- ANALOGUE ELECTRONIC

Active Filter

Introduction

- Filters are circuits that are capable of *passing signals within a band* of frequencies while *rejecting or blocking* signals of frequencies *outside this band*. This property of filters is also called "frequency selectivity".

- Filter can be passive or active filter.

Passive filters: The circuits built using RC, RL, or RLC circuits.

Active filters : The circuits that employ one or more op-amps in the design an addition to resistors and capacitors

Advantages of Active Filters over Passive Filters

- Active filters can be designed to provide required gain, and hence no attenuation as in the case of passive filters
- No loading problem, because of high input resistance and low output resistance of op-amp.
- Active Filters are cost effective as a wide variety of economical op-amps are available.

Applications

- Active filters are mainly used in communication and signal processing circuits.
- They are also employed in a wide range of applications such as entertainment, medical electronics, etc.

Active Filters

- There are 4 basic categories of active filters:

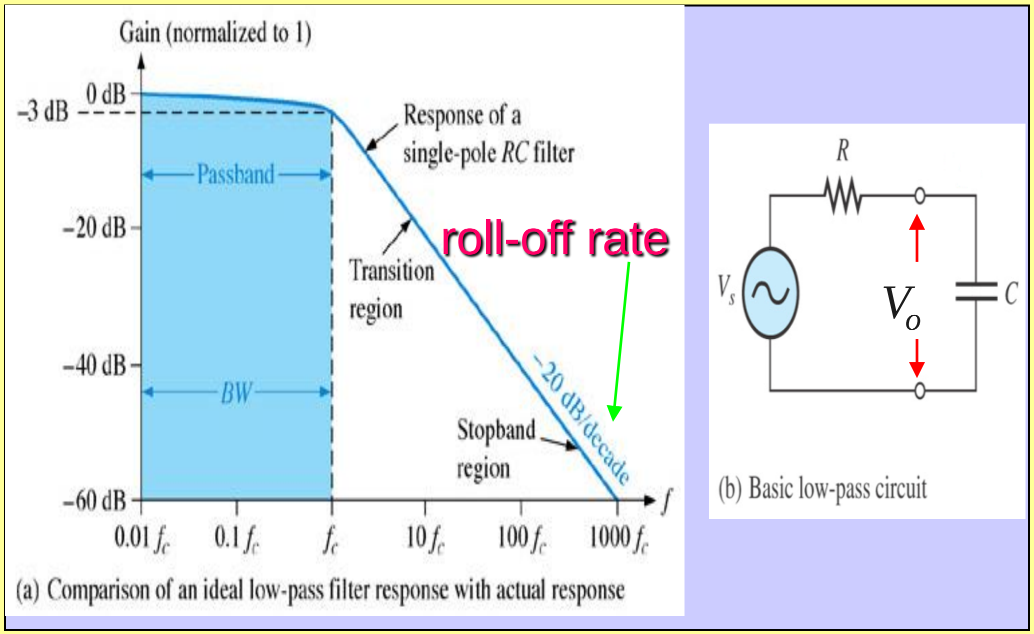
  1. **Low-pass filters**
  2. **High-pass filters**
  3. **Band-pass filters**
  4. **Band-reject filters**

- Each of these filters can be built by using op-amp as the active element combined with RC, RL or RLC circuit as the passive elements.

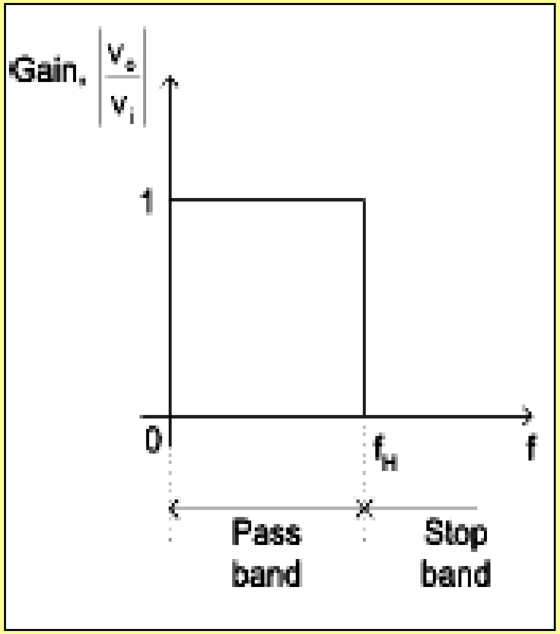
BASIC FILTER RESPONSES

Low-Pass Filter Response

➢ A low-pass filter is a filter that passes frequencies from 0Hz to critical frequency, f_c and significantly attenuates all other frequencies.



