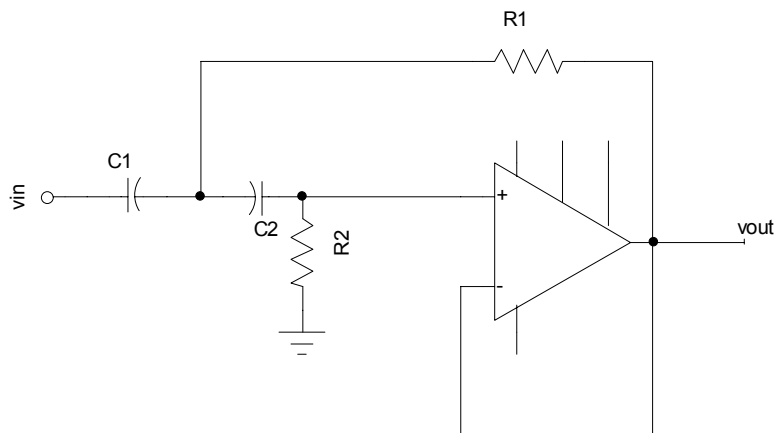


Figure 4. Two-pole High Pass Active Filter

$$A_v(s) = \frac{s^2}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2} \quad (9-3)$$

$$\text{where } \omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}, \omega_0 \text{ is the cutoff frequency, and } Q = \sqrt{\frac{R_2}{R_1}} * \frac{\sqrt{C_1 C_2}}{C_1 + C_2} \quad (9-4)$$

Band Pass Active Filters

Figure 5 shows a two-pole band pass active filter. The voltage transfer function is specified in equation (9-5).

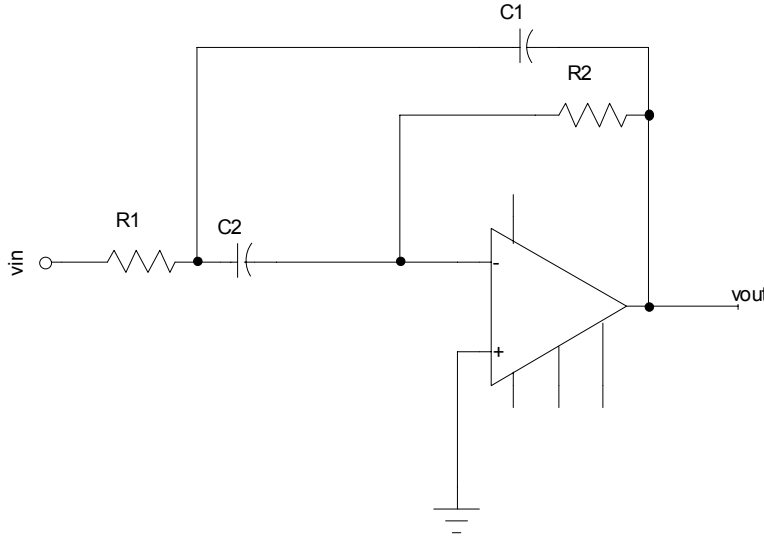


Figure 5. Two-pole Band Pass Active Filter

$$A_v(s) = -\sqrt{\frac{R_2 C_2}{R_1 C_1}} \frac{s \omega_0}{s^2 + s \frac{\omega_0}{Q} + \omega_0^2} \quad (9-5)$$

$$\text{where } \omega_0 = \frac{1}{\sqrt{R_1 R_2 C_1 C_2}}, \omega_0 \text{ is the center frequency, and } Q = \sqrt{\frac{R_2}{R_1}} * \frac{\sqrt{C_1 C_2}}{C_1 + C_2} \quad (9-6)$$

PREPARATION

Because the lab assistant does not have all possible values for capacitors, please limit the values you use for the capacitors to those that can be implemented by using few serial and parallel combinations of 0.01 μ F capacitors.

