ACTIVE FILTERS

15

CHAPTER OUTLINE

CHAPTER OBJECTIVES

- Describe and analyze the gain-versus-frequency responses of basic types of filters
- Describe three types of filter response characteristics and other parameters
- Identify and analyze active low-pass filters
- Identify and analyze active high-pass filters
- Analyze basic types of active band-pass filters
- Describe basic types of active band-stop filters
- Discuss two methods for measuring frequency response

KEY TERMS

- Filter
- Low-pass filter
- Pole
- Roll-off
- High-pass filter
- Band-pass filter
- Band-stop filter
- Damping factor

APPLICATION ACTIVITY PREVIEW

RFID stands for Radio Frequency Identification and is a technology that enables the tracking and/or identification of objects. Typically, an RFID system consists of an RF tag containing an IC chip that transmits data about the object, a reader that receives transmitted data from the tag, and a data-processing system that processes and stores the data passed to it by the reader. In this application, you will focus on the RFID reader. RFID systems are used in metering applications such as electronic toll collection, inventory control and tracking, merchandise control, asset tracking and recovery, tracking parts moving through a manufacturing process, and tracking goods in a supply chain.

VISIT THE COMPANION WEBSITE

Study aids and Multisim files for this chapter are available at http://www.pearsonhighered.com/electronics

INTRODUCTION

Power supply filters were introduced in Chapter 2. In this chapter, active filters that are used for signal processing are introduced. Filters are circuits that are capable of passing signals with certain selected frequencies while rejecting signals with other frequencies. This property is called *selectivity.*

Active filters use transistors or op-amps combined with passive *RC*, *RL*, or *RLC* circuits. The active devices provide voltage gain, and the passive circuits provide frequency selectivity. In terms of general response, the four basic categories of active filters are low-pass, high-pass, band-pass, and band-stop. In this chapter, you will study active filters using op-amps and *RC* circuits.

15–1 BASIC FILTER RESPONSES

Filters are usually categorized by the manner in which the output voltage varies with the frequency of the input voltage. The categories of active filters are low-pass, high-pass, band-pass, and band-stop. Each of these general responses are examined.

After completing this section, you should be able to

- **Describe and analyze the gain-versus-frequency responses of basic types of filters**
- Describe low-pass filter response
  - Define *passband* and *critical frequency* ◆ Determine the bandwidth
  - Define *pole* ◆ Explain roll-off rate and define its unit ◆ Calculate the critical frequency
- Describe high-pass filter response
  - Explain how the passband is limited ◆ Calculate the critical frequency
- Describe band-pass filter response
  - Determine the bandwidth ◆ Determine the center frequency ◆ Calculate the quality factor (Q)
- Describe band-stop filter response
  - Determine the bandwidth

Low-Pass Filter Response

A **filter** is a circuit that passes certain frequencies and attenuates or rejects all other frequencies. The **passband** of a filter is the range of frequencies that are allowed to pass through the filter with minimum attenuation (usually defined as less than -3 dB of attenuation). The **critical frequency,** f_c, (also called the *cutoff frequency*) defines the end of the passband and is normally specified at the point where the response drops -3 dB (70.7%) from the passband response. Following the passband is a region called the *transition region* that leads into a region called the *stopband.* There is no precise point between the transition region and the stopband.

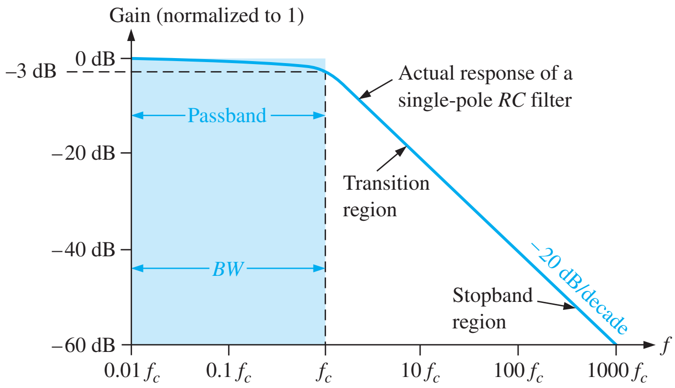
A **low-pass filter** is one that passes frequencies from dc to f_c and significantly attenuates all other frequencies. The passband of the ideal low-pass filter is shown in the blue-shaded area of Figure 15–1(a); the response drops to zero at frequencies beyond the passband. This ideal response is sometimes referred to as a "brick-wall" because nothing gets through beyond the wall. The bandwidth of an ideal low-pass filter is equal to f_c.

Equation 15–1

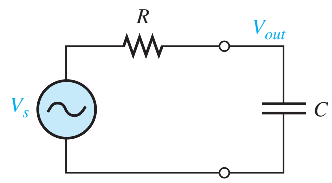
$$BW = f_c$$

The ideal response shown in Figure 15–1(a) is not attainable by any practical filter. Actual filter responses depend on the number of **poles**, a term used with filters to describe the number of RC circuits contained in the filter. The most basic low-pass filter is a simple RC circuit consisting of just one resistor and one capacitor; the output is taken across the capacitor as shown in Figure 15–1(b). This basic RC filter has a single pole, and it rolls off at -20 dB/decade beyond the critical frequency. The actual response is indicated by the blue line in Figure 15–1(a). The response is plotted on a standard log plot that is used for filters to show details of the curve as the gain drops. Notice that the gain drops off slowly until the frequency is at the critical frequency; after this, the gain drops rapidly.

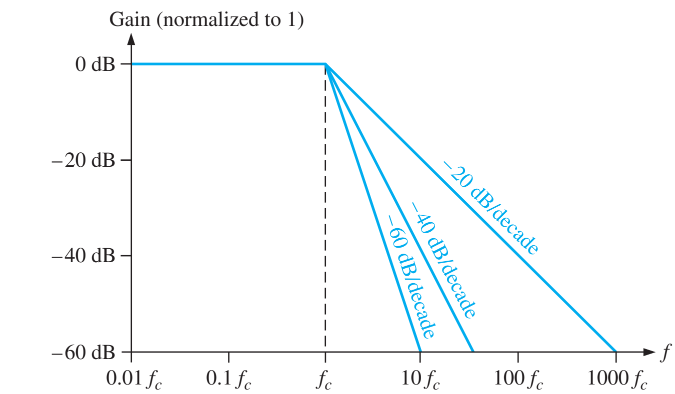
The -20 dB/decade **roll-off** rate for the gain of a basic RC filter means that at a frequency of $10f_c$, the output will be -20 dB (10%) of the input. This roll-off rate is not a particularly good filter characteristic because too much of the unwanted frequencies (beyond the passband) are allowed through the filter.



(a) Comparison of an ideal low-pass filter response (blue area) with actual response. Although not shown on log scale, response extends down to $f_c = 0$.



(b) Basic low-pass circuit



(c) Idealized low-pass filter responses

▲ **FIGURE 15–1**

Low-pass filter responses.

The critical frequency of a low-pass *RC* filter occurs when $X_C = R$, where

$$f_c = \frac{1}{2\pi RC}$$

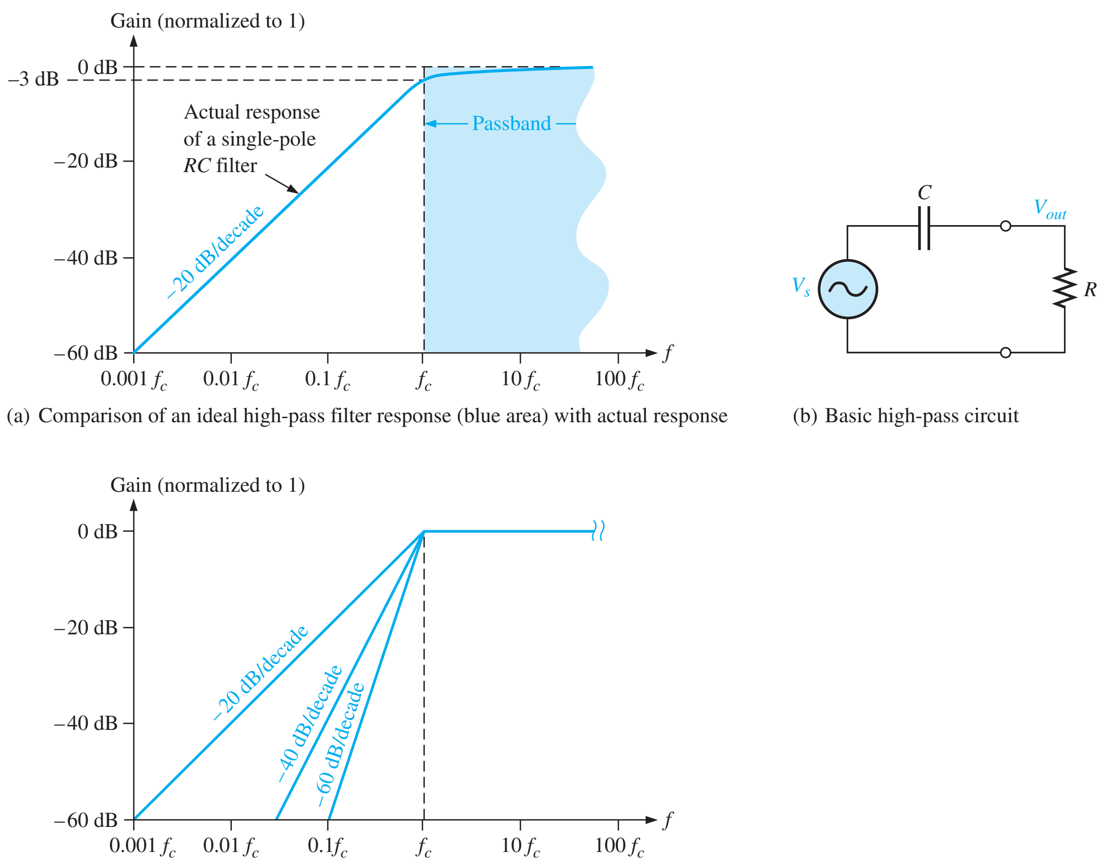
Recall from your basic dc/ac studies that the output at the critical frequency is 70.7% of the input. This response is equivalent to an attenuation of −3 dB.

Figure 15–1(c) illustrates three idealized low-pass response curves including the basic one-pole response (−20 dB/decade). The approximations show a flat response to the cutoff frequency and a roll-off at a constant rate after the cutoff frequency. Actual filters do not have a perfectly flat response up to the cutoff frequency but drop to −3 dB at this point as described previously.

In order to produce a filter that has a steeper transition region (and hence form a more effective filter), it is necessary to add additional circuitry to the basic filter. Responses that are steeper than −20 dB/decade in the transition region cannot be obtained by simply cascading identical *RC* stages (due to loading effects). However, by combining an op-amp with frequency-selective feedback circuits, filters can be designed with roll-off rates of −40, −60, or more dB/decade. Filters that include one or more op-amps in the design are called **active filters.** These filters can optimize the roll-off rate or other attribute (such as phase response) with a particular filter design. In general, the more poles the filter uses, the steeper its transition region will be. The exact response depends on the type of filter and the number of poles.

High-Pass Filter Response

A **high-pass filter** is one that significantly attenuates or rejects all frequencies below f_c and passes all frequencies above f_c. The critical frequency is, again, the frequency at which the output is 70.7% of the input (or -3 dB) as shown in Figure 15–2(a). The ideal response, indicated by the blue-shaded area, has an instantaneous drop at f_c, which, of course, is not achievable. Ideally, the passband of a high-pass filter is all frequencies above the critical frequency. The high-frequency response of practical circuits is limited by the op-amp or other components that make up the filter.



(a) Comparison of an ideal high-pass filter response (blue area) with actual response

(b) Basic high-pass circuit

(c) Idealized high-pass filter responses

▲ **FIGURE 15–2**

High-pass filter responses.

A simple *RC* circuit consisting of a single resistor and capacitor can be configured as a high-pass filter by taking the output across the resistor as shown in Figure 15–2(b). As in the case of the low-pass filter, the basic *RC* circuit has a roll-off rate of -20 dB/decade, as indicated by the blue line in Figure 15–2(a). Also, the critical frequency for the basic high-pass filter occurs when $X_C = R$, where

$$f_c = \frac{1}{2\pi RC}$$

Figure 15–2(c) illustrates three idealized high-pass response curves including the basic one-pole response (-20 dB/decade) for a high-pass *RC* circuit. As in the case of the low-pass filter, the approximations show a flat response to the cutoff frequency and a roll-off at a constant rate after the cutoff frequency. Actual high-pass filters do not have the perfectly flat response indicated or the precise roll-off rate shown. Responses that are steeper than -20 dB/decade in the transition region are also possible with active high-pass filters; the particular response depends on the type of filter and the number of poles.

Band-Pass Filter Response

A **band-pass filter** passes all signals lying within a band between a lower-frequency limit and an upper-frequency limit and essentially rejects all other frequencies that are outside this specified band. A generalized band-pass response curve is shown in Figure 15–3. The bandwidth (*BW*) is defined as the difference between the upper critical frequency (f_{c2}) and the lower critical frequency (f_{c1}).

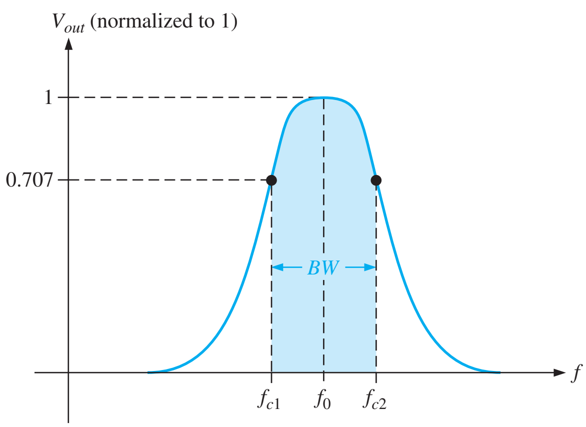
$$BW = f_{c2} - f_{c1}$$

Equation 15–2

The critical frequencies are, of course, the points at which the response curve is 70.7% of its maximum. Recall from Chapter 12 that these critical frequencies are also called *3 dB frequencies.* The frequency about which the passband is centered is called the *center frequency,* f_0, defined as the geometric mean of the critical frequencies.

$$f_0 = \sqrt{f_{c1}f_{c2}}$$

Equation 15–3



▲ FIGURE 15–3

General band-pass response curve.

Quality Factor The **quality factor (*Q*)** of a band-pass filter is the ratio of the center frequency to the bandwidth.

$$Q = \frac{f_0}{BW}$$

Equation 15–4

The value of Q is an indication of the selectivity of a band-pass filter. The higher the value of Q, the narrower the bandwidth and the better the selectivity for a given value of f_0. Band-pass filters are sometimes classified as narrow-band ($Q > 10$) or wide-band ($Q < 10$). The quality factor (Q) can also be expressed in terms of the damping factor (DF) of the filter as

$$Q = \frac{1}{DF}$$

You will study the damping factor in Section 15–2.

EXAMPLE 15–1

A certain band-pass filter has a center frequency of 15 kHz and a bandwidth of 1 kHz. Determine Q and classify the filter as narrow-band or wide-band.

Solution

$$Q = \frac{f_0}{BW} = \frac{15\text{ kHz}}{1\text{ kHz}} = \mathbf{15}$$

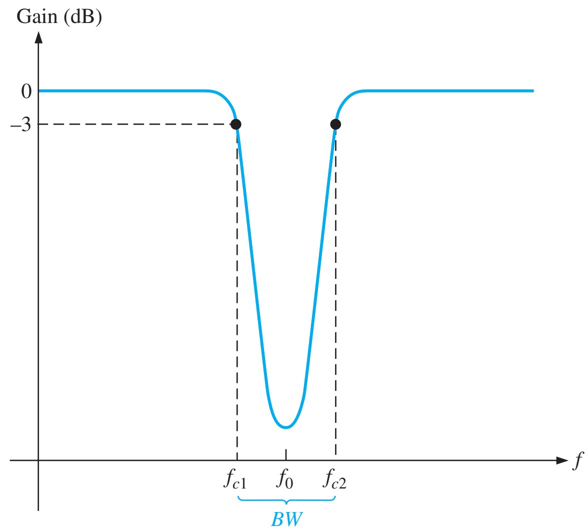
Because $Q > 10$, this is a narrow-band filter.

*Related Problem** If the quality factor of the filter is doubled, what will the bandwidth be?

*Answers can be found at www.pearsonhighered.com/floyd.

Band-Stop Filter Response

Another category of active filter is the **band-stop filter**, also known as *notch, band-reject,* or *band-elimination* filter. You can think of the operation as opposite to that of the band-pass filter because frequencies within a certain bandwidth are rejected, and frequencies outside the bandwidth are passed. A general response curve for a band-stop filter is shown in Figure 15–4. Notice that the bandwidth is the band of frequencies between the 3 dB points, just as in the case of the band-pass filter response.



▶ **FIGURE 15–4**

General band-stop filter response.

SECTION 15–1 CHECKUP
Answers can be found at www.pearsonhighered.com/floyd.

1. What determines the bandwidth of a low-pass filter?
2. What limits the passband of an active high-pass filter?
3. How are the Q and the bandwidth of a band-pass filter related? Explain how the selectivity is affected by the Q of a filter.

15–2 FILTER RESPONSE CHARACTERISTICS

Each type of filter response (low-pass, high-pass, band-pass, or band-stop) can be tailored by circuit component values to have either a Butterworth, Chebyshev, or Bessel characteristic. Each of these characteristics is identified by the shape of the response curve, and each has an advantage in certain applications.