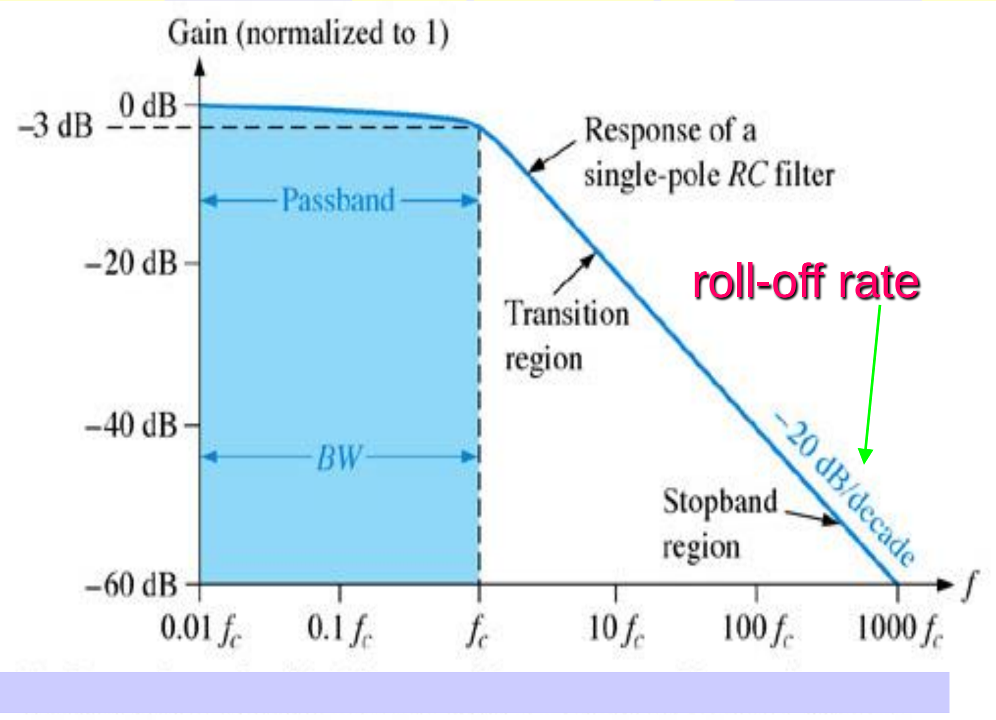
Actual response



Ideal response

➢ Ideally, the response drops abruptly at the critical frequency, f_H

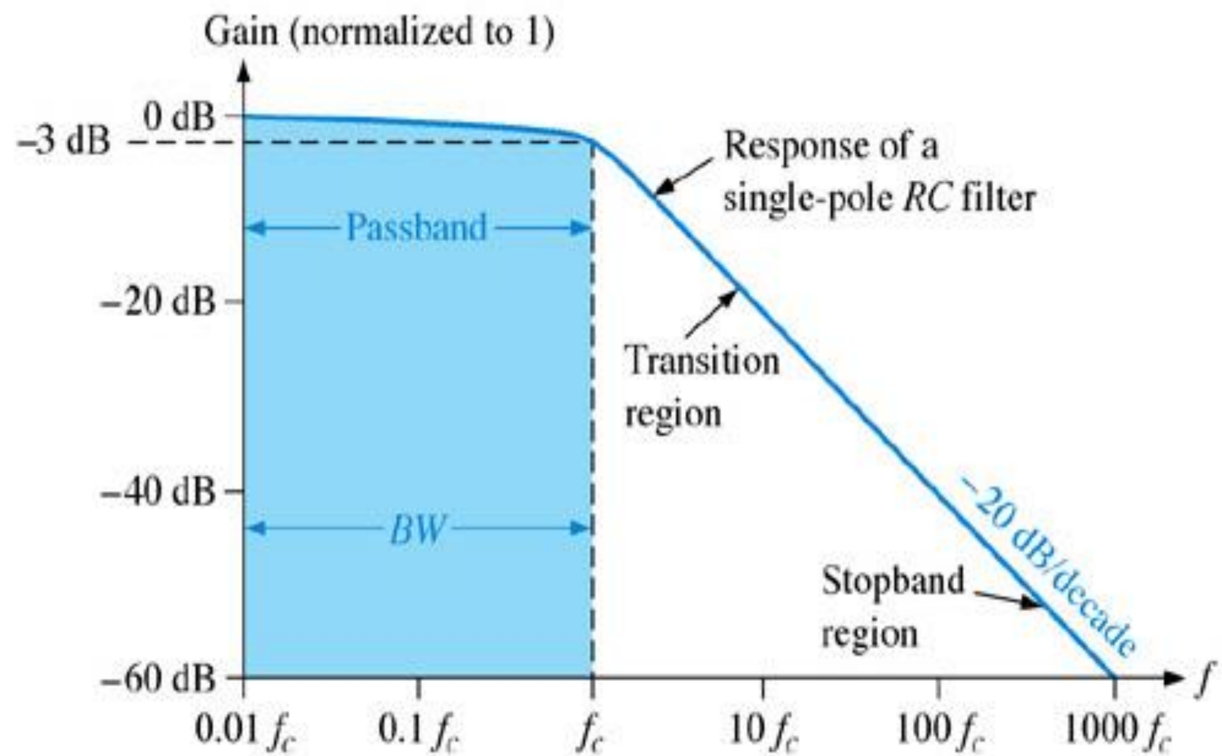
Passband of a filter is the range of frequencies that are allowed to pass through the filter with minimum attenuation (usually defined as less than -3 dB of attenuation).



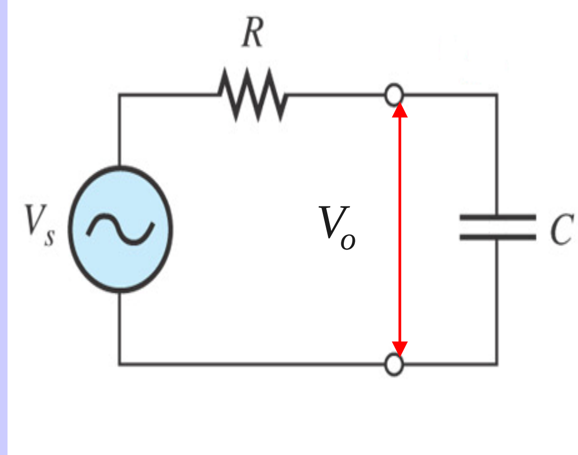
Transition region shows the area where the fall-off occurs.

Stopband is the range of frequencies that have the most attenuation.

Critical frequency, **f_c**, (also called the cutoff frequency) defines the end of the passband and normally specified at the point where the response drops – 3 dB (70.7%) from the passband response.



(a) Comparison of an ideal low-pass filter response with actual response



(b) Basic low-pass circuit

➢ At low frequencies, X_C is very high and the capacitor circuit can be considered as open circuit. Under this condition, $V_o = V_{in}$ or $A_V = 1$ (unity).

➢ At very high frequencies, X_C is very low and the V_o is small as compared with V_{in}. Hence the gain falls and drops off gradually as the frequency is increased.

- The **bandwidth** of an **ideal** low-pass filter is equal to f_c:

$$\boxed{BW = f_c}$$

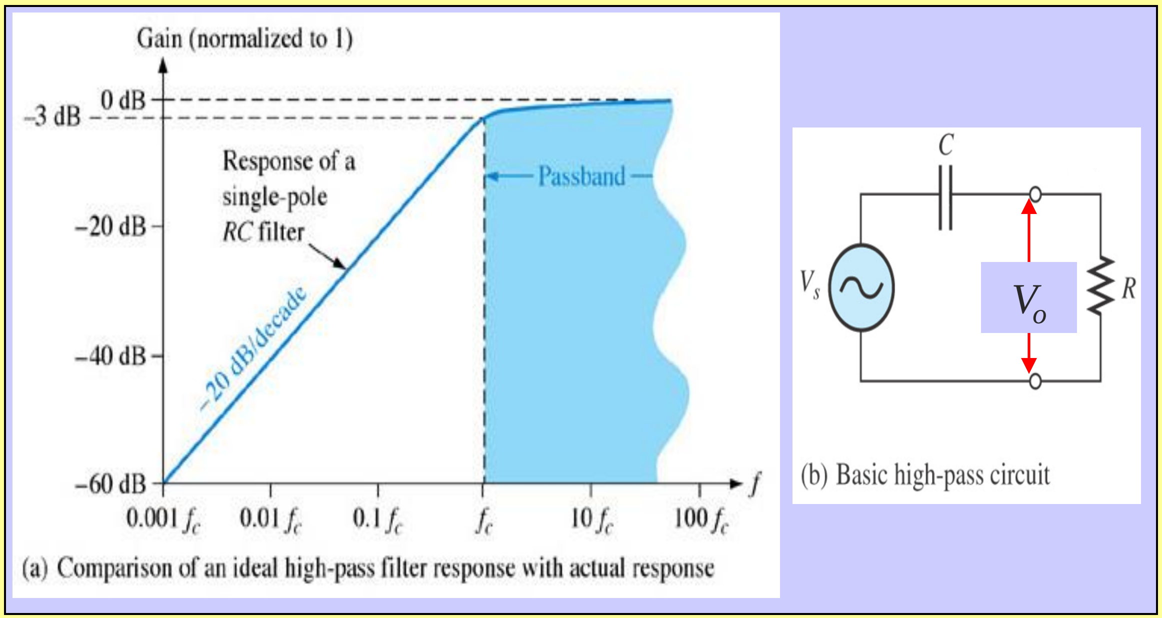
- The critical frequency of a low-pass RC filter occurs when **$X_C = R$** and can be calculated using the formula below:

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

High-Pass Filter Response

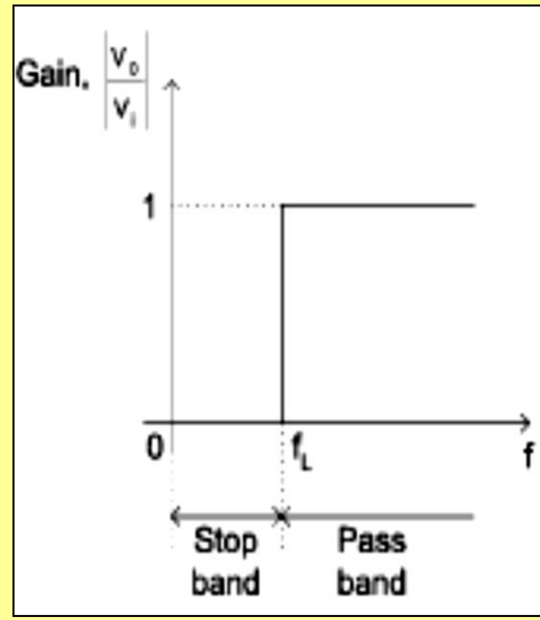
➢ A **high-pass filter** is a filter that significantly attenuates or rejects all frequencies **below** f_c and passes all frequencies **above** f_c.

➢ The passband of a high-pass filter is all frequencies above the critical frequency.