Low Pass Passive Filter:

1. Design a low-pass passive circuit with a single pole that has a cutoff frequency at 20 kHz. Use only capacitors and resistors. For your design, show the values you choose for all passive elements and derive the voltage transfer function.
2. For your design, create a PSPICE plot that shows the frequency response for your circuit. Use an AC sweep with a logarithmic X-axis, frequency response from 1 Hz to 100 kHz, and 10 points per decade.

High Pass Passive Filter:

1. Design a high-pass passive circuit with a single pole that has a cutoff frequency at 20 kHz. Use only capacitors and resistors. For your design, show the values you choose for all passive elements and derive the voltage transfer function.
2. For your design, create a PSPICE plot that shows the frequency response for your circuit. Use an AC sweep with a logarithmic X-axis, frequency response from 1 Hz to 100 kHz, and 10 points per decade.

Band Pass Passive Filter:

1. Design a band-pass passive circuit with a center frequency at 20 kHz and Q of 0.71. Use only capacitors and resistors. For your design, show the values you choose for all passive elements and derive the voltage transfer function.
2. For your design, create a PSPICE plot that shows the frequency response for your circuit. Use an AC sweep with a logarithmic X-axis, frequency response from 1 Hz to 100 kHz, and 10 points per decade.

Low Pass Active Filter:

1. Design a low-pass active filter circuit that has a cutoff frequency at 20 kHz. For your design, show the values you choose for all passive elements and compute the gain at the cutoff frequency.
2. For your design, create a PSPICE plot that shows the frequency response for your circuit. Use an AC sweep with a logarithmic X-axis, frequency response from 1 Hz to 100 kHz, and 10 points per decade.

High Pass Active Filter:

1. Design a high-pass active filter circuit that has a cutoff frequency at 20 kHz. For your design, show the values you choose for all passive elements and compute the gain at the cutoff frequency.
2. For your design, create a PSPICE plot that shows the frequency response for your circuit. Use an AC sweep with a logarithmic X-axis, frequency response from 1 Hz to 100 kHz, and 10 points per decade.

Band Pass Active Filter:

1. Design a high-pass active filter circuit center frequency at 20 kHz and Q of 0.71. For your design, show the values you choose for all passive elements and compute the gain at the center frequency.
2. For your design, create a PSPICE plot that shows the frequency response for your circuit. Use an AC sweep with a logarithmic X-axis, frequency response from 1 Hz to 100 kHz, and 10 points per decade.

PROCEDURE²

Low Pass, High Pass, and Band Pass Passive Filters:

1. Construct circuits that implement your designs for the passive filters.
2. For each of your circuits, measure and plot the voltage gain (V_{out}/V_{in}). Also, measure the phase shift from the input to the output. For the measurements, keep V_{in} at 5Vp-p from function generator, monitor frequency on freq. counter, and measure V_{out} (p-p) with the oscilloscope. Pay particular attention to the frequency range around cut off. It is important to monitor the input and check/re-adjust to proper 5V p-p at each frequency. Record V_{out} and the phase shift for each value of the frequency you measure. Plot the frequency response of the voltage gain. Also plot the phase shift as a function of frequency.

Low Pass, High Pass, and Band Pass Active Filters:

1. Construct circuits that implement your designs for the active filters.
2. For each of your circuits, measure and plot the voltage gain (V_{out}/V_{in}). Also, measure the phase shift from the input to the output. For the measurements, keep V_{in} at 5Vp-p from function generator, monitor frequency on freq. counter, and measure V_{out} (p-p) with the oscilloscope. Pay particular attention to the frequency range around cut off. It is important to monitor the input and check/re-adjust to proper 5V p-p at each frequency. Record V_{out} and the phase shift for each value of the frequency you measure. Plot the frequency response of the voltage gain. Also plot the phase shift as a function of frequency.

ANALYSIS

1. Compute the cutoff frequencies for all of your circuits, and estimate the rolloff rate for the cutoff frequencies (in dB per decade). In addition, for the Band Pass Filters, compute the Q.
2. For each type of filter (low pass, high pass, band pass), compare the performance of the passive and active filters. Explain which of the two technologies you would choose and why.

² Material in this section were obtained from
<http://www.educatorscorner.com/experiments/html/exp15.shtml>