After completing this section, you should be able to

- **Describe three types of filter response characteristics and other parameters**
- Discuss the Butterworth characteristic
- Describe the Chebyshev characteristic
- Discuss the Bessel characteristic
- Define *damping factor*
  - Calculate the damping factor
  - Show the block diagram of an active filter
- Analyze a filter for critical frequency and roll-off rate
  - Explain how to obtain multi-order filters
  - Describe the effects of cascading on roll-off rate

Butterworth, Chebyshev, or Bessel response characteristics can be realized with most active filter circuit configurations by proper selection of certain component values. A general comparison of the three response characteristics for a low-pass filter response curve is shown in Figure 15–5. High-pass and band-pass filters can also be designed to have any one of the characteristics.

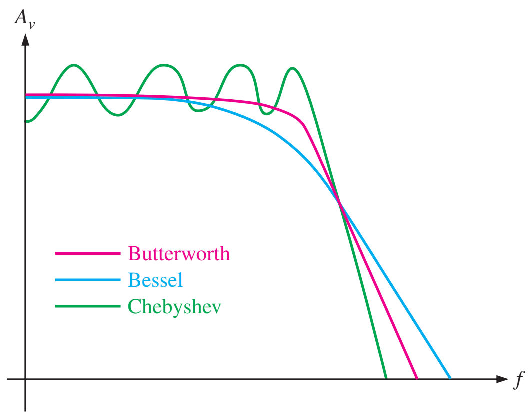


FIGURE 15–5

Comparative plots of three types of filter response characteristics.

The Butterworth Characteristic The **Butterworth** characteristic provides a very flat amplitude response in the passband and a roll-off rate of −20 dB/decade/pole. The phase response is not linear, however, and the phase shift (thus, time delay) of signals passing through the filter varies nonlinearly with frequency. Therefore, a pulse applied to a filter with a Butterworth response will cause overshoots on the output because each frequency component of the pulse's rising and falling edges experiences a different time delay. Filters with the Butterworth response are normally used when all frequencies in the passband must have the same gain. The Butterworth response is often referred to as a maximally flat response.

The Chebyshev Characteristic Filters with the **Chebyshev** response characteristic are useful when a rapid roll-off is required because it provides a roll-off rate greater than −20 dB/decade/pole. This is a greater rate than that of the Butterworth, so filters can be implemented with the Chebyshev response with fewer poles and less complex circuitry for a given roll-off rate. This type of filter response is characterized by overshoot or ripples in the passband (depending on the number of poles) and an even less linear phase response than the Butterworth.

The Bessel Characteristic The **Bessel** response exhibits a linear phase characteristic, meaning that the phase shift increases linearly with frequency. The result is almost no overshoot on the output with a pulse input. For this reason, filters with the Bessel response are used for filtering pulse waveforms without distorting the shape of the waveform.

The Damping Factor

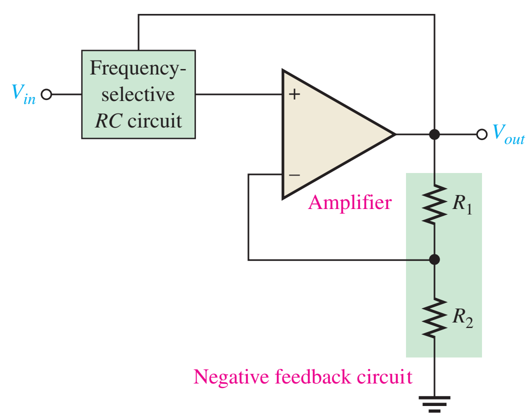
As mentioned, an active filter can be designed to have either a Butterworth, Chebyshev, or Bessel response characteristic regardless of whether it is a low-pass, high-pass, band-pass, or band-stop type. The **damping factor (*DF*)** of an active filter circuit determines which response characteristic the filter exhibits. To explain the basic concept, a generalized active filter is shown in Figure 15–6. It includes an amplifier, a negative feedback circuit, and a filter section. The amplifier and feedback are connected in a noninverting configuration. The damping factor is determined by the negative feedback circuit and is defined by the following equation:

Equation 15–5

$$DF = 2 - \frac{R_1}{R_2}$$

▶ FIGURE 15–6

General diagram of an active filter.



Basically, the damping factor affects the filter response by negative feedback action. Any attempted increase or decrease in the output voltage is offset by the opposing effect of the negative feedback. This tends to make the response curve flat in the passband of the filter if the value for the damping factor is precisely set. By advanced mathematics, which we will not cover, values for the damping factor have been derived for various orders of filters to achieve the maximally flat response of the Butterworth characteristic.

The value of the damping factor required to produce a desired response characteristic depends on the **order** (number of poles) of the filter. A *pole,* for our purposes, is simply a circuit with one resistor and one capacitor. The more poles a filter has, the faster its roll-off rate is. To achieve a second-order Butterworth response, for example, the damping factor must be 1.414. To implement this damping factor, the feedback resistor ratio must be

$$\frac{R_1}{R_2} = 2 - DF = 2 - 1.414 = 0.586$$

This ratio gives the closed-loop gain of the noninverting amplifier portion of the filter, $A_{cl(\mathrm{NI})}$, a value of 1.586, derived as follows:

$$A_{cl(\mathrm{NI})} = \frac{1}{B} = \frac{1}{R_2/(R_1 + R_2)} = \frac{R_1 + R_2}{R_2} = \frac{R_1}{R_2} + 1 = 0.586 + 1 = 1.586$$

EXAMPLE 15–2

If resistor R_2 in the feedback circuit of an active single-pole filter of the type in Figure 15–6 is 10 kΩ, what value must R_1 be to obtain a maximally flat Butterworth response?

Solution

$$\frac{R_1}{R_2} = 0.586$$

$$R_1 = 0.586R_2 = 0.586(10\text{ k}\Omega) = \mathbf{5.86\text{ k}\Omega}$$

Using the nearest standard 5 percent value of 5.6 kΩ will get very close to the ideal Butterworth response.

Related Problem

What is the damping factor for $R_2 = 10\text{ k}\Omega$ and $R_1 = 5.6\text{ k}\Omega$?

Critical Frequency and Roll-Off Rate

The critical frequency is determined by the values of the resistors and capacitors in the frequency-selective *RC* circuit shown in Figure 15–6. For a single-pole (first-order) filter, as shown in Figure 15–7, the critical frequency is

$$f_c = \frac{1}{2\pi RC}$$

Although we show a low-pass configuration, the same formula is used for the f_c of a single-pole high-pass filter. The number of poles determines the roll-off rate of the filter. A Butterworth response produces −20 dB/decade/pole. So, a first-order (one-pole) filter has a roll-off of −20 dB/decade; a second-order (two-pole) filter has a roll-off rate of −40 dB/decade; a third-order (three-pole) filter has a roll-off rate of −60 dB/decade; and so on.

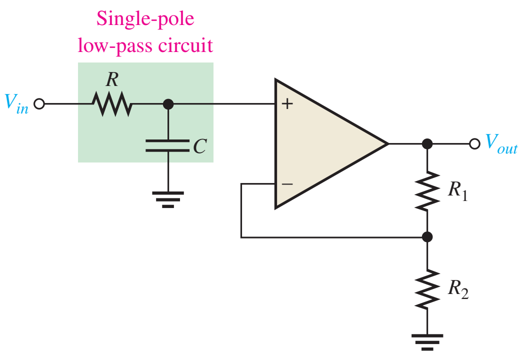
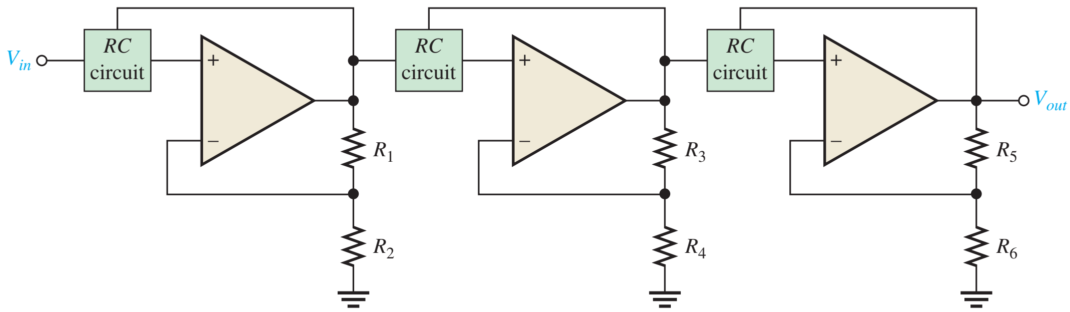


FIGURE 15–7

First-order (one-pole) low-pass filter.

Generally, to obtain a filter with three poles or more, one-pole or two-pole filters are cascaded, as shown in Figure 15–8. To obtain a third-order filter, for example, cascade a second-order and a first-order filter; to obtain a fourth-order filter, cascade two second-order filters; and so on. Each filter in a cascaded arrangement is called a *stage* or *section*.

Because of its maximally flat response, the Butterworth characteristic is the most widely used. Therefore, we will limit our coverage to the Butterworth response to illustrate basic filter concepts. Table 15–1 lists the roll-off rates, damping factors, and feedback resistor ratios for up to sixth-order Butterworth filters. Resistor designations correspond to the gain-setting resistors in Figure 15–8 and may be different on other circuit diagrams.



▲ FIGURE 15–8

The number of filter poles can be increased by cascading.

▼ TABLE 15–1

Values for the Butterworth response.

		1ST STAGE			2ND STAGE			3RD STAGE		
ORDER	ROLL-OFF DB/DECADE	POLES	DF	R_1/R_2	POLES	DF	R_3/R_4	POLES	DF	R_5/R_6
1	−20	1	Optional							
2	−40	2	1.414	0.586						
3	−60	2	1.00	1	1	1.00	1			
4	−80	2	1.848	0.152	2	0.765	1.235			
5	−100	2	1.00	1	2	1.618	0.382	1	0.618	1.382
6	−120	2	1.932	0.068	2	1.414	0.586	2	0.518	1.482

SECTION 15–2 CHECKUP

1. Explain how Butterworth, Chebyshev, and Bessel responses differ.
2. What determines the response characteristic of a filter?
3. Name the basic parts of an active filter.

15–3 ACTIVE LOW-PASS FILTERS

Filters that use op-amps as the active element provide several advantages over passive filters (*R*, *L*, and *C* elements only). The op-amp provides gain, so the signal is not attenuated as it passes through the filter. The high input impedance of the op-amp prevents excessive loading of the driving source, and the low output impedance of the op-amp prevents the filter from being affected by the load that it is driving. Active filters are also easy to adjust over a wide frequency range without altering the desired response.

After completing this section, you should be able to

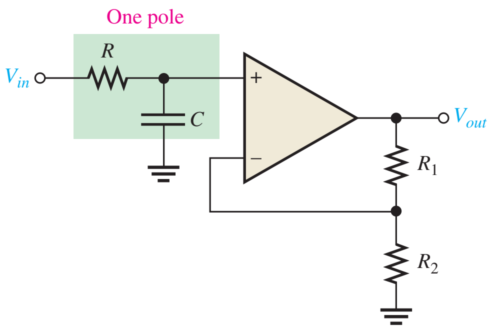
- **Identify and analyze active low-pass filters**
- Identify a single-pole low-pass filter circuit
  - Determine the closed-loop voltage gain
  - Determine the critical frequency
- Identify a Sallen-Key low-pass filter circuit
  - Describe the filter operation
  - Calculate the critical frequency
- Analyze cascaded low-pass filters
  - Explain how the roll-off rate is affected

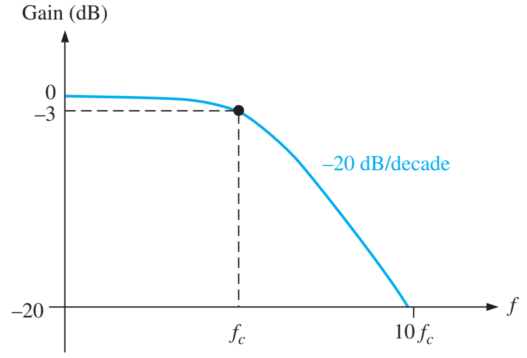
A Single-Pole Filter

Figure 15–9(a) shows an active filter with a single low-pass *RC* frequency-selective circuit that provides a roll-off of −20 dB/decade above the critical frequency, as indicated by the response curve in Figure 15–9(b). The critical frequency of the single-pole filter is $f_c = 1/(2\pi RC)$. The op-amp in this filter is connected as a noninverting amplifier with the closed-loop voltage gain in the passband set by the values of R_1 and R_2.

Equation 15–6

$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$





▲ FIGURE 15–9

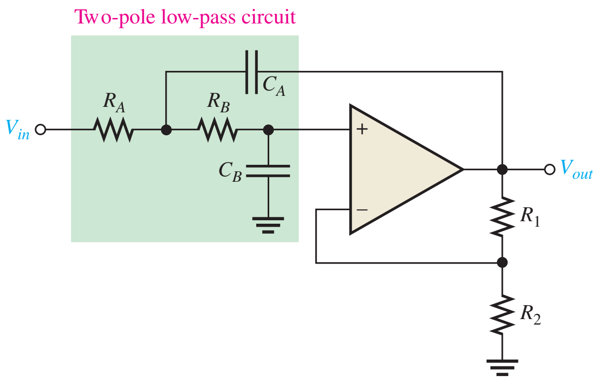
Single-pole active low-pass filter and response curve.

The Sallen-Key Low-Pass Filter

The Sallen-Key is one of the most common configurations for a second-order (two-pole) filter. It is also known as a VCVS (voltage-controlled voltage source) filter. A low-pass version of the Sallen-Key filter is shown in Figure 15–10. Notice that there are two low-pass *RC* circuits that provide a roll-off of −40 dB/decade above the critical frequency (assuming a Butterworth characteristic). One *RC* circuit consists of R_A and C_A, and the second circuit consists of R_B and C_B. A unique feature of the Sallen-Key low-pass filter is the capacitor C_A that provides feedback for shaping the response near the edge of the passband. The critical frequency for the Sallen-Key filter is

Equation 15–7

$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$



◀ FIGURE 15–10

Basic Sallen-Key low-pass filter.

The component values can be made equal so that $R_A = R_B = R$ and $C_A = C_B = C$. In this case, the expression for the critical frequency simplifies to

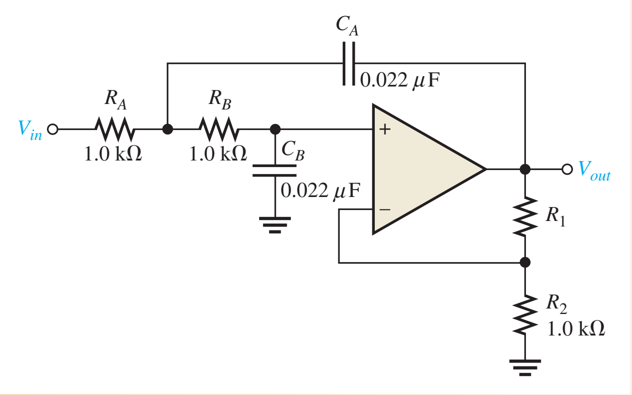
$$f_c = \frac{1}{2\pi RC}$$

As in the single-pole filter, the op-amp in the second-order Sallen-Key filter acts as a noninverting amplifier with the negative feedback provided by resistors R_1 and R_2. As you have learned, the damping factor is set by the values of R_1 and R_2, thus making the filter response either Butterworth, Chebyshev, or Bessel. For example, from Table 15–1, the R_1/R_2 ratio must be 0.586 to produce the damping factor of 1.414 required for a second-order Butterworth response.

EXAMPLE 15–3

Determine the critical frequency of the Sallen-Key low-pass filter in Figure 15–11, and set the value of R_1 for an approximate Butterworth response.

▶ FIGURE 15–11



Solution Since $R_A = R_B = R = 1.0\text{ k}\Omega$ and $C_A = C_B = C = 0.022\ \mu\text{F}$,

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(1.0\text{ k}\Omega)(0.022\ \mu\text{F})} = \mathbf{7.23\ kHz}$$

For a Butterworth response, $R_1/R_2 = 0.586$.

$$R_1 = 0.586R_2 = 0.586(1.0\text{ k}\Omega) = \mathbf{586\ \Omega}$$

Select a standard value as near as possible to this calculated value.

Related Problem Determine f_c for Figure 15–11 if $R_A = R_B = R_2 = 2.2\text{ k}\Omega$ and $C_A = C_B = 0.01\ \mu\text{F}$. Also determine the value of R_1 for a Butterworth response.

Open the Multisim file E15-03 in the Examples folder on the companion website. Determine the critical frequency and compare with the calculated value.

Cascaded Low-Pass Filters

A three-pole filter is required to get a third-order low-pass response (−60 dB/decade). This is done by cascading a two-pole Sallen-Key low-pass filter and a single-pole low-pass filter, as shown in Figure 15–12(a). Figure 15–12(b) shows a four-pole configuration obtained by cascading two Sallen-Key (2-pole) low-pass filters. In general, a four-pole filter is preferred because it uses the same number of op-amps to achieve a faster roll-off.