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

Actual response



Ideal response

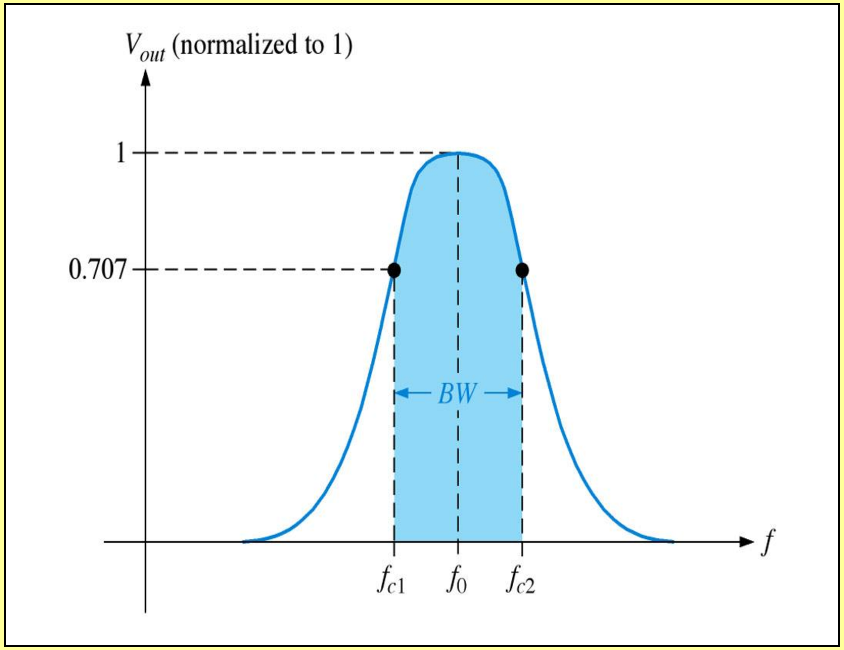
➢ Ideally, the response rises abruptly at the critical frequency, f_L

- The critical frequency of a high-pass RC filter occurs when **$X_C = R$** and can be calculated using the formula below:

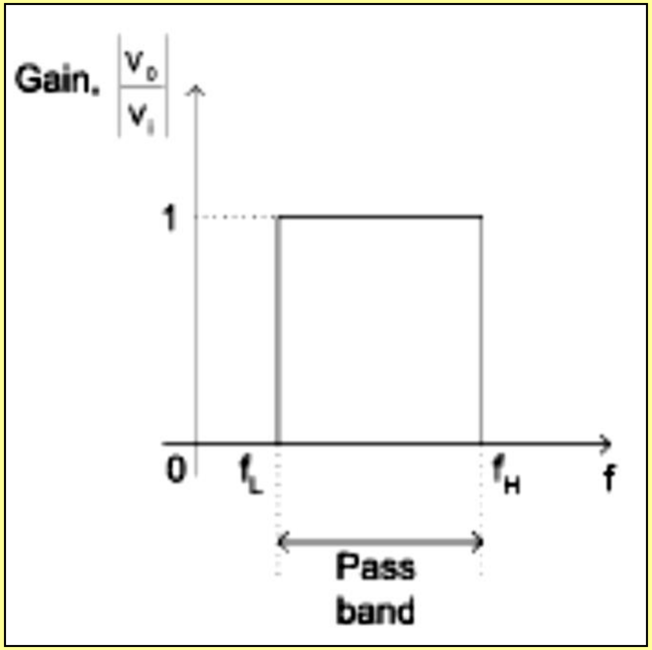
$$f_c = \frac{1}{2\pi RC}$$

Band-Pass Filter Response

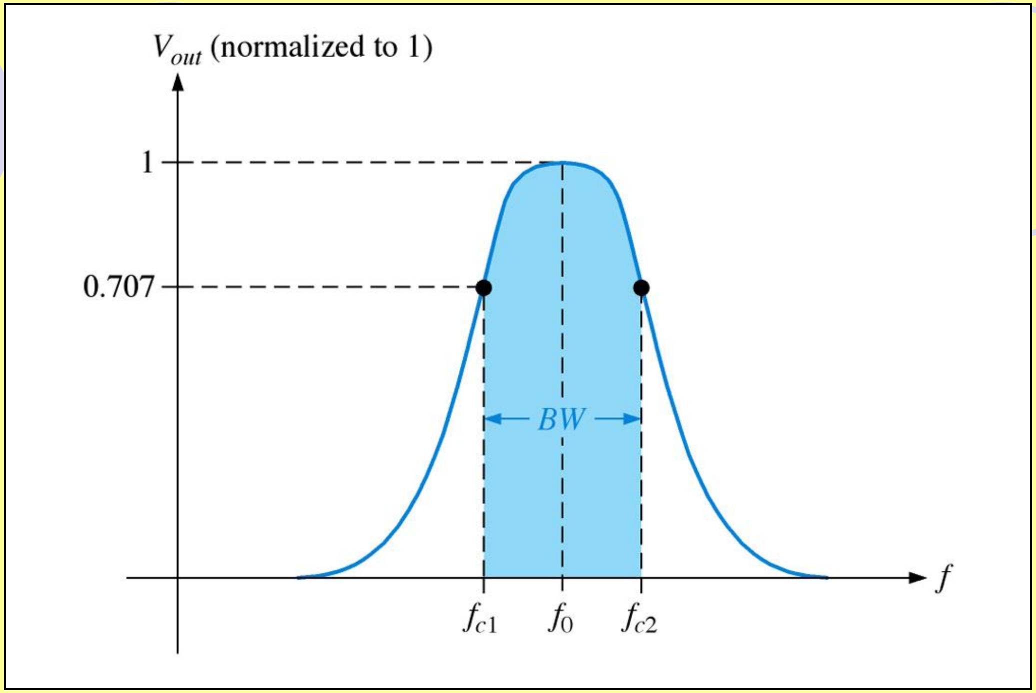
➢ A band-pass filter passes all signals lying within a band between a lower-frequency limit and upper-frequency limit and essentially rejects all other frequencies that are outside this specified band.



Actual response



Ideal response



➢ The bandwidth (BW) is defined as the difference between the upper critical frequency (f_{c2}) and the lower critical frequency (f_{c1}).

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

- The frequency about which the pass band is centered is called the ***center frequency***, $\boldsymbol{f_o}$ and defined as the geometric mean of the critical frequencies.

$$\boxed{f_o = \sqrt{f_{c1} f_{c2}}}$$

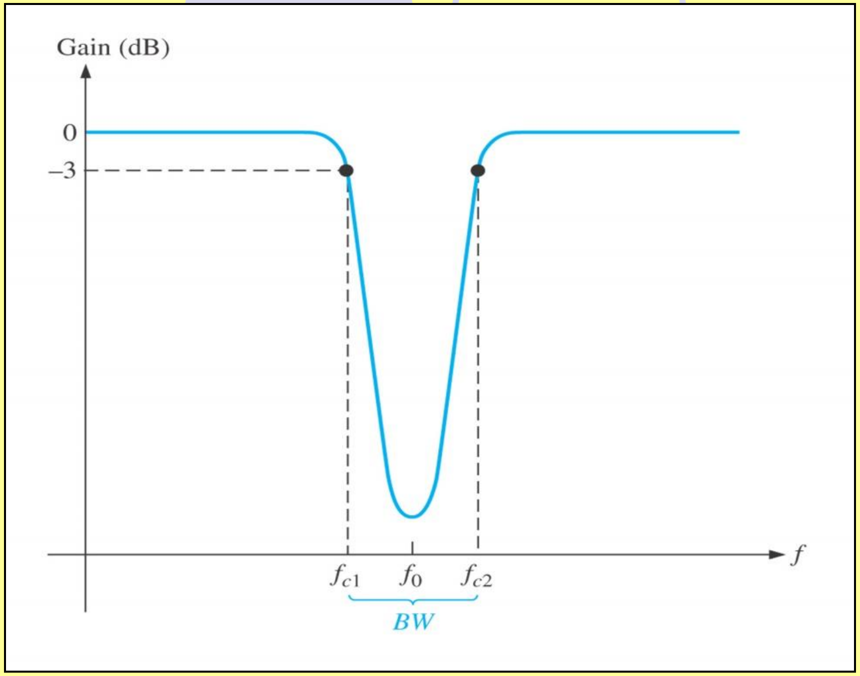
- The ***quality factor (Q)*** of a band-pass filter is the ratio of the center frequency to the bandwidth.