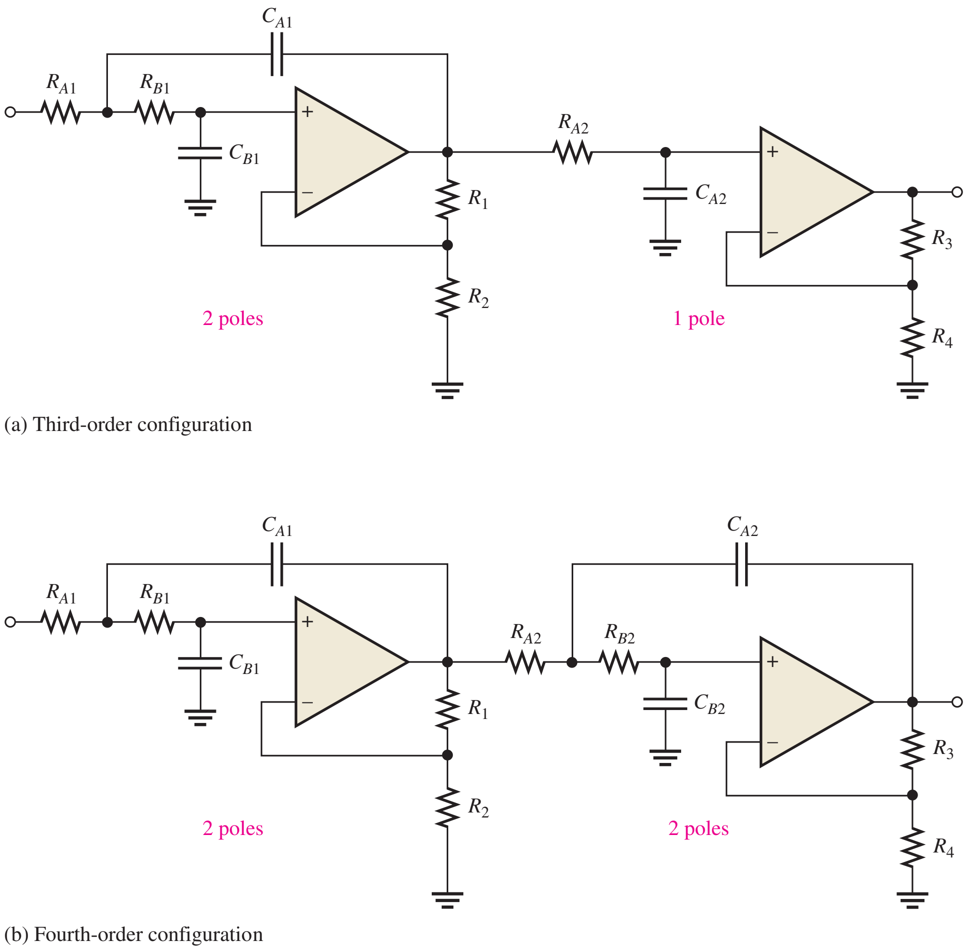


FIGURE 15–12

Cascaded low-pass filters.

EXAMPLE 15–4

For the four-pole filter in Figure 15–12(b), determine the capacitance values required to produce a critical frequency of 2680 Hz if all the resistors in the *RC* low-pass circuits are 1.8 kΩ. Also select values for the feedback resistors to get a Butterworth response.

Solution Both stages must have the same f_c. Assuming equal-value capacitors,

$$f_c = \frac{1}{2\pi RC}$$

$$C = \frac{1}{2\pi R f_c} = \frac{1}{2\pi(1.8\text{ k}\Omega)(2680\text{ Hz})} = 0.033\ \mu\text{F}$$

$$C_{A1} = C_{B1} = C_{A2} = C_{B2} = \mathbf{0.033\ \mu F}$$

Also select $R_2 = R_4 = 1.8\text{ k}\Omega$ for simplicity. Refer to Table 15–1. For a Butterworth response in the first stage, $DF = 1.848$ and $R_1/R_2 = 0.152$. Therefore,

$$R_1 = 0.152R_2 = 0.152(1800\ \Omega) = \mathbf{274\ \Omega}$$

Choose $R_1 = 270\ \Omega$.

In the second stage, $DF = 0.765$ and $R_3/R_4 = 1.235$. Therefore,

$$R_3 = 1.235R_4 = 1.235(1800\ \Omega) = \mathbf{2.22\ k\Omega}$$

Choose $R_3 = 2.2\text{ k}\Omega$.

Related Problem For the filter in Figure 15–12(b), determine the capacitance values for $f_c = 1\text{ kHz}$ if all the filter resistors are 680 Ω. Also specify the values for the feedback resistors to produce a Butterworth response.

SECTION 15–3 CHECKUP

1. How many poles does a second-order low-pass filter have? How many resistors and how many capacitors are used in the frequency-selective circuit?
2. Why is the damping factor of a filter important?
3. What is the primary purpose of cascading low-pass filters?

15–4 ACTIVE HIGH-PASS FILTERS

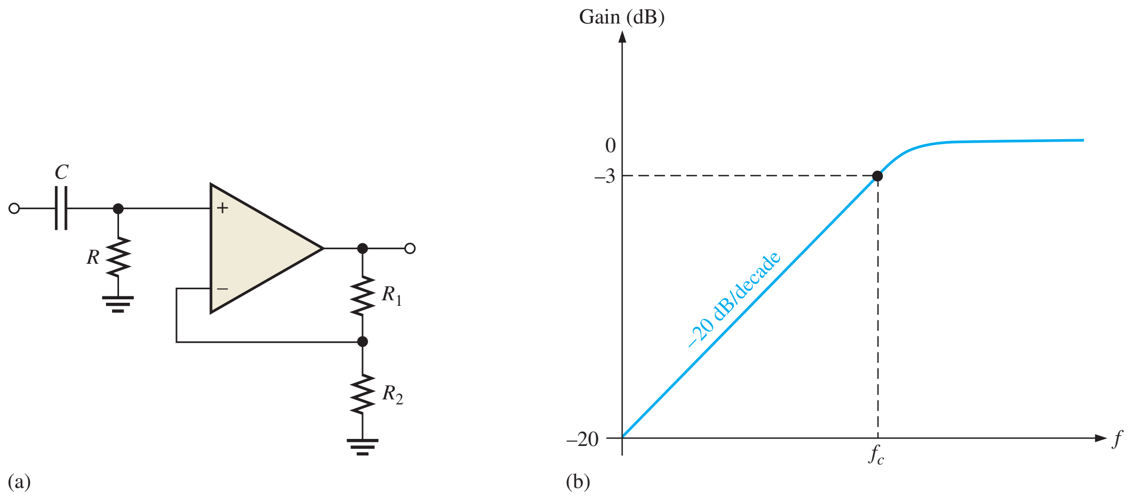
In high-pass filters, the roles of the capacitor and resistor are reversed in the *RC* circuits. Otherwise, the basic parameters are the same as for the low-pass filters.

After completing this section, you should be able to

- **Identify and analyze active high-pass filters**
- Identify a single-pole high-pass filter circuit
  - Explain limitations at higher pass-band frequencies
- Identify a Sallen-Key high-pass filter circuit
  - Describe the filter operation ◆ Calculate component values
- Discuss cascaded high-pass filters
  - Describe a six-pole filter

A Single-Pole Filter

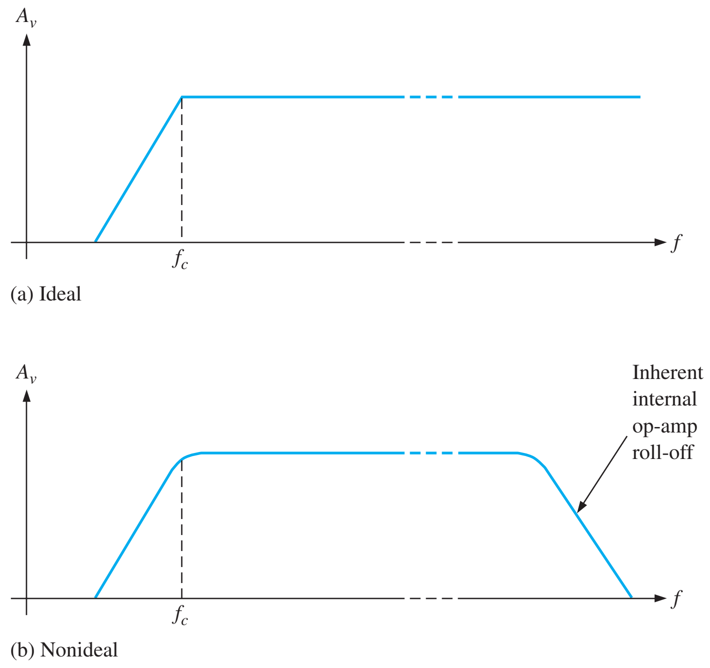
A high-pass active filter with a −20 dB/decade roll-off is shown in Figure 15–13(a). Notice that the input circuit is a single high-pass *RC* circuit. The negative feedback circuit is the same as for the low-pass filters previously discussed. The high-pass response curve is shown in Figure 15–13(b).



▲ FIGURE 15–13

Single-pole active high-pass filter and response curve.

Ideally, a high-pass filter passes all frequencies above f_c without limit, as indicated in Figure 15–14(a), although in practice, this is not the case. As you have learned, all op-amps inherently have internal *RC* circuits that limit the amplifier's response at high frequencies.



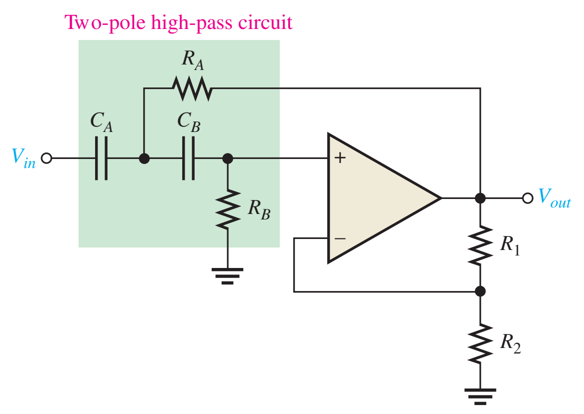
▲ FIGURE 15–14

High-pass filter response.

Therefore, there is an upper-frequency limit on the high-pass filter's response which, in effect, makes it a band-pass filter with a very wide bandwidth. In the majority of applications, the internal high-frequency limitation is so much greater than that of the filter's critical frequency that the limitation can be neglected. In some applications, discrete transistors are used for the gain element to increase the high-frequency limitation beyond that realizable with available op-amps.

The Sallen-Key High-Pass Filter

A high-pass Sallen-Key configuration is shown in Figure 15–15. The components R_A, C_A, R_B, and C_B form the two-pole frequency-selective circuit. Notice that the positions of the resistors and capacitors in the frequency-selective circuit are opposite to those in the low-pass configuration. As with the other filters, the response characteristic can be optimized by proper selection of the feedback resistors, R_1 and R_2.



◀ FIGURE 15–15

Basic Sallen-Key high-pass filter.

EXAMPLE 15–5

Choose values for the Sallen-Key high-pass filter in Figure 15–15 to implement an equal-value second-order Butterworth response with a critical frequency of approximately 10 kHz.

Solution Start by selecting a value for R_A and R_B (R_1 or R_2 can also be the same value as R_A and R_B for simplicity).

$$R = R_A = R_B = R_2 = \mathbf{3.3\,k\Omega} \text{ (an arbitrary selection)}$$

Next, calculate the capacitance value from $f_c = 1/(2\pi RC)$.

$$C = C_A = C_B = \frac{1}{2\pi Rf_c} = \frac{1}{2\pi(3.3\,\text{k}\Omega)(10\,\text{kHz})} = \mathbf{0.0048\,\mu F}$$

For a Butterworth response, the damping factor must be 1.414 and $R_1/R_2 = 0.586$.

$$R_1 = 0.586R_2 = 0.586(3.3\,\text{k}\Omega) = \mathbf{1.93\,k\Omega}$$

If you had chosen $R_1 = 3.3\,\text{k}\Omega$, then

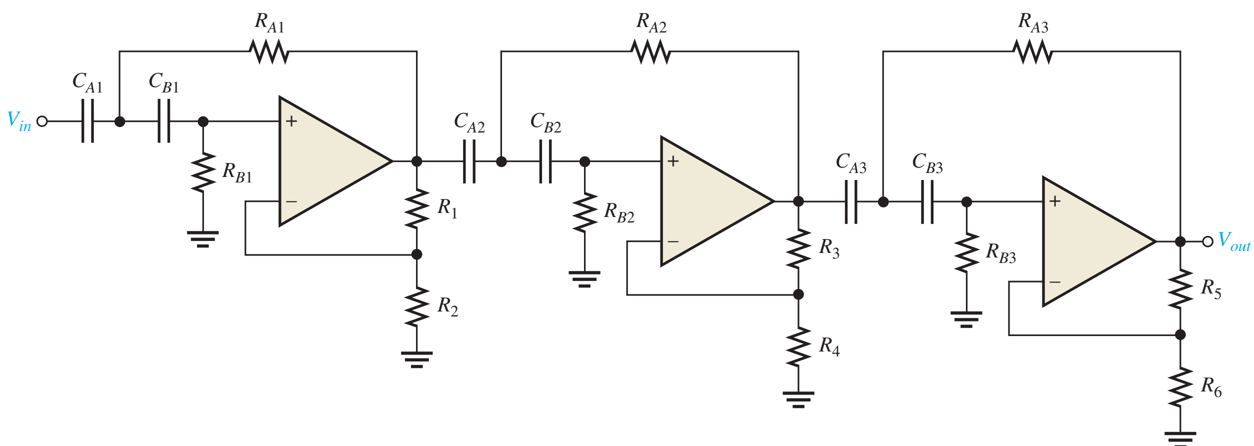
$$R_2 = \frac{R_1}{0.586} = \frac{3.3\,\text{k}\Omega}{0.586} = 5.63\,\text{k}\Omega$$

Either way, an approximate Butterworth response is realized by choosing the nearest standard values.

Related Problem Select values for all the components in the high-pass filter of Figure 15–15 to obtain an $f_c = 300$ Hz. Use equal-value components with $R = 10\,\text{k}\Omega$ and optimize for a Butterworth response.

Cascading High-Pass Filters

As with the low-pass configuration, first- and second-order high-pass filters can be cascaded to provide three or more poles and thereby create faster roll-off rates. Figure 15–16 shows a six-pole high-pass filter consisting of three Sallen-Key two-pole stages. With this configuration optimized for a Butterworth response, a roll-off of −120 dB/decade is achieved.



▲ **FIGURE 15–16**

Sixth-order high-pass filter.

SECTION 15–4 CHECKUP

1. How does a high-pass Sallen-Key filter differ from the low-pass configuration?
2. To increase the critical frequency of a high-pass filter, would you increase or decrease the resistor values?
3. If three two-pole high-pass filters and one single-pole high-pass filter are cascaded, what is the resulting roll-off?

15–5 ACTIVE BAND-PASS FILTERS

As mentioned, band-pass filters pass all frequencies bounded by a lower-frequency limit and an upper-frequency limit and reject all others lying outside this specified band. A band-pass response can be thought of as the overlapping of a low-frequency response curve and a high-frequency response curve.

After completing this section, you should be able to

- **Analyze basic types of active band-pass filters**
- Describe how to cascade low-pass and high-pass filters to create a band-pass filter
  - Calculate the critical frequencies and the center frequency
- Identify and analyze a multiple-feedback band-pass filter
  - Determine the center frequency, quality factor (Q), and bandwidth ◆ Calculate the voltage gain
- Identify and describe the state-variable filter
  - Explain the basic filter operation ◆ Determine the Q
- Identify and discuss the biquad filter

Cascaded Low-Pass and High-Pass Filters

One way to implement a band-pass filter is a cascaded arrangement of a high-pass filter and a low-pass filter, as shown in Figure 15–17(a), as long as the critical frequencies are sufficiently separated. Each of the filters shown is a Sallen-Key Butterworth configuration so that the roll-off rates are -40 dB/decade, indicated in the composite response curve of Figure 15–17(b). The critical frequency of each filter is chosen so that the response curves overlap sufficiently, as indicated. The critical frequency of the high-pass filter must be sufficiently lower than that of the low-pass stage. This filter is generally limited to wide bandwidth applications.

The lower frequency f_{c1} of the passband is the critical frequency of the high-pass filter. The upper frequency f_{c2} is the critical frequency of the low-pass filter. Ideally, as discussed earlier, the center frequency f_0 of the passband is the geometric mean of f_{c1} and f_{c2}. The following formulas express the three frequencies of the band-pass filter in Figure 15–17.

$$f_{c1} = \frac{1}{2\pi\sqrt{R_{A1}R_{B1}C_{A1}C_{B1}}}$$

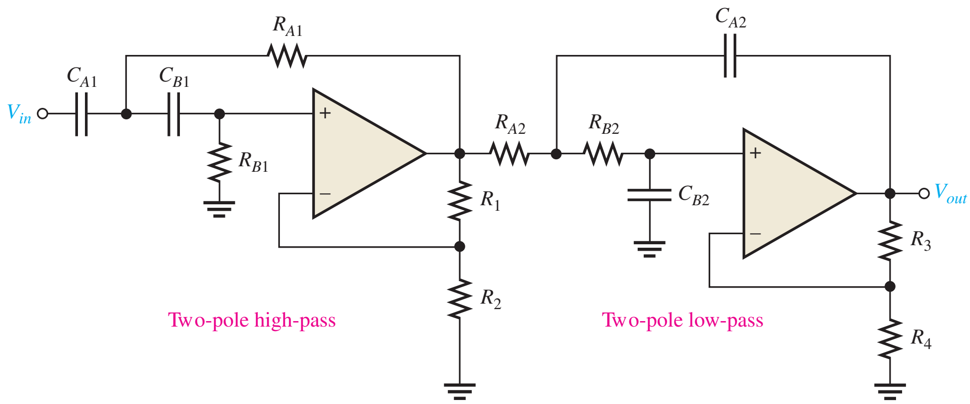
$$f_{c2} = \frac{1}{2\pi\sqrt{R_{A2}R_{B2}C_{A2}C_{B2}}}$$

$$f_0 = \sqrt{f_{c1}f_{c2}}$$

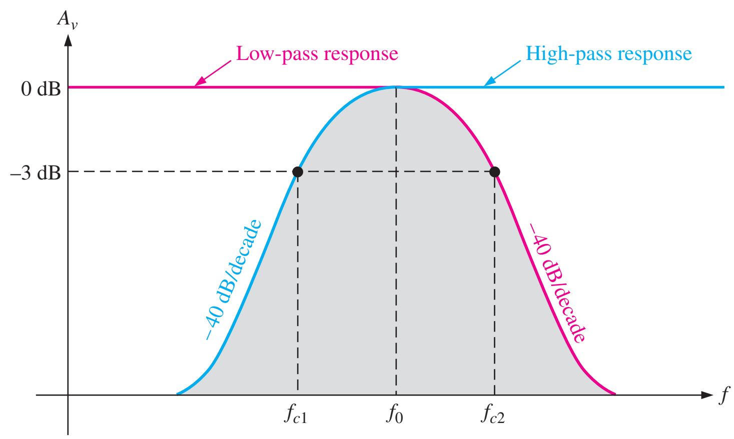
Of course, if equal-value components are used in implementing each filter, the critical frequency equations simplify to the form $f_c = 1/(2\pi RC)$.