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

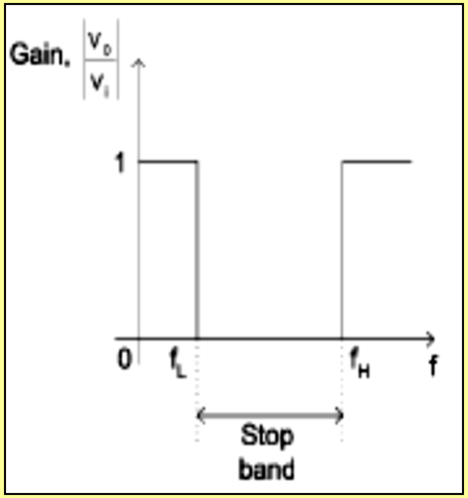
- The higher value of Q, the narrower the bandwidth and the better the selectivity for a given value of f_o.
- (Q>10) as a narrow-band or (Q<10) as a wide-band
- The quality factor (Q) can also be expressed in terms of the damping factor (DF) of the filter as :

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

Band-Stop Filter Response



Actual response



Ideal response

- Band-stop filter is a filter which its operation is opposite to that of the band-pass filter because the frequencies within the bandwidth are rejected, and the frequencies above f_{c1} and f_{c2} are passed.
- For the band-stop filter, the bandwidth is a band of frequencies between the 3 dB points, just as in the case of the band-pass filter response.

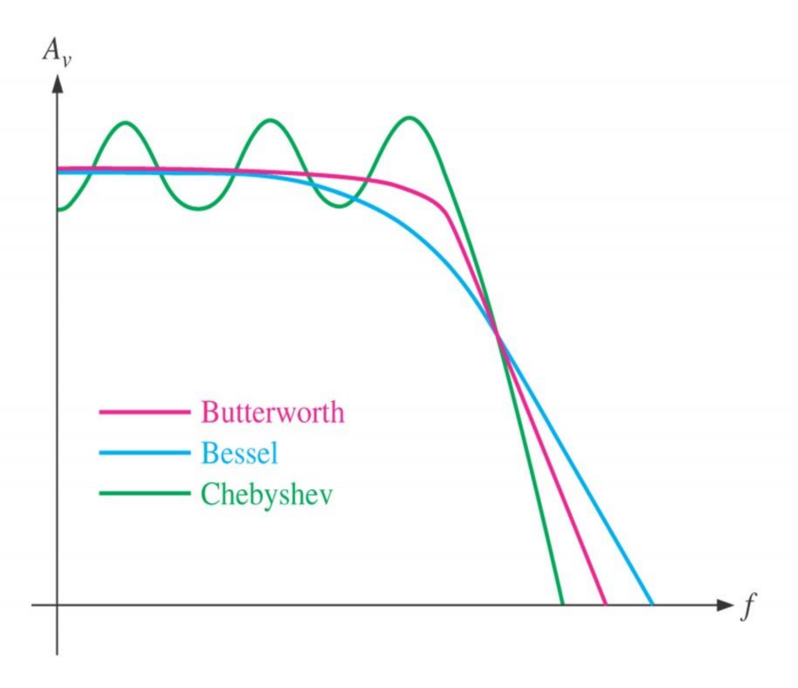
FILTER RESPONSE CHARACTERISTICS

- There are **3** characteristics of filter response :

i) **Butterworth** characteristic

ii) **Chebyshev** characteristic

iii) **Bessel** characteristic.

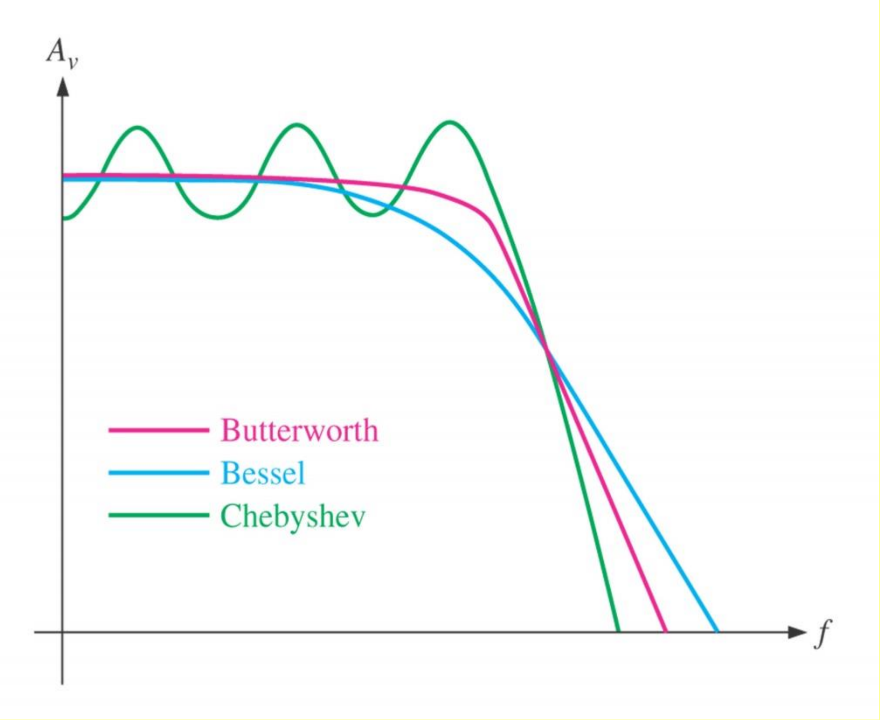


Comparative plots of three types of filter response characteristics.

- Each of the characteristics is identified by the shape of the response curve

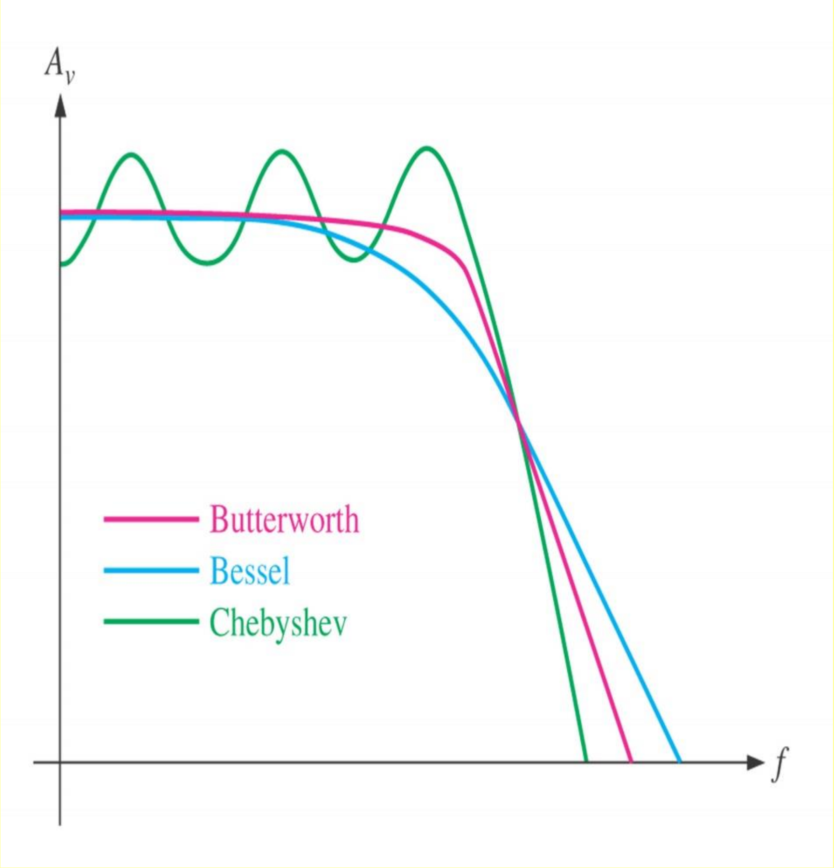
Butterwoth Characteristic

- Filter response is characterized by flat amplitude response in the passband.
- Provides a roll-off rate of -20 dB/decade/pole.
- Filters with the Butterworth response are normally used when all frequencies in the passband must have the ***same gain***.



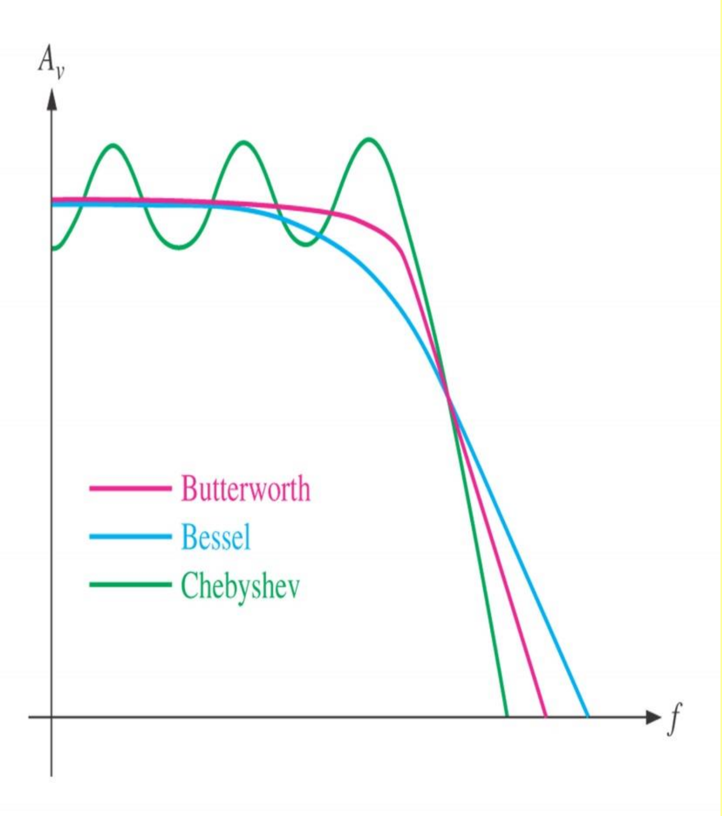
Chebyshev Characteristic

- Filter response is characterized by overshoot or ripples in the passband.
- Provides a roll-off rate greater than -20 dB/decade/pole.
- Filters with the Chebyshev response can be implemented with fewer poles and less complex circuitry for a given roll-off rate



Bessel Characteristic

- Filter response is characterized by a linear characteristic, meaning that the phase shift increases linearly with frequency.
- Filters with the Bessel response are used for filtering pulse waveforms without distorting the shape of waveform.



DAMPING FACTOR

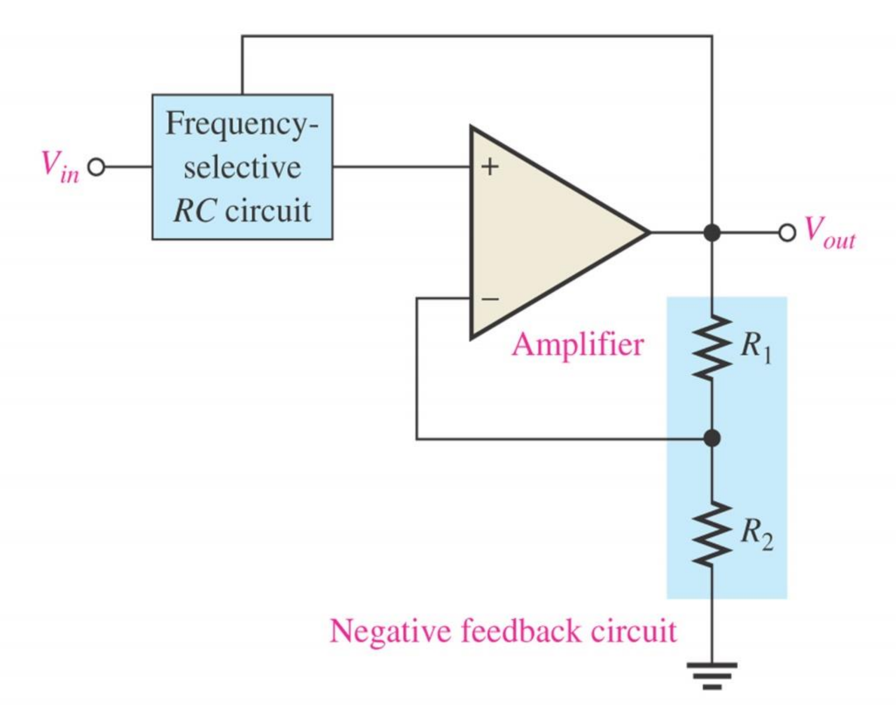
➢ The damping factor (DF) of an active filter determines which response characteristic the filter exhibits.

➢ This active filter consists of an amplifier, a negative feedback circuit and RC circuit.

➢ The amplifier and feedback are connected in a non-inverting configuration.

➢ DF is determined by the negative feedback and defined as :

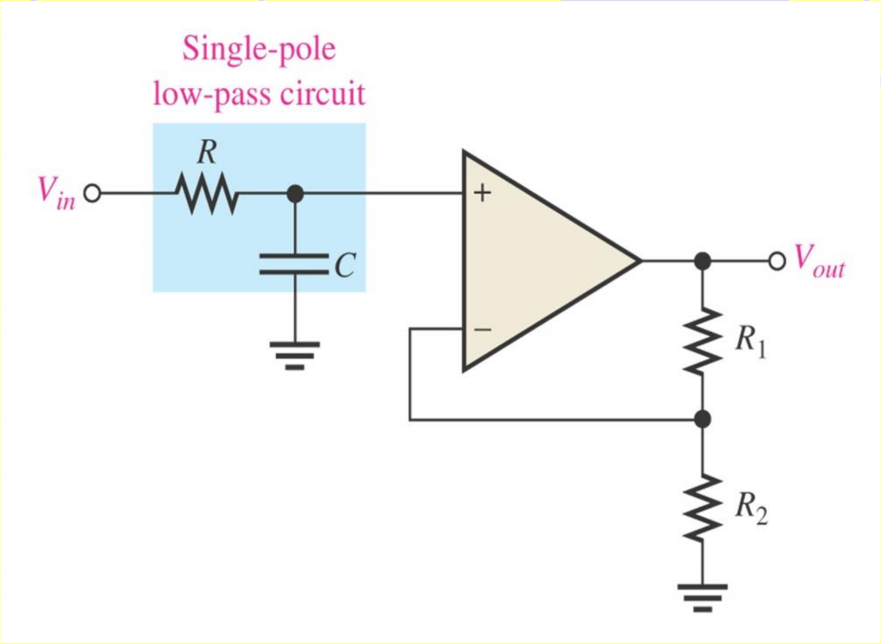
$$DF = 2 - \frac{R_1}{R_2}$$



General diagram of active filter

- The value of DF required to produce a desired response characteristics depends on order (number of poles) of the filter.
- A pole (single pole) is simply one resistor and one capacitor.
- The more poles filter has, the faster its roll-off rate

CRITICAL FREQUENCY AND ROLL-OFF RATE



One-pole (first-order) low-pass filter.

- The critical frequency, f_c is determined by the values of **R** and **C** in the frequency-selective RC circuit.
- Each RC set of filter components represents a pole.
- Greater roll-off rates can be achieved with more poles.
- Each pole represents a -20dB/decade increase in roll-off.

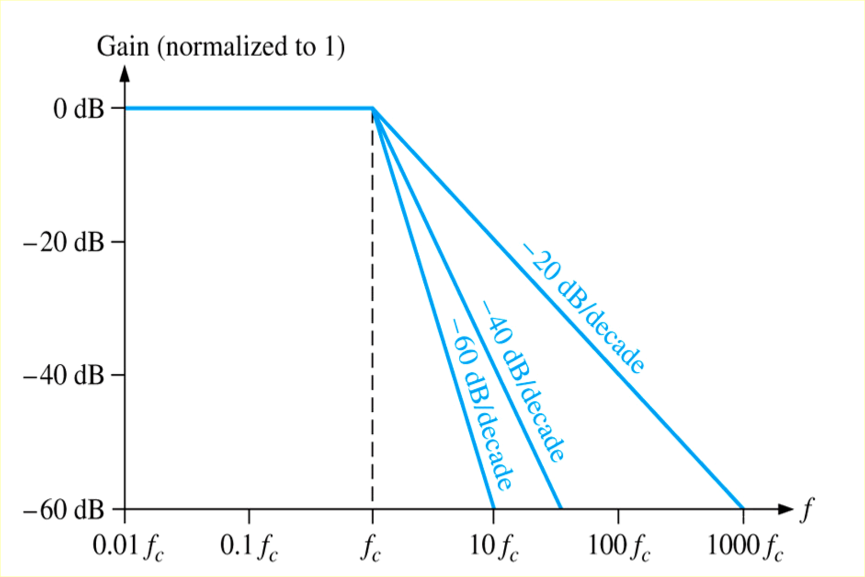
- For a single-pole (first-order) filter, the critical frequency is :