▶ FIGURE 15–17

Band-pass filter formed by cascading a two-pole high-pass and a two-pole low-pass filter (it does not matter in which order the filters are cascaded).



(a)



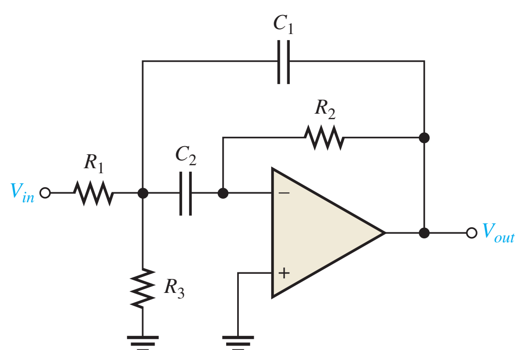
(b)

Multiple-Feedback Band-Pass Filter

Another type of filter configuration, shown in Figure 15–18, is a multiple-feedback band-pass filter. The two feedback paths are through R_2 and C_1. Components R_1 and C_1 provide the low-pass response, and R_2 and C_2 provide the high-pass response. The maximum gain, A_0, occurs at the center frequency. Q values of less than 10 are typical in this type of filter.

▶ FIGURE 15–18

Multiple-feedback band-pass filter.



An expression for the center frequency is developed as follows, recognizing that R_1 and R_3 appear in parallel as viewed from the C_1 feedback path (with the V_{in} source replaced by a short).

$$f_0 = \frac{1}{2\pi\sqrt{(R_1 \| R_3)R_2C_1C_2}}$$

Making $C_1 = C_2 = C$ yields

$$f_0 = \frac{1}{2\pi\sqrt{(R_1 \| R_3)R_2C^2}} = \frac{1}{2\pi C\sqrt{(R_1 \| R_3)R_2}}$$

$$= \frac{1}{2\pi C}\sqrt{\frac{1}{R_2(R_1 \| R_3)}} = \frac{1}{2\pi C}\sqrt{\left(\frac{1}{R_2}\right)\left(\frac{1}{R_1R_3/R_1 + R_3}\right)}$$

$$\mathbf{f_0 = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_3}{R_1R_2R_3}}}$$ **Equation 15–8**

A value for the capacitors is chosen and then the three resistor values are calculated to achieve the desired values for f_0, BW, and A_0. As you know, the Q can be determined from the relation $Q = f_0/BW$. The resistor values can be found using the following formulas (stated without derivation):

$$R_1 = \frac{Q}{2\pi f_0 C A_0}$$

$$R_2 = \frac{Q}{\pi f_0 C}$$

$$R_3 = \frac{Q}{2\pi f_0 C(2Q^2 - A_0)}$$

To develop a gain expression, solve for Q in the R_1 and R_2 formulas as follows:

$$Q = 2\pi f_0 A_0 C R_1$$
$$Q = \pi f_0 C R_2$$

Then,

$$2\pi f_0 A_0 C R_1 = \pi f_0 C R_2$$

Cancelling yields

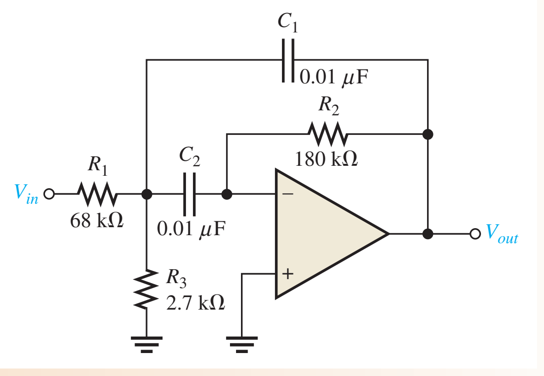
$$2A_0R_1 = R_2$$

$$\mathbf{A_0 = \frac{R_2}{2R_1}}$$ **Equation 15–9**

In order for the denominator of the equation $R_3 = Q/[2\pi f_0 C(2Q^2 - A_0)]$ to be positive, $A_0 < 2Q^2$, which imposes a limitation on the gain.

EXAMPLE 15–6 Determine the center frequency, maximum gain, and bandwidth for the filter in Figure 15–19.

▶ **FIGURE 15–19**



Solution

$$f_0 = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_3}{R_1 R_2 R_3}} = \frac{1}{2\pi(0.01\ \mu\text{F})}\sqrt{\frac{68\ \text{k}\Omega + 2.7\ \text{k}\Omega}{(68\ \text{k}\Omega)(180\ \text{k}\Omega)(2.7\ \text{k}\Omega)}} = \mathbf{736\ Hz}$$

$$A_0 = \frac{R_2}{2R_1} = \frac{180\ \text{k}\Omega}{2(68\ \text{k}\Omega)} = \mathbf{1.32}$$

$$Q = \pi f_0 C R_2 = \pi(736\ \text{Hz})(0.01\ \mu\text{F})(180\ \text{k}\Omega) = 4.16$$

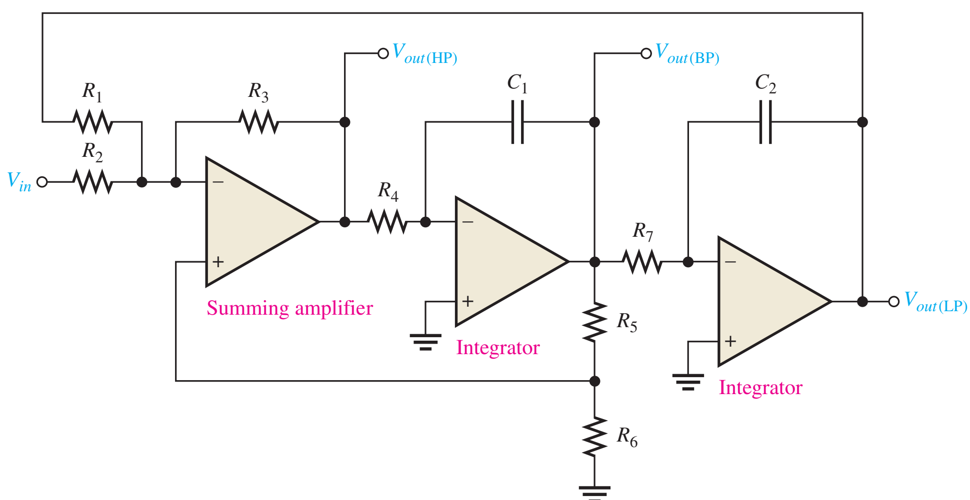
$$BW = \frac{f_0}{Q} = \frac{736\ \text{Hz}}{4.16} = \mathbf{177\ Hz}$$

Related Problem If R_2 in Figure 15–19 is increased to 330 kΩ, determine the gain, center frequency, and bandwidth of the filter?

Open the Multisim file E15-06 in the Examples folder on the companion website. Measure the center frequency and the bandwidth and compare to the calculated values.

State-Variable Filter

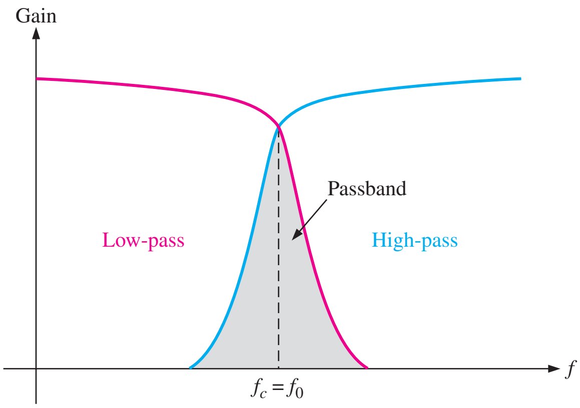
The state-variable or universal active filter is widely used for band-pass applications. As shown in Figure 15–20, it consists of a summing amplifier and two op-amp integrators (which act as single-pole low-pass filters) that are combined in a cascaded arrangement to form a second-order filter. Although used primarily as a band-pass (BP) filter, the state-variable configuration also provides low-pass (LP) and high-pass (HP) outputs. The center frequency is set by the *RC* circuits in both integrators. When used as a band-pass filter, the critical frequencies of the integrators are usually made equal, thus setting the center frequency of the passband.



▶ **FIGURE 15–20**

State-variable filter.

Basic Operation At input frequencies below f_c, the input signal passes through the summing amplifier and integrators and is fed back 180° out of phase. Thus, the feedback signal and input signal cancel for all frequencies below approximately f_c. As the low-pass response of the integrators rolls off, the feedback signal diminishes, thus allowing the input to pass through to the band-pass output. Above f_c, the low-pass response disappears, thus preventing the input signal from passing through the integrators. As a result, the band-pass filter output peaks sharply at f_c, as indicated in Figure 15–21. Stable Qs up to 100 can be obtained with



▲ FIGURE 15–21

General state-variable response curves.

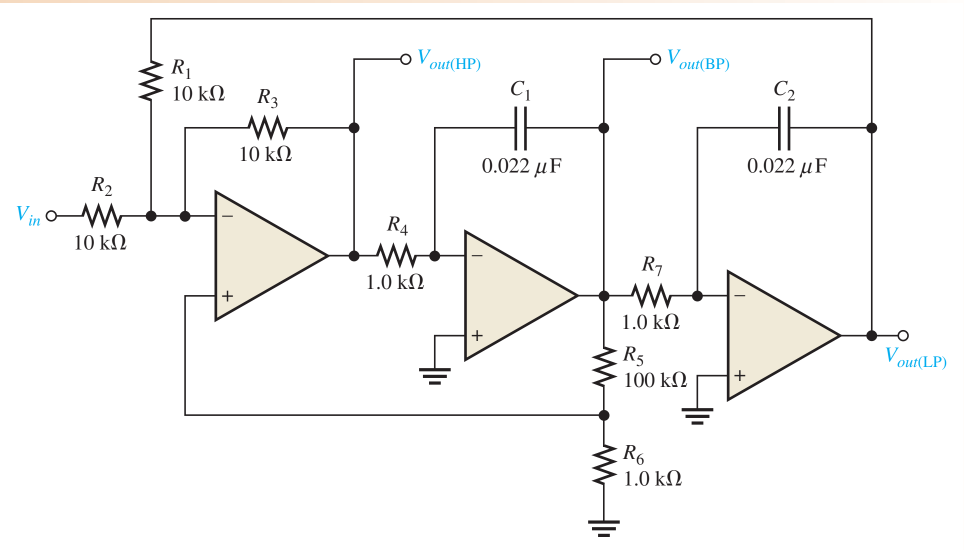
this type of filter. The Q is set by the feedback resistors R_5 and R_6 according to the following equation:

$$Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right)$$

The state-variable filter cannot be optimized for low-pass, high-pass, and narrow band-pass performance simultaneously for this reason: To optimize for a low-pass or a high-pass Butterworth response, DF must equal 1.414. Since $Q = 1/DF$, a Q of 0.707 will result. Such a low Q provides a very wide band-pass response (large BW and poor selectivity). For optimization as a narrow band-pass filter, the Q must be set high.

EXAMPLE 15–7

Determine the center frequency, Q, and BW for the passband of the state-variable filter in Figure 15–22.



▲ FIGURE 15–22

Solution For each integrator,

$$f_c = \frac{1}{2\pi R_4C_1} = \frac{1}{2\pi R_7C_2} = \frac{1}{2\pi(1.0\text{ k}\Omega)(0.022\ \mu\text{F})} = 7.23\text{ kHz}$$

The center frequency is approximately equal to the critical frequencies of the integrators.

$$f_0 = f_c = \mathbf{7.23\ kHz}$$

$$Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right) = \frac{1}{3}\left(\frac{100\text{ k}\Omega}{1.0\text{ k}\Omega} + 1\right) = \mathbf{33.7}$$

$$BW = \frac{f_0}{Q} = \frac{7.23\text{ kHz}}{33.7} = \mathbf{215\ Hz}$$

Related Problem Determine f_0, Q, and BW for the filter in Figure 15–22 if $R_4 = R_6 = R_7 = 330\ \Omega$ with all other component values the same as shown on the schematic.

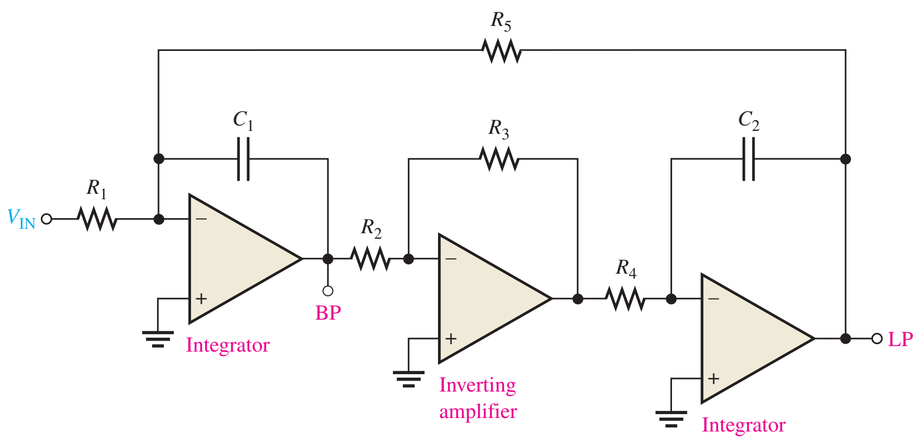
Open the Multisim file E15-07 in the Examples folder on the companion website. Measure the center frequency and the bandwidth and compare to the calculated values.

The Biquad Filter

The biquad filter is similar to the state-variable filter except that it consists of an integrator, followed by an inverting amplifier, and then another integrator, as shown in Figure 15–23. These differences in the configuration between a biquad and a state-variable filter result in some operational differences although both allow a very high Q value. In a biquad filter, the bandwidth is independent and the Q is dependent on the critical frequency; however, in the state-variable filter it is just the opposite: the bandwidth is dependent and the Q is independent on the critical frequency. Also, the biquad filter provides only band-pass and low-pass outputs.

▶ **FIGURE 15–23**

A biquad filter.



SECTION 15–5 CHECKUP

1. What determines selectivity in a band-pass filter?
2. One filter has a $Q = 5$ and another has a $Q = 25$. Which has the narrower bandwidth?
3. List the active elements that make up a state-variable filter.
4. List the active elements that make up a biquad filter.

15–6 ACTIVE BAND-STOP FILTERS

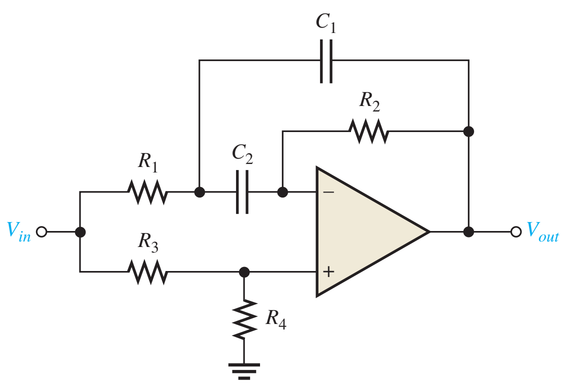
Band-stop filters reject a specified band of frequencies and pass all others. The response is opposite to that of a band-pass filter. Band-stop filters are sometimes referred to as notch filters.

After completing this section, you should be able to

- **Describe basic types of active band-stop filters**
- Identify and describe a multiple-feedback band-stop filter
- Identify and analyze the state-variable filter

Multiple-Feedback Band-Stop Filter

Figure 15–24 shows a multiple-feedback band-stop filter. Notice that this configuration is similar to the band-pass version in Figure 15–18 except that R_3 has been moved and R_4 has been added.

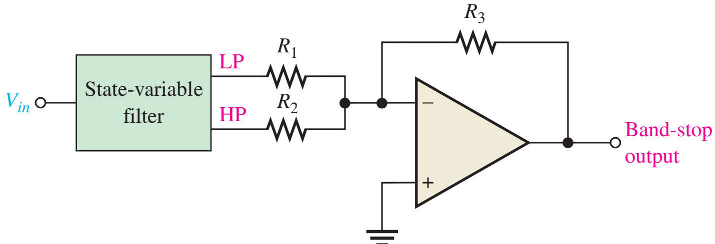


◀ FIGURE 15–24

Multiple-feedback band-stop filter.