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

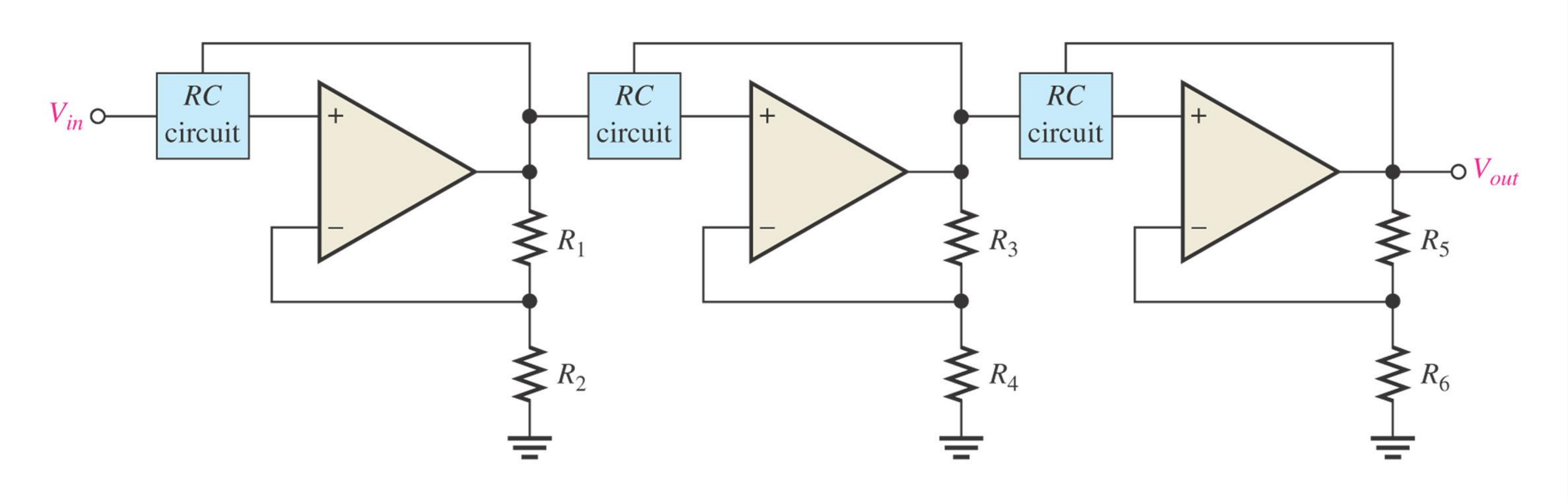
- The above formula can be used for both low-pass and high-pass filters.

➢ The number of poles determines the roll-off rate of the filter. For example, a Butterworth response produces -20dB/decade/pole. This means that:

- One-pole (first-order) filter has a roll-off of -20 dB/decade
- Two-pole (second-order) filter has a roll-off of -40 dB/decade
- Three-pole (third-order) filter has a roll-off of -60 dB/decade



➢ The number of filter poles can be increased by ***cascading***. To obtain a filter with three poles, cascade a two-pole with one-pole filters.



Three-pole (third-order) low-pass filter.

ACTIVE LOW-PASS FILTERS

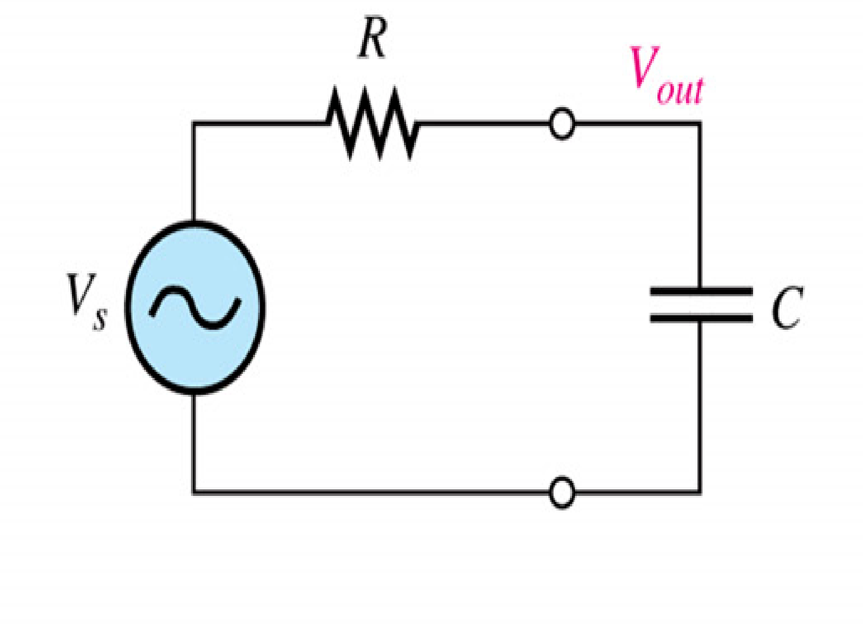
Advantages of active filters over passive filters (R, L, and C elements only):

1. By containing the op-amp, active filters can be designed to provide required gain, and hence **no signal attenuation** as the signal passes through the filter.

2. **No loading problem**, due to 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.

3. **Easy to adjust over a wide frequency range** without altering the desired response.

- Figure below shows the basic Low-Pass filter circuit



(b) Basic low-pass circuit

At critical frequency,

Resistance = Capacitance

$$R = X_c$$

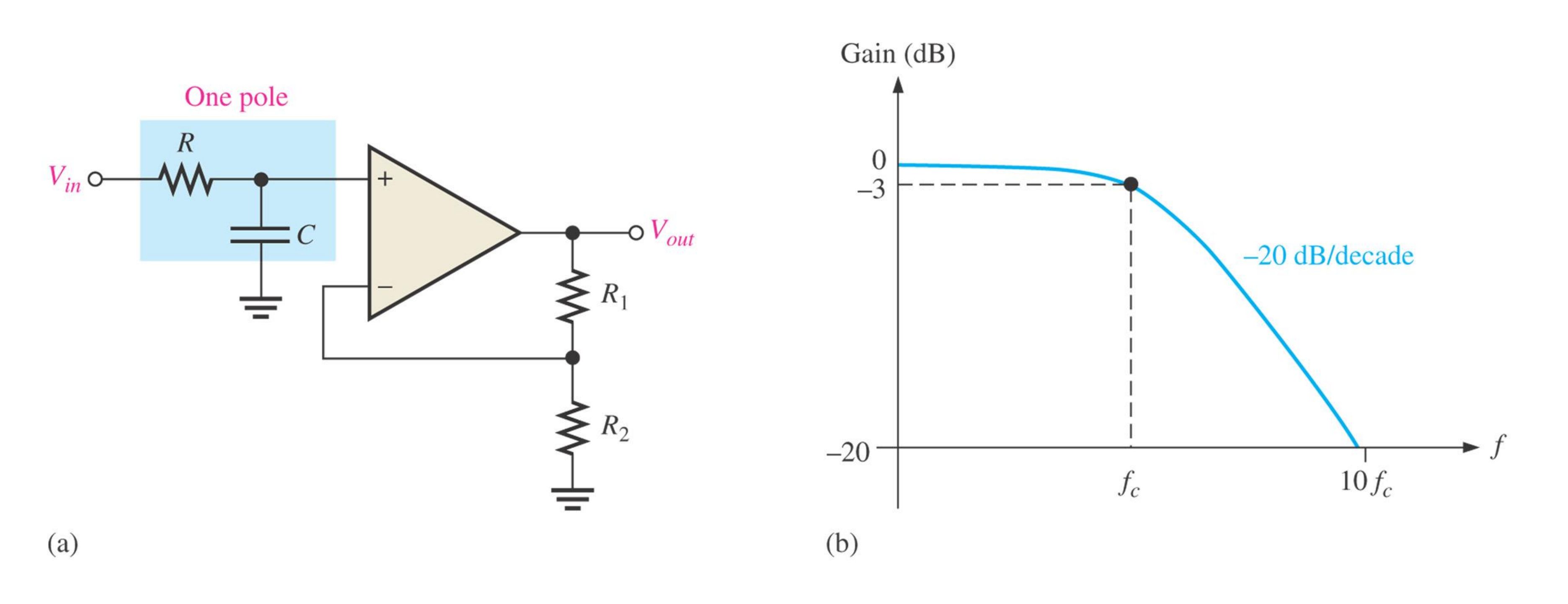
$$R = \frac{1}{\omega_c C}$$

$$R = \frac{1}{2\pi f_c C}$$

So, critical frequency ;

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

Single-Pole Filter



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

- This filter provides a roll-off rate of -20 dB/decade above the critical frequency.

- The op-amp in single-pole filter is connected as a noninverting amplifier with the closed-loop voltage gain in the passband is set by the values of R_1 and R_2 :

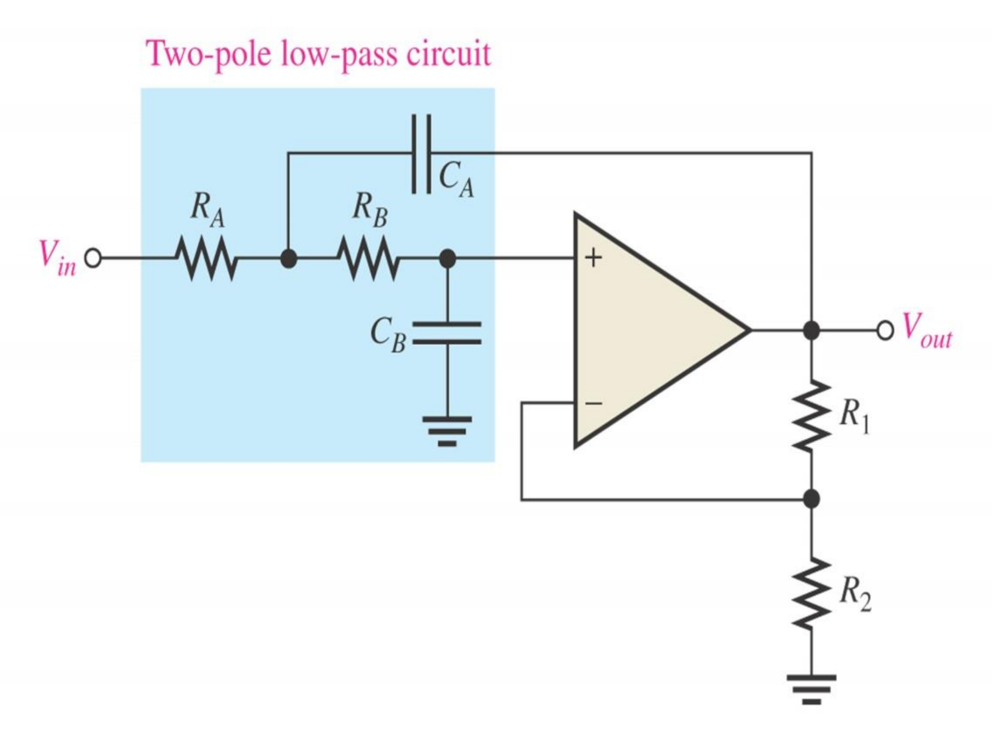
$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$

- The critical frequency of the single-pole filter is :

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

Sallen-Key Low-Pass Filter

➢ Sallen-Key is one of the most common configurations for a second order (two-pole) filter.



Basic Sallen-Key low-pass filter.

➢ There are two low-pass RC circuits that provide a roll-off of -40 dB/decade above f_c (assuming a Butterworth characteristics).

➢ One RC circuit consists of R_A and C_A, and the second circuit consists of R_B and C_B.

- The critical frequency for the Sallen-Key filter is :

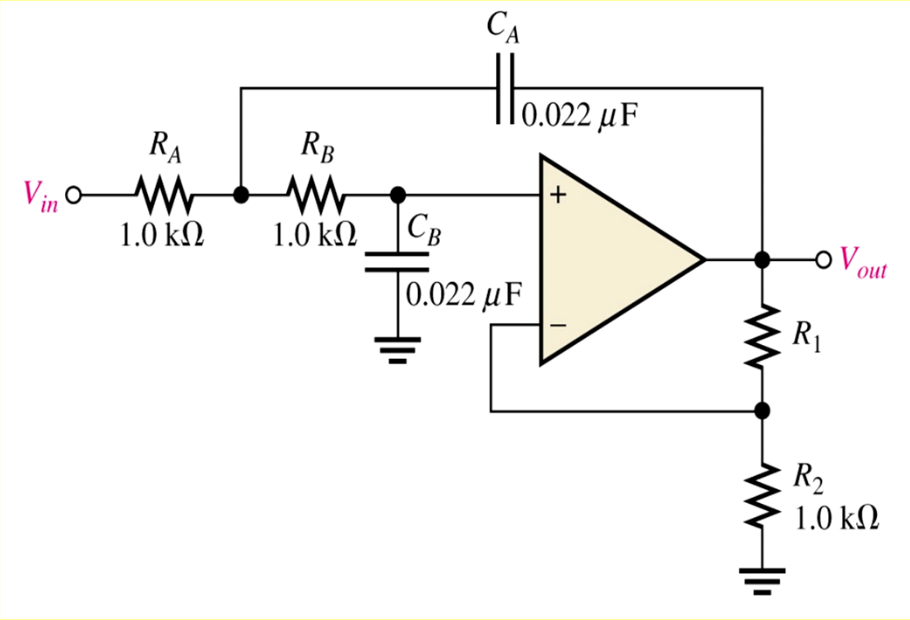
$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

- For $R_A = R_B = R$ and $C_A = C_B = C$, thus the critical frequency :

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

Example :

- Determine critical frequency
- Set the value of R_1 for Butterworth response by giving that Butterworth response for second order is 0.586



- Critical frequency

$$\boxed{f_c = \frac{1}{2\pi RC} = 7.23kHz}$$

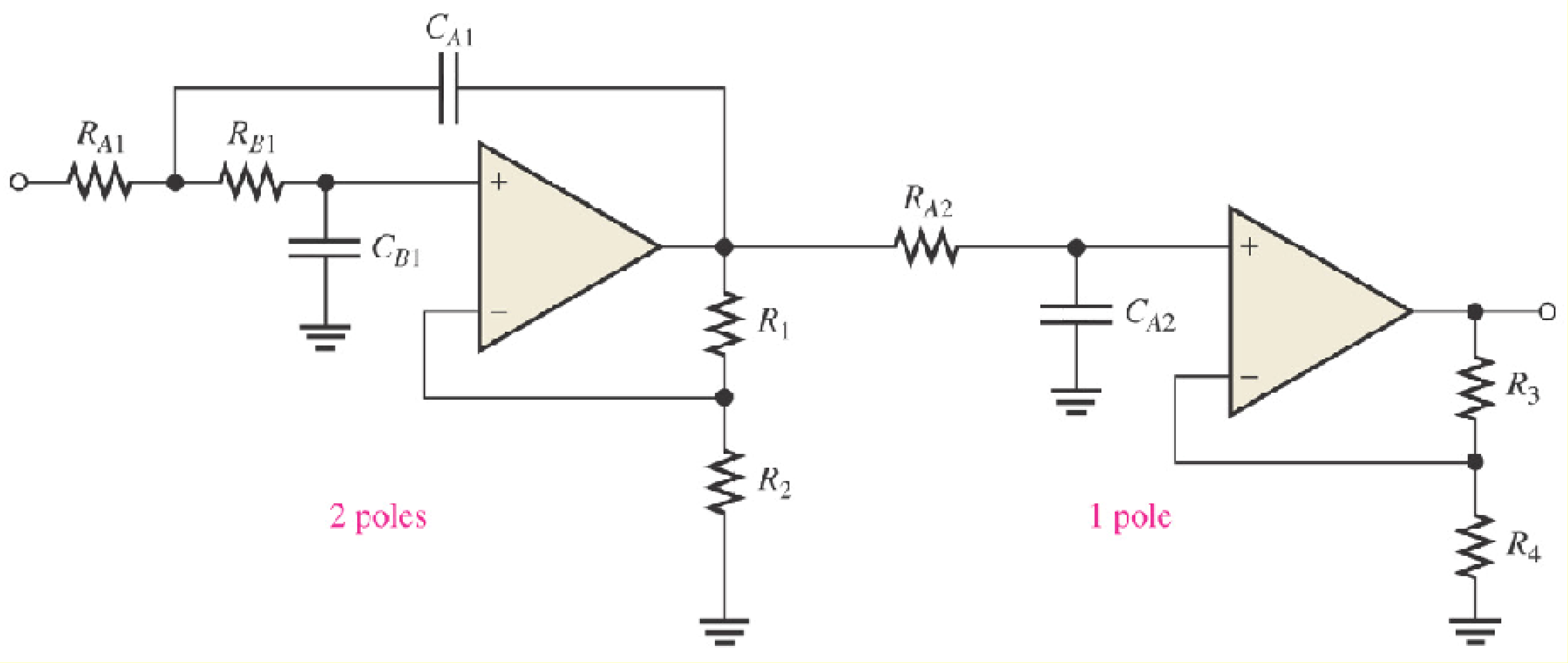
- Butterworth response given $R_1/R_2 = 0.586$