State-Variable Band-Stop Filter

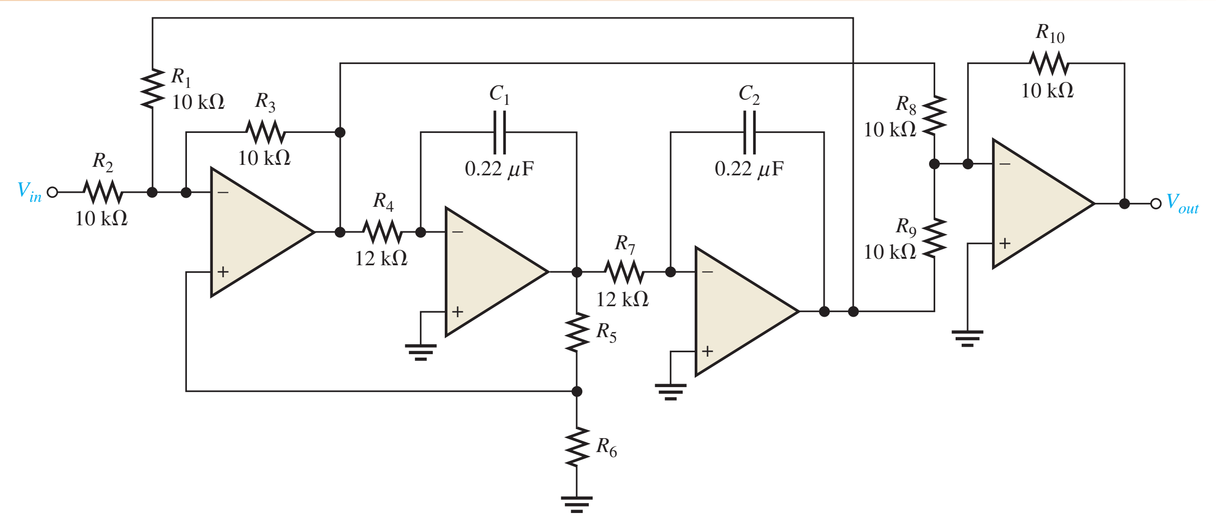
Summing the low-pass and the high-pass responses of the state-variable filter covered in Section 15–5 with a summing amplifier creates a band-stop filter, as shown in Figure 15–25. One important application of this filter is minimizing the 60 Hz "hum" in audio systems by setting the center frequency to 60 Hz.



▲ FIGURE 15–25

State-variable band-stop filter.

EXAMPLE 15–8 Verify that the band-stop filter in Figure 15–26 has a center frequency of 60 Hz, and optimize the filter for a Q of 10.



▲ **FIGURE 15–26**

Solution f_0 equals the f_c of the integrator stages. (In practice, component values are critical.)

$$f_0 = \frac{1}{2\pi R_4 C_1} = \frac{1}{2\pi R_7 C_2} = \frac{1}{2\pi(12\text{ k}\Omega)(0.22\ \mu\text{F})} = \mathbf{60\ Hz}$$

You can obtain a $Q = 10$ by choosing R_6 and then calculating R_5.

$$Q = \frac{1}{3}\left(\frac{R_5}{R_6} + 1\right)$$

$$R_5 = (3Q - 1)R_6$$

Choose $R_6 = \mathbf{3.3\ k\Omega}$. Then

$$R_5 = [3(10) - 1]3.3\text{ k}\Omega = \mathbf{95.7\ k\Omega}$$

Use the nearest standard value of 100 kΩ.

Related Problem How would you change the center frequency to 120 Hz in Figure 15–26?

Open the Multisim file E15-08 in the Examples folder on the companion website and verify that the center frequency is approximately 60 Hz.

SECTION 15–6 CHECKUP

1. How does a band-stop response differ from a band-pass response?
2. How is a state-variable band-pass filter converted to a band-stop filter?

15–7 FILTER RESPONSE MEASUREMENTS

Two methods of determining a filter's response by measurement are discrete point measurement and swept frequency measurement.

After completing this section, you should be able to

- **Discuss two methods for measuring frequency response**
- Explain discrete-point measurement
  - List the steps in the procedure ◆ Show a test setup
- Explain swept frequency measurement
  - Show a test setup for this method using a spectrum analyzer ◆ Show a test setup for this method using an oscilloscope

Discrete Point Measurement

Figure 15–27 shows an arrangement for taking filter output voltage measurements at discrete values of input frequency using common laboratory instruments. The general procedure is as follows:

1. Set the amplitude of the sine wave generator to a desired voltage level.
2. Set the frequency of the sine wave generator to a value well below the expected critical frequency of the filter under test. For a low-pass filter, set the frequency as near as possible to 0 Hz. For a band-pass filter, set the frequency well below the expected lower critical frequency.
3. Increase the frequency in predetermined steps sufficient to allow enough data points for an accurate response curve.
4. Maintain a constant input voltage amplitude while varying the frequency.
5. Record the output voltage at each value of frequency.
6. After recording a sufficient number of points, plot a graph of output voltage versus frequency.

If the frequencies to be measured exceed the frequency response of the DMM, an oscilloscope may have to be used instead.

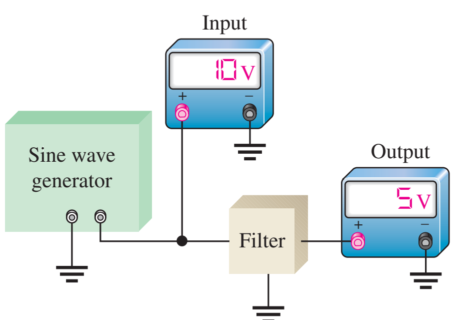
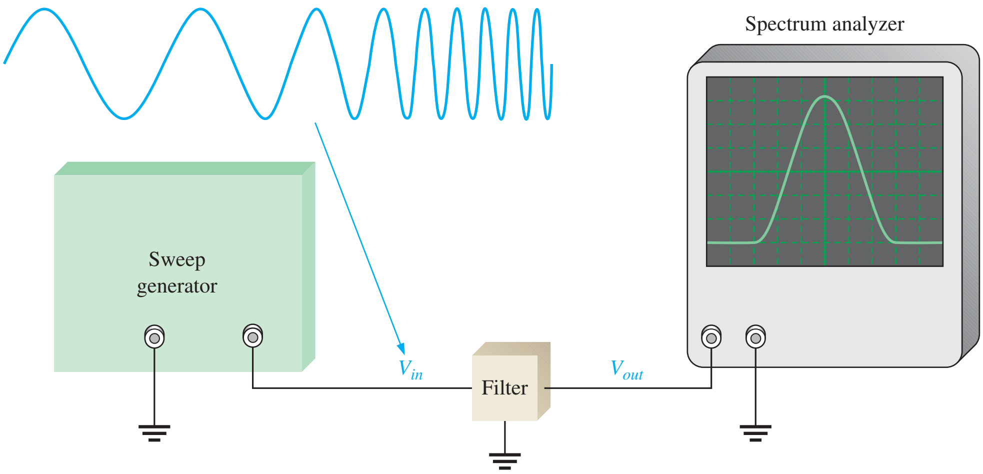


FIGURE 15–27

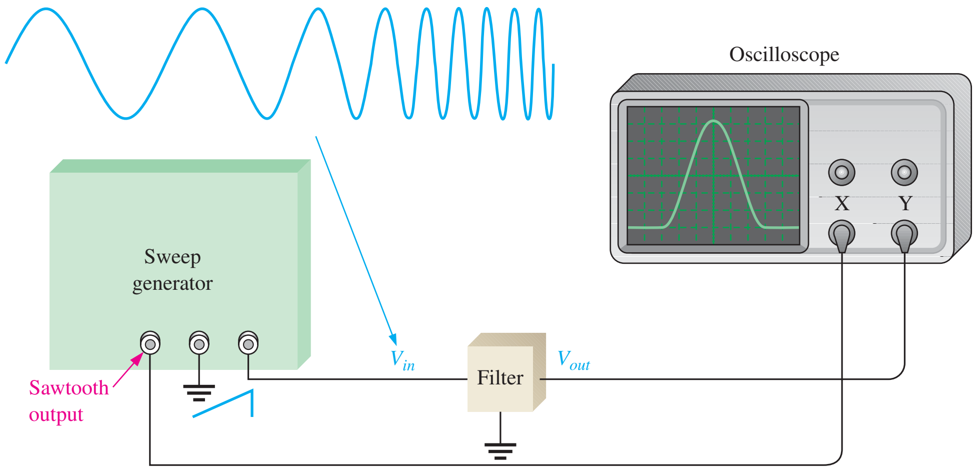
Test setup for discrete point measurement of the filter response. (Readings are arbitrary and for display only.)

Swept Frequency Measurement

The swept frequency method requires more elaborate test equipment than does the discrete point method, but it is much more efficient and can result in a more accurate response curve. A general test setup is shown in Figure 15–28(a) using a swept frequency



(a) Test setup for a filter response using a spectrum analyzer



(b) Test setup for a filter response using an oscilloscope. The scope is placed in X-Y mode. The sawtooth waveform from the sweep generator drives the X-channel of the oscilloscope.

▲ **FIGURE 15–28**

Test setup for swept frequency measurement of the filter response.

generator and a spectrum analyzer. Figure 15–28(b) shows how the test can be made with an oscilloscope.

The swept frequency generator produces a constant amplitude output signal whose frequency increases linearly between two preset limits, as indicated in Figure 15–28. The spectrum analyzer is essentially an elaborate oscilloscope that can be calibrated for a desired *frequency span/division* rather than for the usual *time/division* setting. Therefore, as the input frequency to the filter sweeps through a preselected range, the response curve is traced out on the screen of the spectrum analyzer or an oscilloscope.

SECTION 15–7 CHECKUP

1. What is the purpose of the two tests discussed in this section?
2. Name one disadvantage and one advantage of each test method.

Application Activity: *RFID System*

RFID (radio frequency identification) is a technology that enables the tracking and/or identification of objects. Typically, an RFID system contains an *RFID tag* that consists of an IC chip that transmits data about the object, an *RFID reader* that receives transmitted data from the tag, and a *data-processing system* that processes and stores the data passed to it by the reader. A basic block diagram is shown in Figure 15–29.

▲ FIGURE 15–29

Basic block diagram of an RFID system.

The RFID Tag

RFID tags are tiny, very thin microchips with memory and a coil antenna. The tags listen for a radio signal sent by an RFID reader. When a tag receives a signal, it responds by transmitting its unique ID code and other data back to the reader.

Passive RFID Tag This type of tag does not require batteries. The tag is inactive until powered by the energy from the electromagnetic field of an RFID reader. Passive tags can be read from distances up to about 20 feet and are generally read-only, meaning the data they contain cannot be altered or written over.

Active RFID Tag This type of tag is powered by a battery and is capable of communicating up to 100 feet or more from the RFID reader. Generally, the active tag is larger and more expensive than a passive tag, but can hold more data about the product and is commonly used for identification of high-value assets. Active tags may be read-write, meaning the data they contain can be written over.

Tags are available in a variety of shapes. Depending on the application, they may be embedded in glass or epoxy, or they may be in label or card form. Another type of tag, often called the *smart label,* is a paper (or similar material) label with printing, but also with the RF circuitry and antenna embedded in it.

Some advantages of RFID tags compared to bar codes are

- Non-line-of-sight identification
- More information can be stored
- Coverage at greater distances
- Unattended operations are possible
- Ability to identify moving objects that have tags embedded
- Can be used in diverse environments

Disadvantages of RFID tags are that they are expensive compared to the bar code and they are bulkier because the electronics is embedded in the tag.

RFID tags and readers must be tuned to the same frequency to communicate. RFID systems use many different frequencies, but generally the most common are low frequency

(125 kHz), high frequency (13.56 MHz), and ultra-high frequency, or UHF (850–900 MHz). Microwave (2.45 GHz) is also used in some applications. The frequency used depends on the particular type of application.

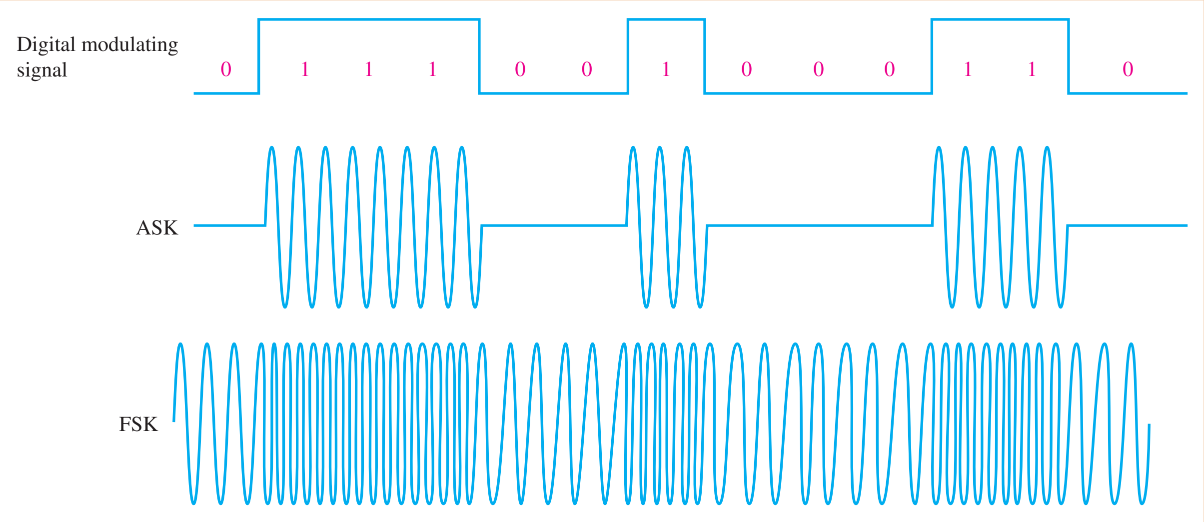
Low-frequency systems are the least expensive and have the shortest range. They are most commonly used in security access, asset tracking, and animal identification applications. High-frequency systems are used for applications such as railroad car tracking and automated toll collection.

Some typical RFID application areas are

- Metering applications such as electronic toll collection
- Inventory control and tracking such as merchandise control
- Asset tracking and recovery
- Tracking parts moving through a manufacturing process
- Tracking goods in a supply chain

The RFID Reader

Data is stored on the RFID tag in digital form and is transmitted to the reader as a modulated signal. Many RFID systems use ASK (amplitude shift keying) or FSK (frequency shift keying). In ASK, the amplitude of a carrier signal is varied by the digital data. In FSK, the frequency of a carrier signal is varied by the digital data. Examples of these forms of modulation are shown Figure 15–30. In this system, the carrier is 125 kHz, and the modulating signal is a digital waveform at the rate of 10 kHz, representing a stream of 1s and 0s.

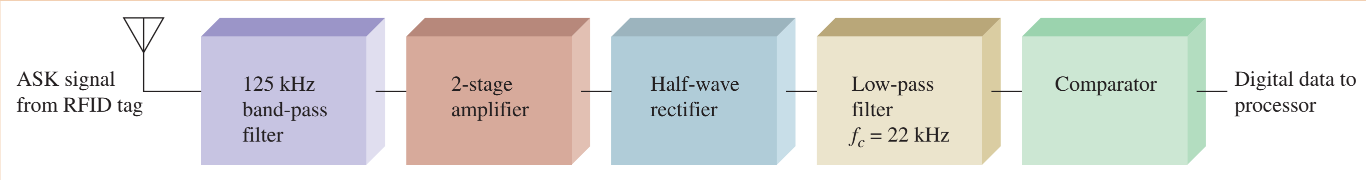


▲ FIGURE 15–30

Examples of ASK and FSK modulation transmitted by an RFID tag.

Project

Your company is developing a new RFID reader using ASK modulation at a carrier frequency of 125 kHz. A block diagram is shown in Figure 15–31. The purpose of each block is as follows. The band-pass filter passes the 125 kHz signal and reduces signals and noise from other sources; the 2-stage amplifier increases the very small signal from the tag to a usable level; the rectifier eliminates the negative portions of the modulated signal; the low-pass filter eliminates the 125 kHz carrier frequency but passes the 10 kHz



▲ FIGURE 15–31

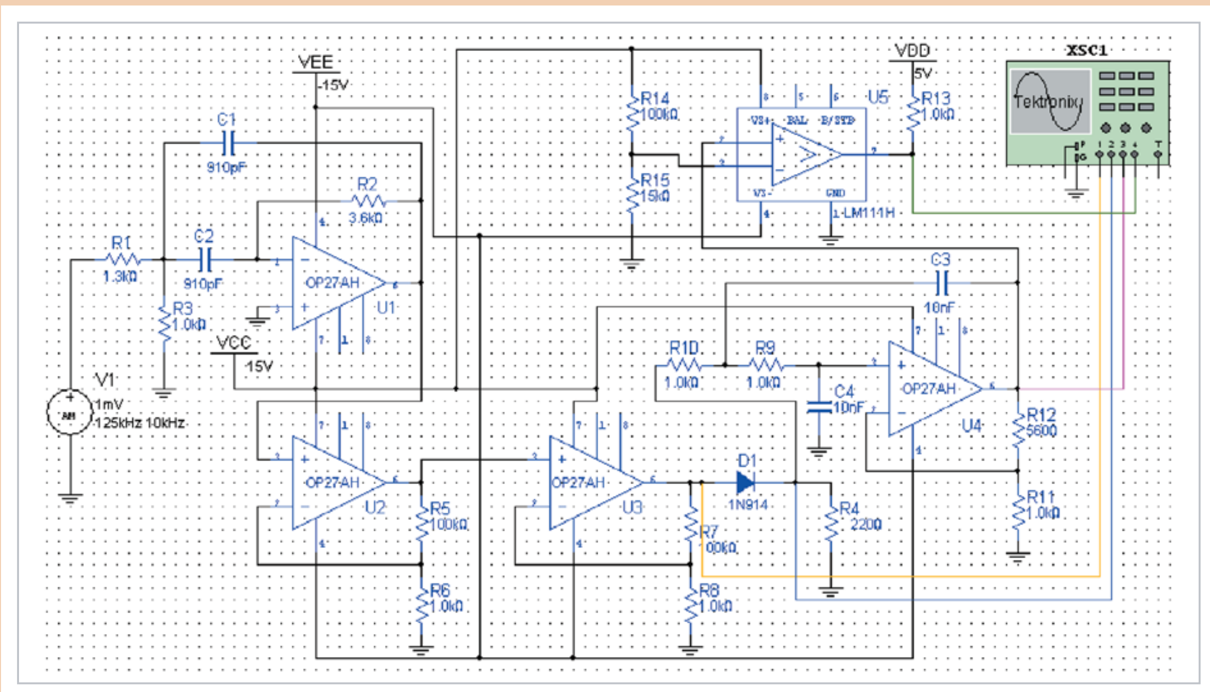
Block diagram of RFID reader.

modulating signal; and the comparator restores the digital signal to a usable stream of digital data.

1. In general, what are RFID systems used for?
2. Name the three basic components of an RFID system.
3. Explain the purpose of an RFID tag.
4. Explain the purpose of an RFID reader.

Simulation

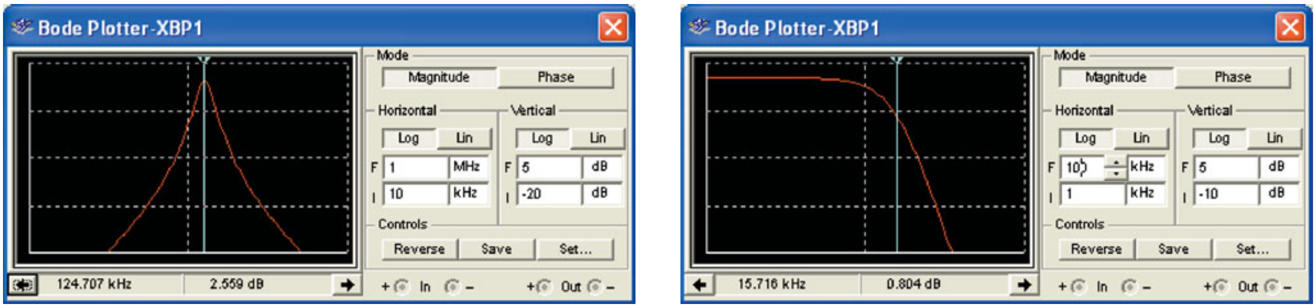
The RFID reader is simulated with Multisim using an input signal of 1 mV at 125 kHz to represent the output of the RFID tag. For purposes of simulation, the 125 kHz carrier is modulated with a 10 kHz sine wave although the actual modulating signal will be a pulse waveform containing digital data. In Multisim it is difficult to produce a sinusoidal carrier signal modulated with a pulse signal, so the sinusoidal modulating signal serves to verify system operation. The simulated circuit is shown in Figure 15–32. The band-pass filter is U1, the amplifier stages are U2 and U3, the half-wave rectifier is D1, the low-pass filter is U4, and the comparator is U5. Datasheets for the OP27AH op-amp and the LM111H comparator are available at www.analog.com.



▲ FIGURE 15–32

Multisim circuit screen for the RFID reader.

The frequency responses of the band-pass filter and the low-pass filter are shown on the Bode plotters in Figure 15–33. As you can see, the peak response of the band-pass filter is approximately 125 kHz and the critical frequency of the low-pass filter is approximately 16 kHz.



(a) Band-pass response

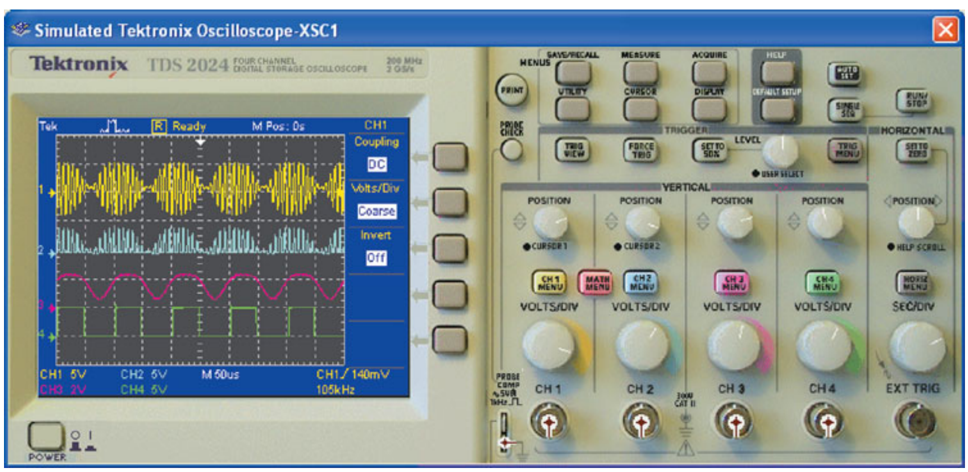
(b) Low-pass response

▲ **FIGURE 15–33**

Bode plots for the RFID reader filters.

5. What is the purpose of the band-pass filter in the RFID reader?
6. What is the purpose of the low-pass filter in the RFID reader?
7. Calculate the gain of each amplifier in the reader in Figure 15–32.
8. Use the formula for a multiple-feedback band-pass filter to verify the center frequency of the band-pass filter in the reader.
9. What type of response characteristic is the low-pass filter set up for?
10. Calculate the critical frequency of the low-pass filter and compare to the measured value.
11. Calculate the reference voltage for the comparator and explain why a reference above ground is necessary.

Measurements at points on the reader circuit are shown on the oscilloscope in Figure 15–34. The top waveform is the modulated carrier at the output of amplifier U3. The second waveform is the output of the rectifier D1. The third waveform is the output of the low-pass filter (notice that the carrier frequency has been removed by the filter). The bottom waveform is the output of the comparator and represents the digital data sent to the processor.



▲ **FIGURE 15–34**

RFID reader waveforms.

Simulate the RFID reader circuit using your Multisim software. Observe the operation with the oscilloscope and Bode plotter.

Prototyping and Testing

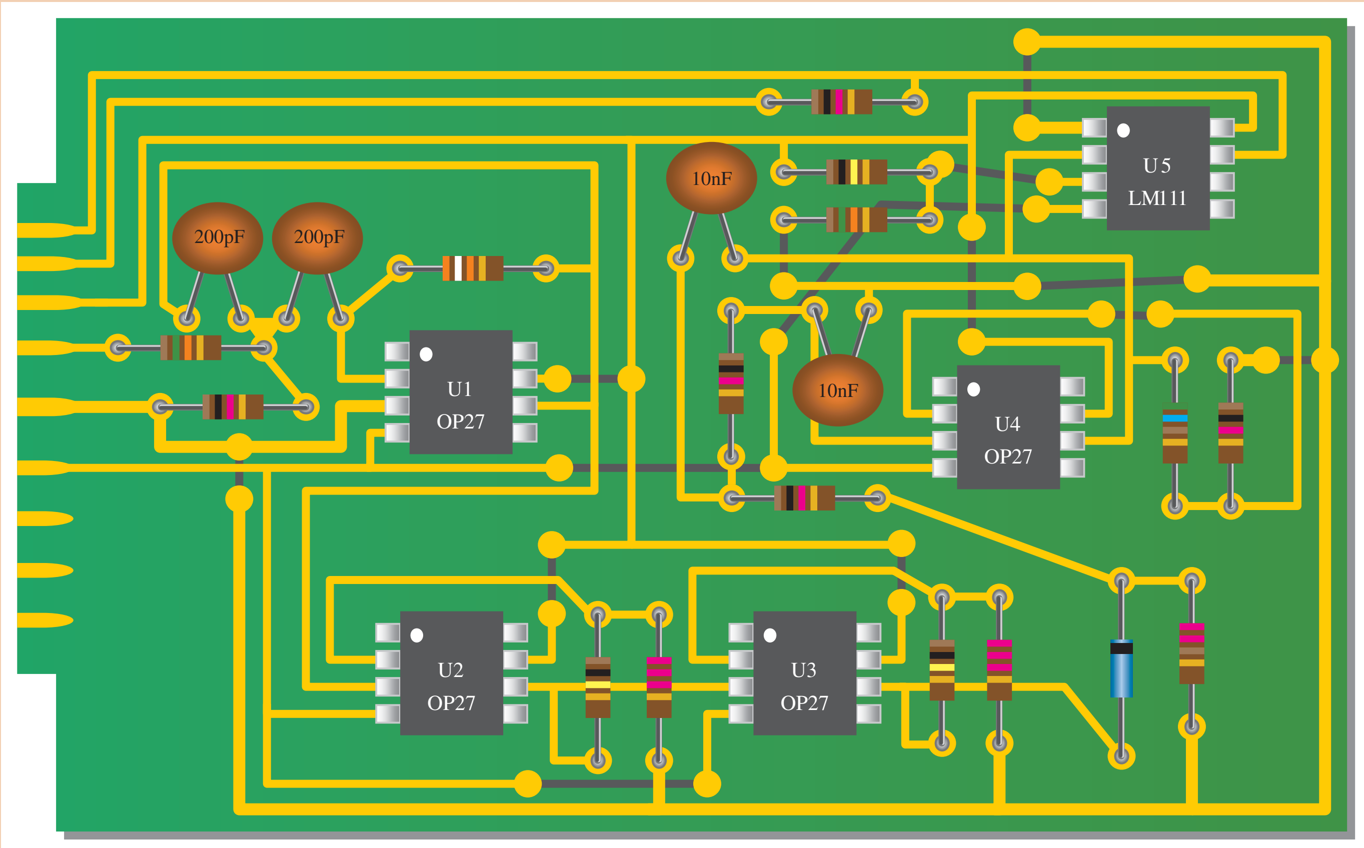
Now that the circuit has been simulated, the prototype circuit is constructed and tested. After the circuit is successfully tested on a protoboard, it is ready to be finalized on a printed circuit board.

Lab Experiment

To build and test a low-pass filter similar to one used in the RFID reader, go to Experiment 15–A in your lab manual (*Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling).

Circuit Board

The RFID reader circuit is implemented on a printed circuit board as shown in Figure 15–35. The dark gray lines represent backside traces.



▲ **FIGURE 15–35**

RFID reader board.

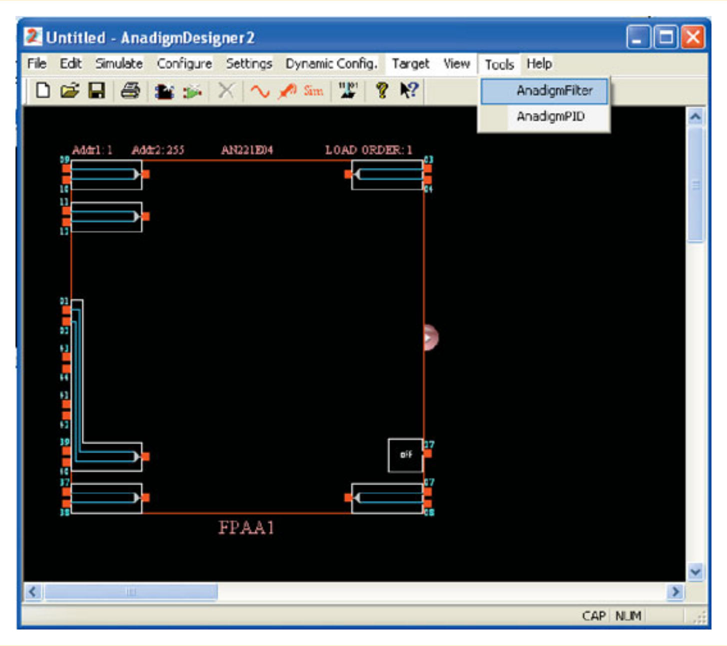
12. Check the printed circuit board and verify that it agrees with the simulation schematic in Figure 15–32.
13. Label each input and output pin according to function.

Programmable Analog Technology

The material you have learned in this chapter is necessary to give you a basic understanding of active filters. However, filter design can be quite complex mathematically. To avoid tedious calculations and trial-and-error breadboarding, the preferred method for development of many filters is to use computer software and then download the design to a programmable analog array. AnadigmDesigner2 software is used in this section to illustrate the ease with which active filters can be developed and implemented in hardware. If you have checked out the optional *Programmable Analog Technology* feature, which appeared first in Chapter 12, you are aware that this software is available and can be downloaded free from www.anadigm.com. You can easily implement a filter design in an FPAA or dpASP chip if you have an evaluation board and interface cable connected to your computer.

Filter Specification

Once you have downloaded the AnadigmDesigner2 software, the first thing you see when opening it is an outline representation of the blank FPAA chip, as shown in Figure 15–36. Under the Tools menu, select *AnadigmFilter,* as shown, and you will get the screen shown in Figure 15–37.



▲ **FIGURE 15–36**

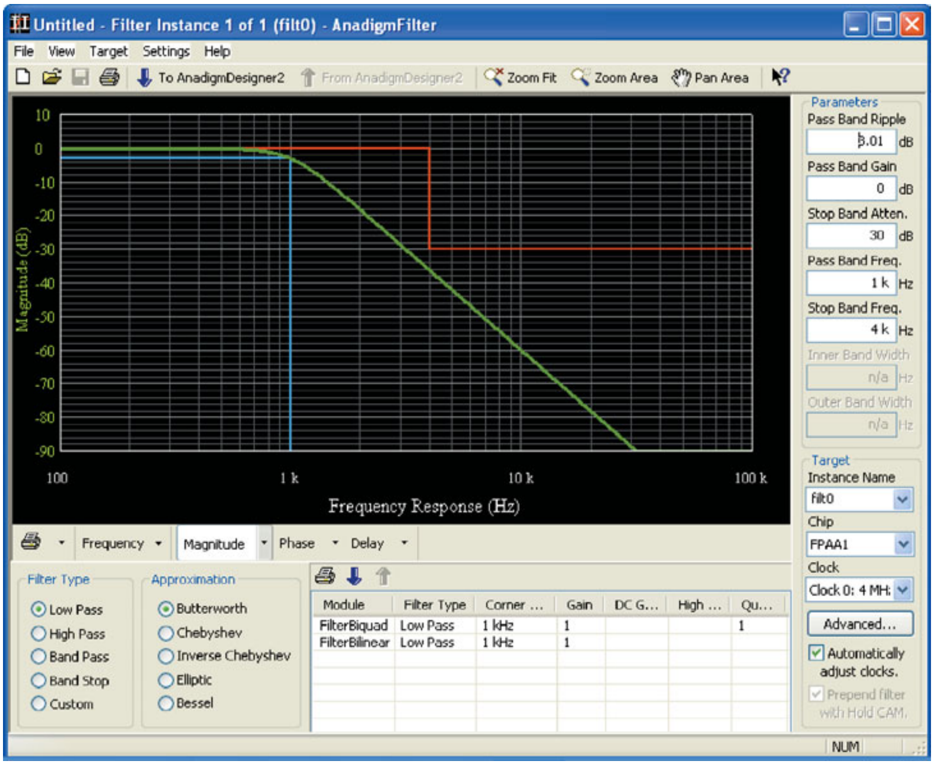
FPAA chip outline screen showing AnadigmFilter selection.

You are now ready to specify a filter. For example, select a filter type and approximation and enter the desired parameters, as shown in Figure 15–38, for a band-pass Butterworth filter. Note that you can use your mouse to drag the limits, shown in red and blue on the screen, to set the desired response.

When the filter has been completely specified, click on "To AnadigmDesigner2" and the filter components will be placed in the FPAA chip screen, as shown in Figure 15–39(a). Notice that the filter consists of three stages, in this case. Now use the connection tool to connect the filter to an input and output, as shown in part (b).

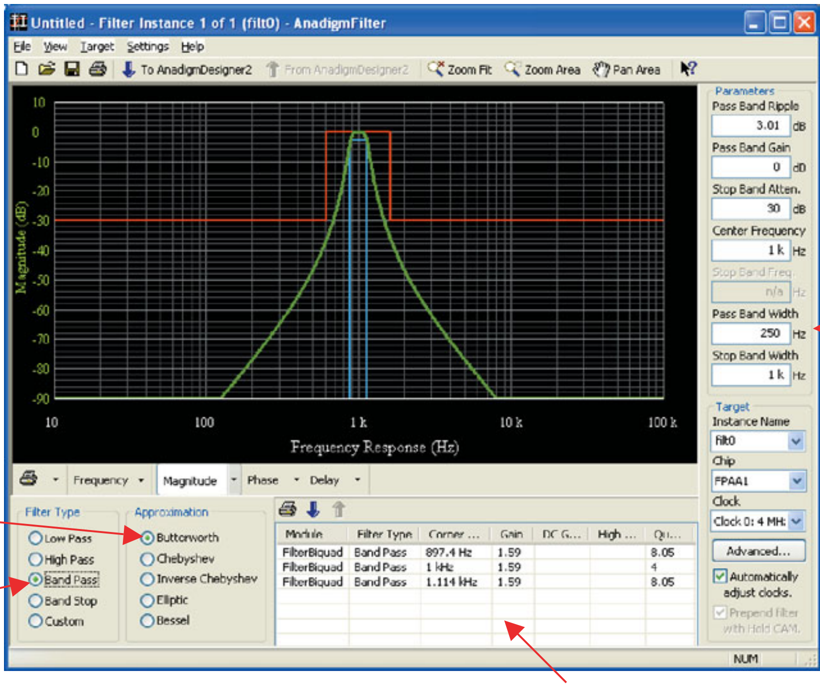
▶ **FIGURE 15–37**

Filter default screen.



Select *Butterworth*

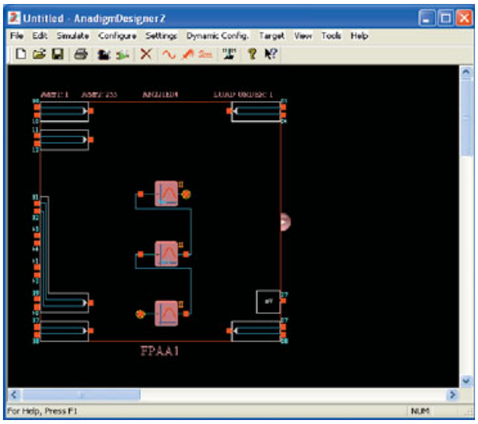
Select *Band Pass*



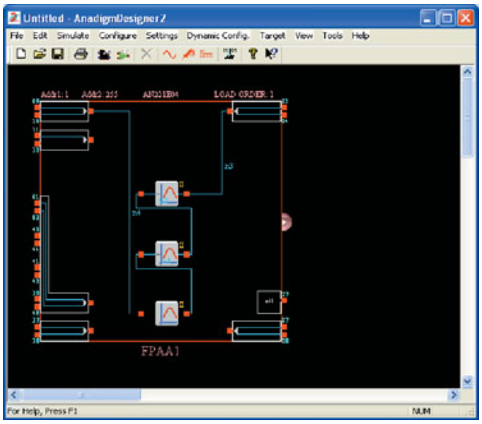
Enter desired parameters

Filter description is shown here

▲ **FIGURE 15–38**



(a)



(b)

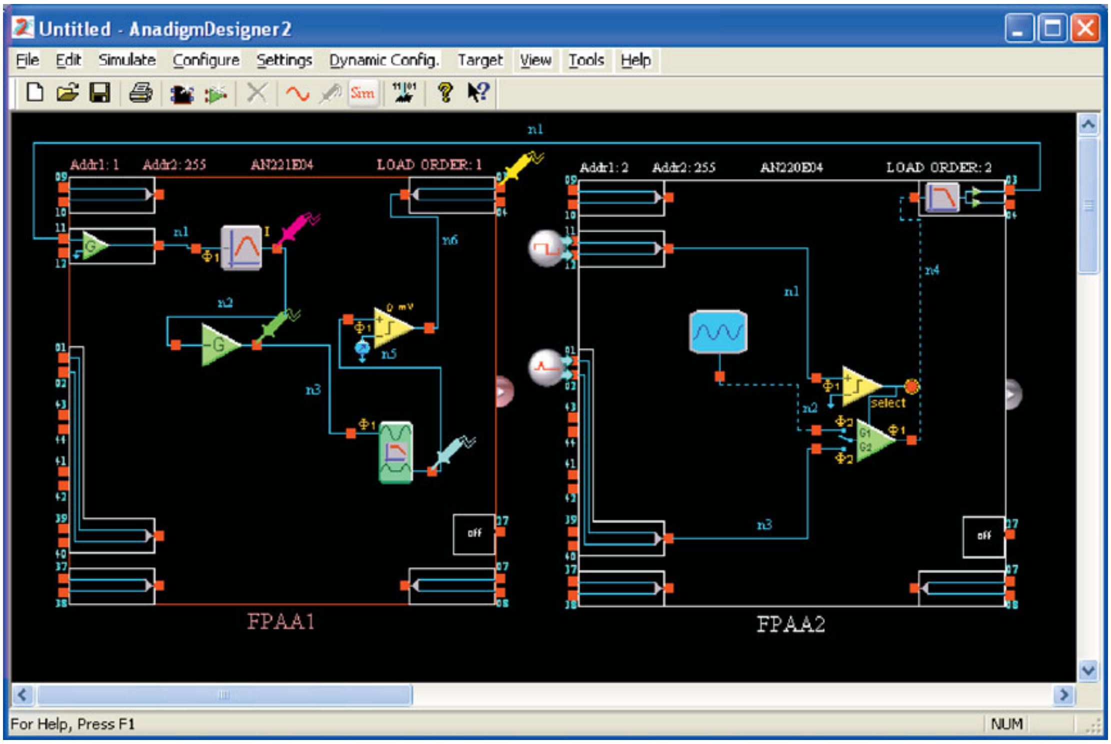
▲ FIGURE 15–39

By attaching actual signal generators and oscilloscope probes to the board, you can verify that the downloaded circuit is behaving just as the simulator indicated it would. Note that an FPAA or dpASP is reprogrammable so you can make circuit changes, download, and test indefinitely.

Design Assignment

Implement the RFID reader circuit using AnadigmDesigner2 software.

Procedure: Figure 15–40 shows a version of the circuit implemented in FPAA1. Because of limitations on implementing the ASK input signal, modifications have been made. Since the input cell

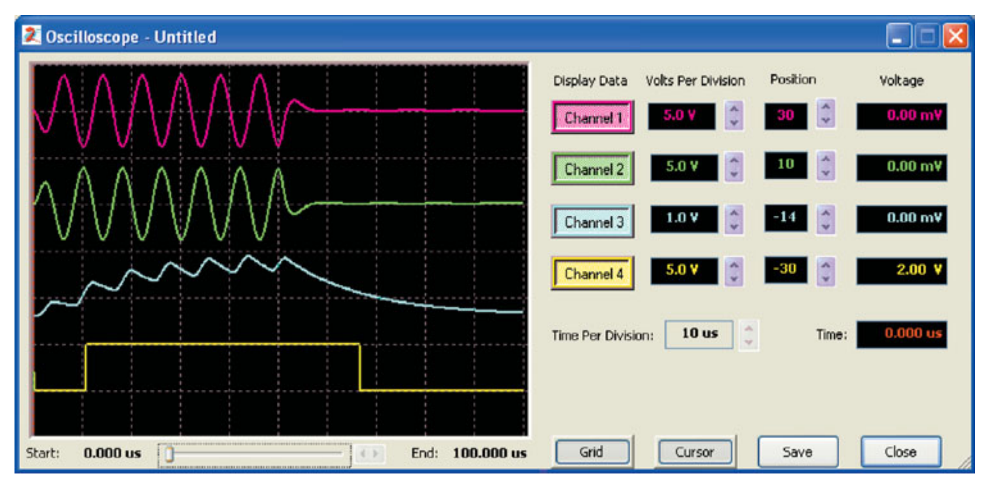


▲ FIGURE 15–40

Design screen showing the RFID reader in FPAA1 and an ASK generator representing the RFID tag in FPAA2.

contains an amplifier with gain, the amplifier in the RFID reader circuit has less gain than if a 1 mV ASK signal were available. Also, the rectifier and low-pass filter are combined in one CAM. FPAA2 is used as a signal source to replicate a 125 kHz carrier modulated with a 10 kHz square wave. This chip is for test purposes only and is not part of the RFID reader.

Analysis: The simulation of the RFID reader is shown in Figure 15–41. The top waveform is the output of the 125 kHz band-pass filter CAM and is an ASK input signal representing a digital 1 followed by a 0. The second waveform is the output of the inverting gain stage CAM with a unity gain. The third waveform is the output of the half-wave rectifier/low-pass filter CAM. The bottom output is the digital signal from the comparator.



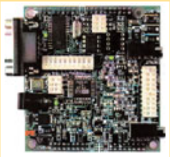
▲ **FIGURE 15–41**

Simulation waveforms for the RFID reader.

Programming Exercises

1. Why is a software program the best way to specify and implement active filters?
2. List the filter types available in the AnadigmFilter software.
3. List the filter approximations available in the AnadigmFilter software.

PAM Experiment



To program, download, and test a circuit using AnadigmDesigner2 software and the programmable analog module (PAM) board, go to Experiment 15–B in *Laboratory Exercises for Electronic Devices* by David Buchla and Steven Wetterling.

SUMMARY

Section 15–1

- ◆ In filter terminology, a single *RC* circuit is called a *pole.*
- ◆ The bandwidth in a low-pass filter equals the critical frequency because the response extends to 0 Hz.
- ◆ The passband of a high-pass filter extends above the critical frequency and is limited only by the inherent frequency limitation of the active circuit.

- A band-pass filter passes all frequencies within a band between a lower and an upper critical frequency and rejects all others outside this band.
- The bandwidth of a band-pass filter is the difference between the upper critical frequency and the lower critical frequency.
- The quality factor Q of a band-pass filter determines the filter's selectivity. The higher the Q, the narrower the bandwidth and the better the selectivity.
- A band-stop filter rejects all frequencies within a specified band and passes all those outside this band.

Section 15–2

- Filters with the Butterworth response characteristic have a very flat response in the passband, exhibit a roll-off of −20 dB/decade/pole, and are used when all the frequencies in the passband must have the same gain.
- Filters with the Chebyshev characteristic have ripples or overshoot in the passband and exhibit a faster roll-off per pole than filters with the Butterworth characteristic.
- Filters with the Bessel characteristic are used for filtering pulse waveforms. Their linear phase characteristic results in minimal waveshape distortion. The roll-off rate per pole is slower than for the Butterworth.
- Each pole in a Butterworth filter causes the output to roll off at a rate of −20 dB/decade.
- The damping factor determines the filter response characteristic (Butterworth, Chebyshev, or Bessel).

Section 15–3

- Single-pole low-pass filters have a −20 dB/decade roll-off.
- The Sallen-Key low-pass filter has two poles (second order) and has a −40 dB/decade roll-off.
- Each additional filter in a cascaded arrangement adds −20 dB to the roll-off rate.

Section 15–4

- Single-pole high-pass filters have a −20 dB/decade roll-off.
- The Sallen-Key high-pass filter has two poles (second order) and has a −40 dB/deacde roll-off.
- Each additional filter in a cascaded arrangement adds −20 dB to the roll-off rate.
- The response of an active high-pass filter is limited by the internal op-amp roll-off.

Section 15–5

- Band-pass filters pass a specified band of frequencies.
- A band-pass filter can be achieved by cascading a low-pass and a high-pass filter.
- The multiple-feedback band-pass filter uses two feedback paths to achieve its response characteristic.
- The state-variable band-pass filter uses a summing amplifier and two integrators.
- The biquad filter consists of an integrator followed by an inverting amplifier and a second integrator.

Section 15–6

- Band-stop filters reject a specified band of frequencies.
- Multiple-feedback and state-variable are common types of band-stop filters.

Section 15–7

- Filter response can be measured using discrete point measurement or swept frequency measurement.

KEY TERMS

Key terms and other bold terms in the chapter are defined in the end-of-book glossary.

Band-pass filter A type of filter that passes a range of frequencies lying between a certain lower frequency and a certain higher frequency.

Band-stop filter A type of filter that blocks or rejects a range of frequencies lying between a certain lower frequency and a certain higher frequency.

Damping factor A filter characteristic that determines the type of response.

Filter A circuit that passes certain frequencies and attenuates or rejects all other frequencies.

High-pass filter A type of filter that passes frequencies above a certain frequency while rejecting lower frequencies.

Low-pass filter A type of filter that passes frequencies below a certain frequency while rejecting higher frequencies.

Pole A circuit containing one resistor and one capacitor that contributes −20 dB/decade to a filter's roll-off rate.

Roll-off The rate of decrease in gain, below or above the critical frequencies of a filter.

KEY FORMULAS

15–1	$BW = f_c$	Low-pass bandwidth
15–2	$BW = f_{c2} - f_{c1}$	Filter bandwidth of a band-pass filter
15–3	$f_0 = \sqrt{f_{c1}f_{c2}}$	Center frequency of a band-pass filter
15–4	$Q = \dfrac{f_0}{BW}$	Quality factor of a band-pass filter
15–5	$DF = 2 - \dfrac{R_1}{R_2}$	Damping factor
15–6	$A_{cl(\mathrm{NI})} = \dfrac{R_1}{R_2} + 1$	Closed-loop voltage gain
15–7	$f_c = \dfrac{1}{2\pi\sqrt{R_AR_BC_AC_B}}$	Critical frequency for a second-order Sallen-Key filter
15–8	$f_0 = \dfrac{1}{2\pi C}\sqrt{\dfrac{R_1 + R_3}{R_1R_2R_3}}$	Center frequency of a multiple-feedback filter
15–9	$A_0 = \dfrac{R_2}{2R_1}$	Gain of a multiple-feedback filter

TRUE/FALSE QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. The response of a filter can be identified by its passband.
2. A filter pole is the cutoff frequency of a filter.
3. A single-pole filter has one *RC* circuit.
4. A single-pole filter produces a roll-off of −25 dB/decade.
5. A low-pass filter can pass a dc voltage.
6. A high-pass filter passes any frequency above dc.
7. The critical frequency of a filter depends only on *R* and *C* values.
8. The band-pass filter has two critical frequencies.
9. The quality factor of a band-pass filter is the ratio of bandwidth to the center frequency.
10. The higher the *Q*, the narrower the bandwidth of a band-pass filter.
11. The Butterworth characteristic provides a flat response in the passband.
12. Filters with a Chebyshev response have a slow roll-off.
13. A Chebyshev response has ripples in the passband.
14. Bessel filters are useful in filtering pulse waveforms.
15. The order of a filter is the number of poles it contains.
16. A Sallen-Key filter is also known as a VCVS filter.
17. Multiple feedback is used in low-pass filters.
18. A state-variable filter uses differentiators.
19. A band-stop filter rejects certain frequencies.
20. Filter response can be measured using a sweep generator.

CIRCUIT-ACTION QUIZ

Answers can be found at www.pearsonhighered.com/floyd.

1. If the critical frequency of a low-pass filter is increased, the bandwidth will
   (a) increase **(b)** decrease **(c)** not change
2. If the critical frequency of a high-pass filter is increased, the bandwidth will
   (a) increase **(b)** decrease **(c)** not change
3. If the Q of a band-pass filter is increased, the bandwidth will
   (a) increase **(b)** decrease **(c)** not change
4. If the value of C_A and C_B in Figure 15–11 are increased by the same amount, the critical frequency will
   (a) increase **(b)** decrease **(c)** not change
5. If the the value of R_2 in Figure 15–11 is increased, the bandwidth will
   (a) increase **(b)** decrease **(c)** not change
6. If two filters like the one in Figure 15–15 are cascaded, the roll-off rate of the frequency response will
   (a) increase **(b)** decrease **(c)** not change
7. If the value of R_2 in Figure 15–19 is decreased, the Q will
   (a) increase **(b)** decrease **(c)** not change
8. If the capacitors in Figure 15–19 are changed to 0.022 μF, the center frequency will
   (a) increase **(b)** decrease **(c)** not change

SELF-TEST

Answers can be found at www.pearsonhighered.com/floyd.

Section 15–1

1. The term *pole* in filter terminology refers to
   (a) a high-gain op-amp **(b)** one complete active filter
   (c) a single RC circuit **(d)** the feedback circuit
2. A single resistor and a single capacitor can be connected to form a filter with a roll-off rate of
   (a) −20 dB/decade **(b)** −40 dB/decade
   (c) −6 dB/octave **(d)** answers (a) and (c)
3. A band-pass response has
   (a) two critical frequencies **(b)** one critical frequency
   (c) a flat curve in the passband **(d)** a wide bandwidth
4. The lowest frequency passed by a low-pass filter is
   (a) 1 Hz **(b)** 0 Hz **(c)** 10 Hz **(d)** dependent on the critical frequency
5. The quality factor (Q) of a band-pass filter depends on
   (a) the critical frequencies **(b)** only the bandwidth
   (c) the center frequency and the bandwidth **(d)** only the center frequency

Section 15–2

6. The damping factor of an active filter determines
   (a) the voltage gain **(b)** the critical frequency
   (c) the response characteristic **(d)** the roll-off rate
7. A maximally flat frequency response is known as
   (a) Chebyshev **(b)** Butterworth **(c)** Bessel **(d)** Colpitts
8. The damping factor of a filter is set by
   (a) the negative feedback circuit **(b)** the positive feedback circuit
   (c) the frequency-selective circuit **(d)** the gain of the op-amp
9. The number of poles in a filter affect the
   (a) voltage gain **(b)** bandwidth
   (c) center frequency **(d)** roll-off rate

Section 15–3

10. Sallen-Key low-pass filters are
(**a**) single-pole filters (**b**) second-order filters
(**c**) Butterworth filters (**d**) band-pass filters

11. When low-pass filters are cascaded, the roll-off rate
(**a**) increases (**b**) decreases (**c**) does not change

Section 15–4

12. In a high-pass filter, the roll-off occurs
(**a**) above the critical frequency (**b**) below the critical frequency
(**c**) during the mid range (**d**) at the center frequency

13. A two-pole Sallen-Key high-pass filter contains
(**a**) one capacitor and two resistors (**b**) two capacitors and two resistors
(**c**) a feedback circuit (**d**) answers (b) and (c)

Section 15–5

14. When a low-pass and a high-pass filter are cascaded to get a band-pass filter, the critical frequency of the low-pass filter must be
(**a**) equal to the critical frequency of the high-pass filter
(**b**) less than the critical frequency of the high-pass filter
(**c**) greater than the critical frequency of the high-pass filter

15. A state-variable filter consists of
(**a**) one op-amp with multiple-feedback paths
(**b**) a summing amplifier and two integrators
(**c**) a summing amplifier and two differentiators
(**d**) three Butterworth stages

Section 15–6

16. When the gain of a filter is minimum at its center frequency, it is
(**a**) a band-pass filter (**b**) a band-stop filter
(**c**) a notch filter (**d**) answers (b) and (c)

PROBLEMS

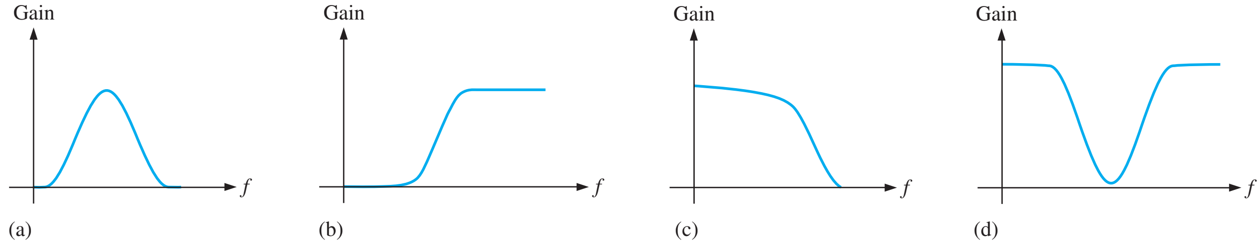
Answers to all odd-numbered problems are at the end of the book.

BASIC PROBLEMS

Section 15–1

Basic Filter Responses

1. Identify each type of filter response (low-pass, high-pass, band-pass, or band-stop) in Figure 15–42.



▲ FIGURE 15–42

2. A certain low-pass filter has a critical frequency of 800 Hz. What is its bandwidth?

3. A single-pole high-pass filter has a frequency-selective circuit with $R = 2.2\ \text{k}\Omega$ and $C = 0.0015\ \mu\text{F}$. What is the critical frequency? Can you determine the bandwidth from the available information?

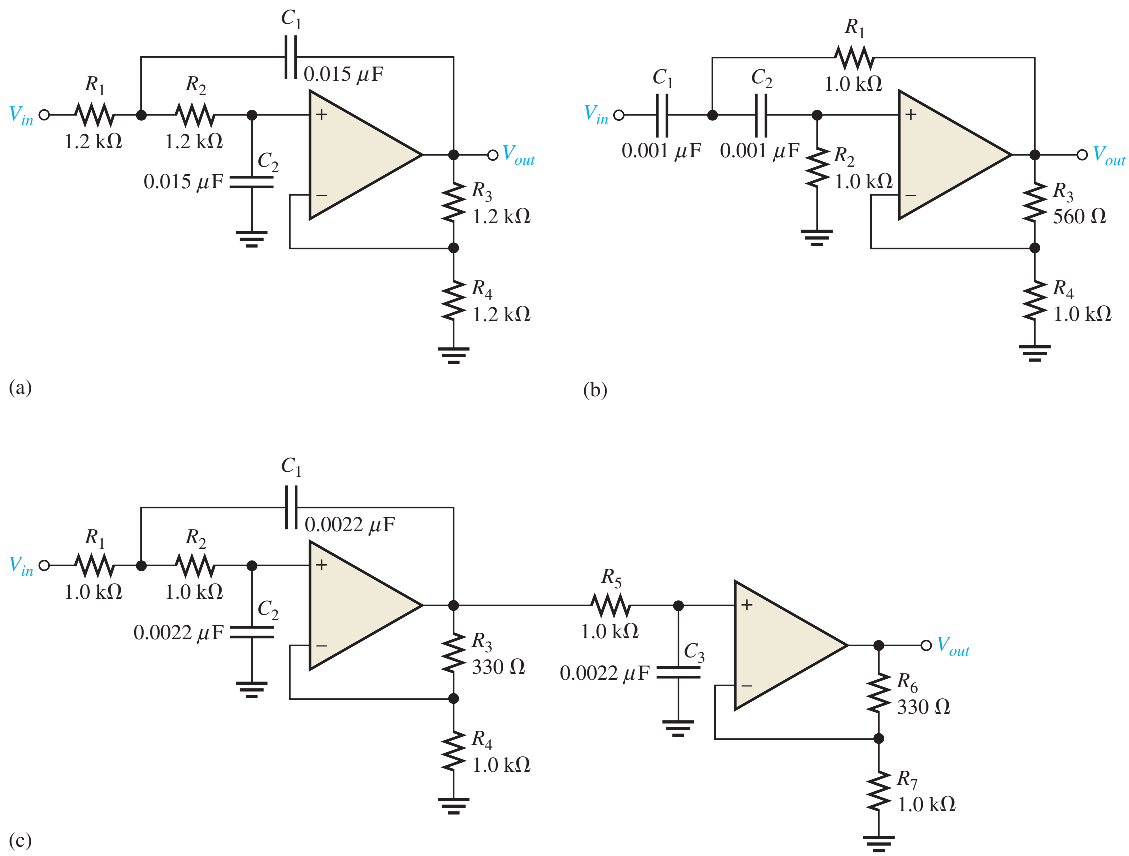
4. What is the roll-off rate of the filter described in Problem 3?

5. What is the bandwidth of a band-pass filter whose critical frequencies are 3.2 kHz and 3.9 kHz? What is the Q of this filter?

6. What is the center frequency of a filter with a Q of 15 and a bandwidth of 1 kHz?

Section 15–2 Filter Response Characteristics

7. What is the damping factor in each active filter shown in Figure 15–43? Which filters are approximately optimized for a Butterworth response characteristic?

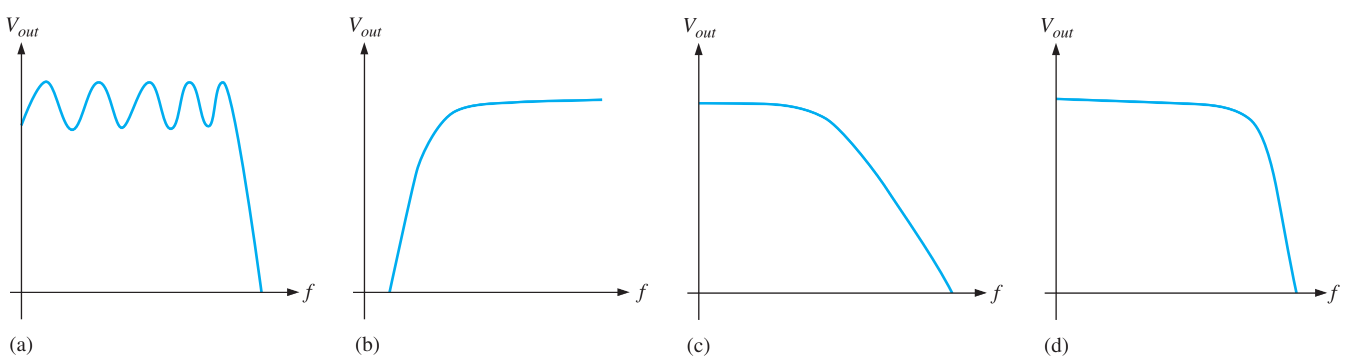


▲ **FIGURE 15–43**

Multisim file circuits are identified with a logo and are in the Problems folder on the companion website. Filenames correspond to figure numbers (e.g., F15-43).

8. For the filters in Figure 15–43 that do not have a Butterworth response, specify the changes necessary to convert them to Butterworth responses. (Use nearest standard values.)

9. Response curves for second-order filters are shown in Figure 15–44. Identify each as Butterworth. Chebyshev, or Bessel.



▲ **FIGURE 15–44**

Section 15–3 Active Low-Pass Filters

10. Is the four-pole filter in Figure 15–45 approximately optimized for a Butterworth response? What is the roll-off rate?

11. Determine the critical frequency in Figure 15–45.

12. Without changing the response curve, adjust the component values in the filter of Figure 15–45 to make it an equal-value filter. Select $C = 0.22\ \mu\text{F}$ for both stages.

13. Modify the filter in Figure 15–45 to increase the roll-off rate to -120 dB/decade while maintaining an approximate Butterworth response.

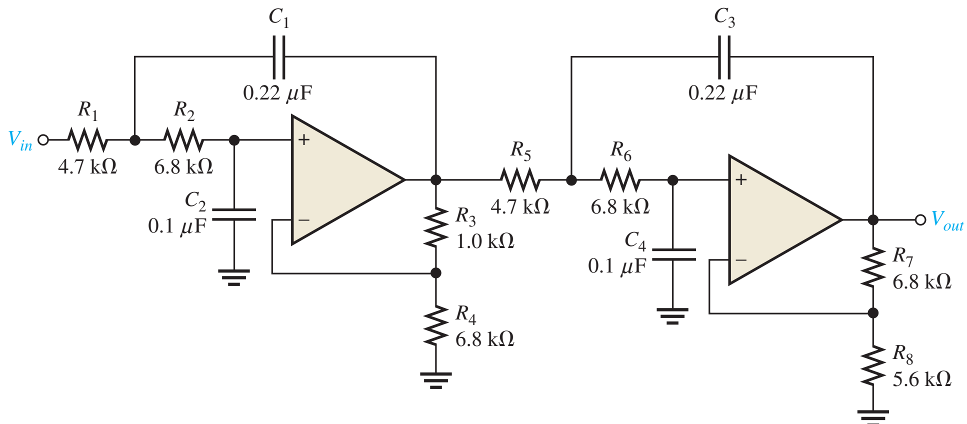
14. Using a block diagram format, show how to implement the following roll-off rates using single-pole and two-pole low-pass filters with Butterworth responses.

(a) -40 dB/decade **(b)** -20 dB/decade

(c) -60 dB/decade **(d)** -100 dB/decade

(e) -120 dB/decade

▶ FIGURE 15–45



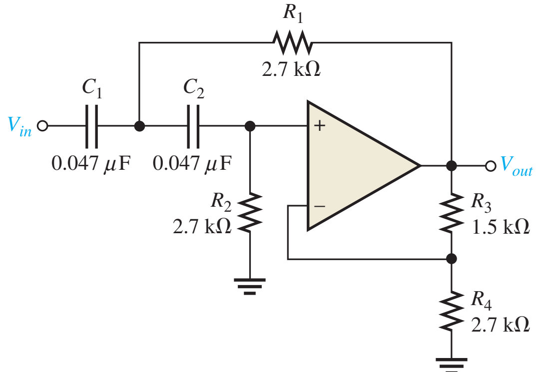
Section 15–4 Active High-Pass Filters

15. Convert the filter in Problem 12 to a high-pass with the same critical frequency and response characteristic.

16. Make the necessary circuit modification to reduce by half the critical frequency in Problem 15.

17. For the filter in Figure 15–46, **(a)** how would you increase the critical frequency? (b) How would you increase the gain?

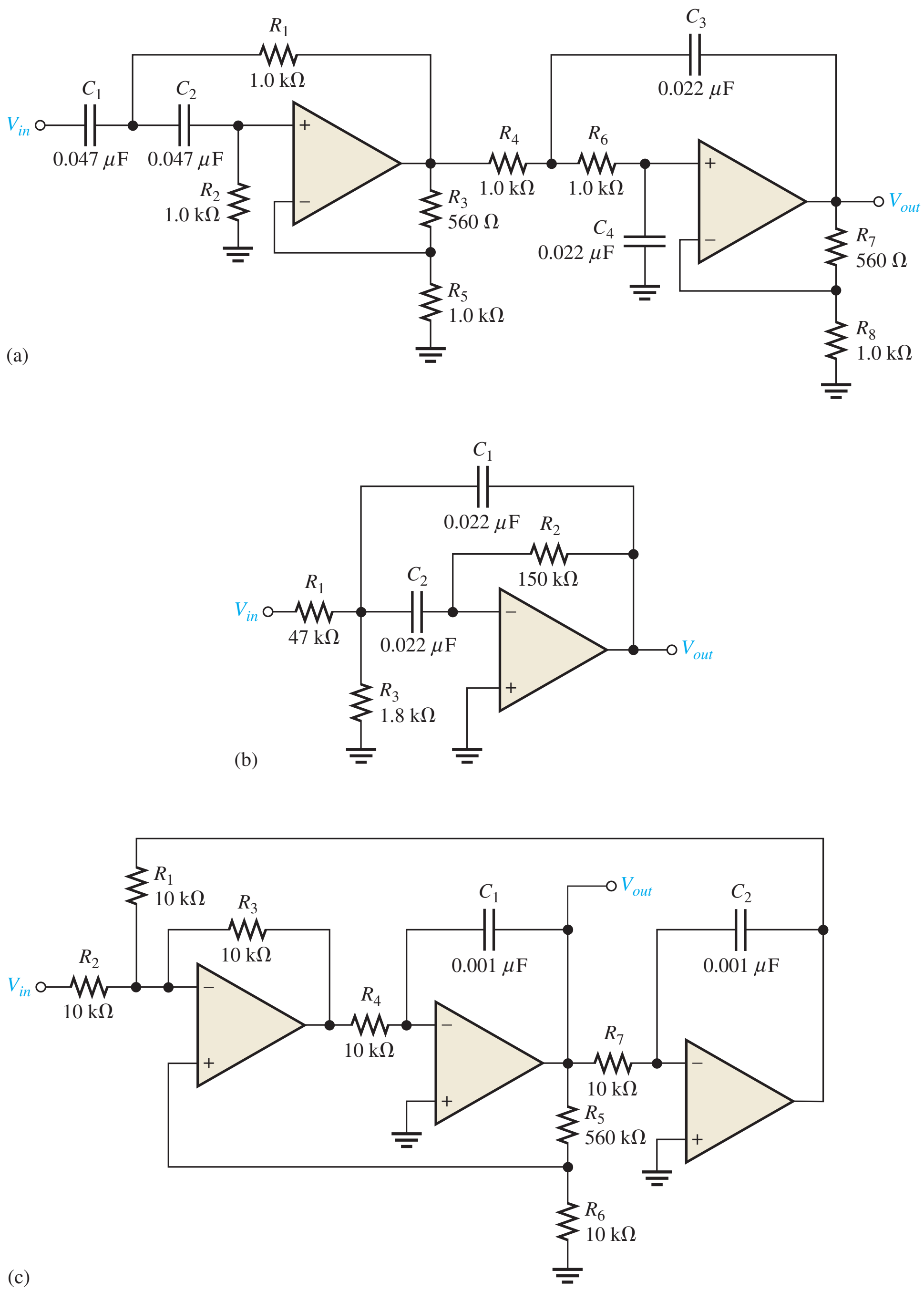
▶ FIGURE 15–46



Section 15–5 Active Band-Pass Filters

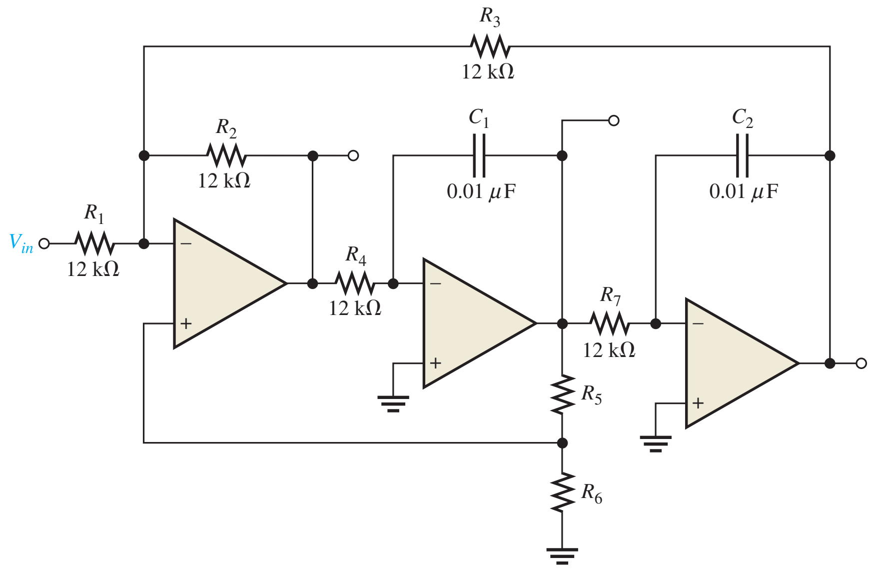
18. Identify each band-pass filter configuration in Figure 15–47.

19. Determine the center frequency and bandwidth for each filter in Figure 15–47.



▲ FIGURE 15–47

▶ FIGURE 15–48



20. Optimize the state-variable filter in Figure 15–48 for $Q = 50$. What bandwidth is achieved?

Section 15–6 Active Band-Stop Filters

21. Show how to make a notch (band-stop) filter using the basic circuit in Figure 15–48.

22. Modify the band-stop filter in Problem 21 for a center frequency of 120 Hz.

MULTISIM TROUBLESHOOTING PROBLEMS

These file circuits are in the Troubleshooting Problems folder on the companion website.

23. Open file TSP15-23 and determine the fault.

24. Open file TSP15-24 and determine the fault.

25. Open file TSP15-25 and determine the fault.

26. Open file TSP15-26 and determine the fault.

27. Open file TSP15-27 and determine the fault.

28. Open file TSP15-28 and determine the fault.

29. Open file TSP15-29 and determine the fault.

30. Open file TSP15-30 and determine the fault.

31. Open file TSP15-31 and determine the fault.