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

$$\boxed{R_1 = 586k\Omega}$$

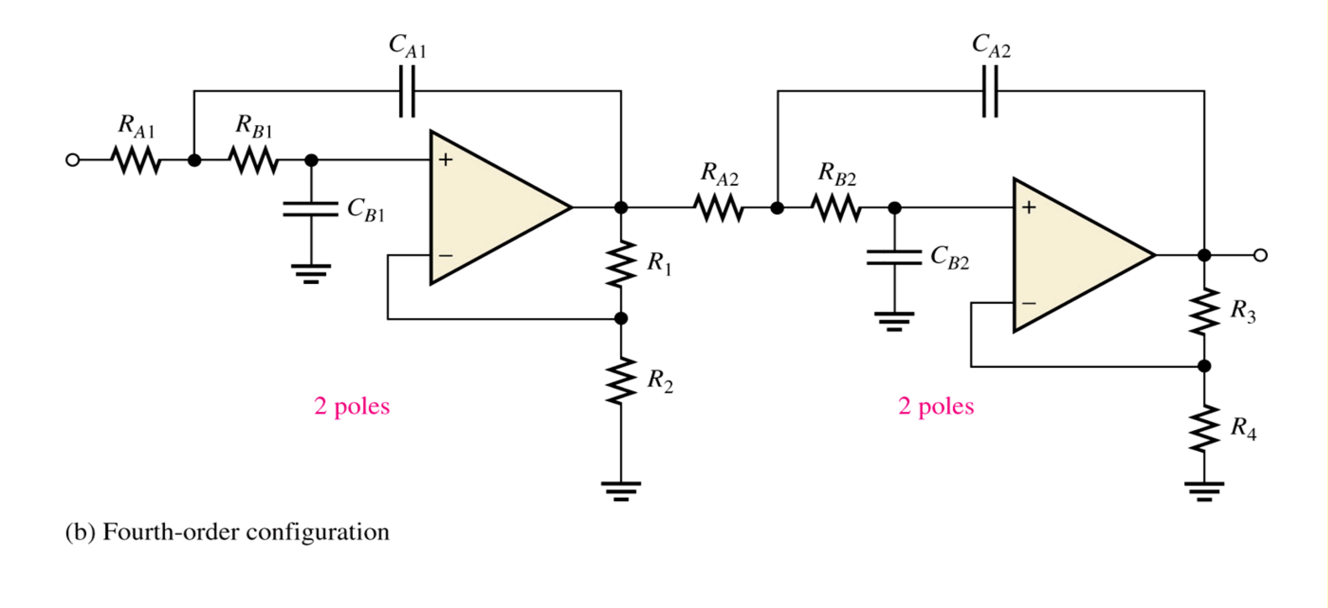
Cascading Low-Pass Filter

➢ A three-pole filter is required to provide a roll-off rate of -60 dB/decade. This is done by cascading a two-pole Sallen-Key low-pass filter and a single-pole low-pass filter.



Cascaded low-pass filter: third-order configuration.

➢ A four-pole filter is required to provide a roll-off rate of -80 dB/decade. This is done by cascading a two-pole Sallen-Key low-pass filter and a two-pole Sallen-Key low-pass filter.

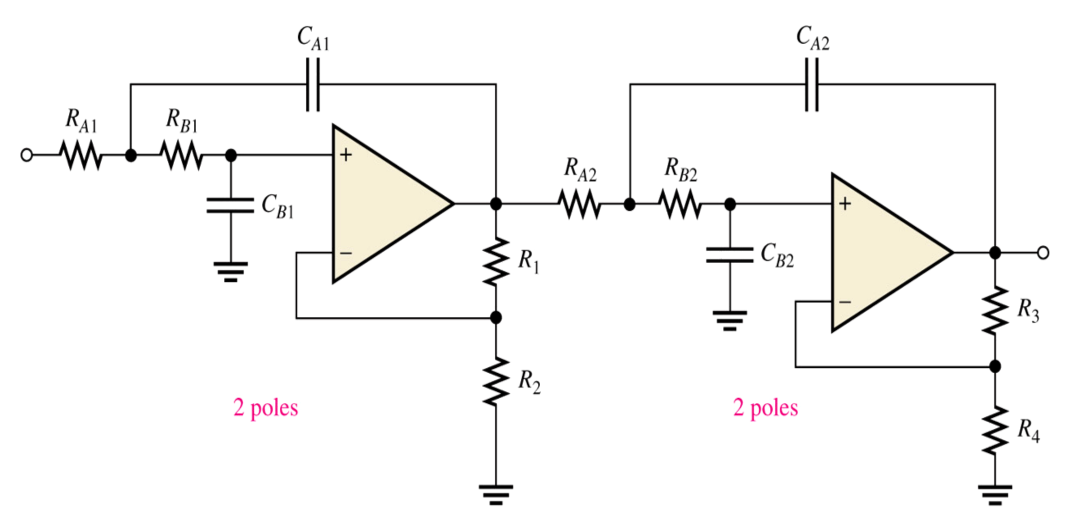


(b) Fourth-order configuration

Cascaded low-pass filter: fourth-order configuration.

Example :

- Determine the capacitance values required to produce a critical frequency of 2680 Hz if all resistors in RC low pass circuit is 1.8kΩ



(b) Fourth-order configuration

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

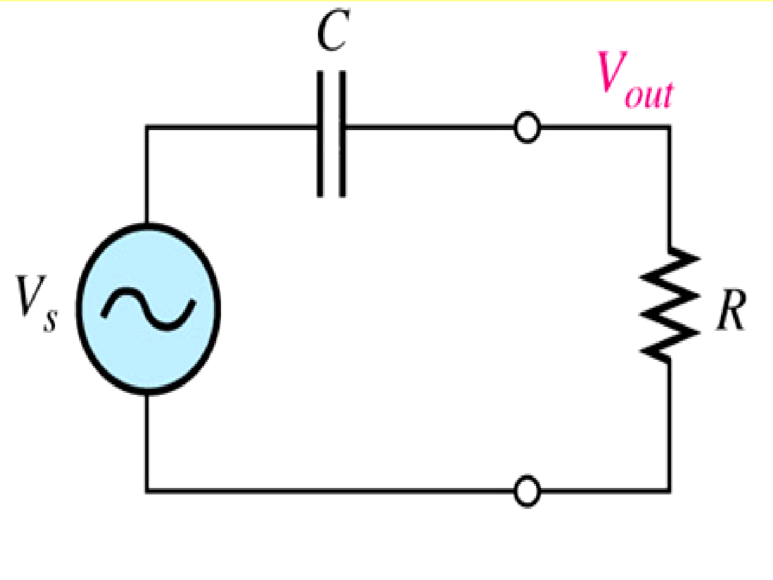
$$C = \frac{1}{2\pi f_c R} = 0.033\mu F$$

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

- Both stages must have the same f_c. Assume equal-value of capacitor

ACTIVE HIGH-PASS FILTERS

- Figure below shows the basic High-Pass filter circuit :



(b) Basic high-pass circuit

At critical frequency,

Resistance = Capacitance

$$R = X_c$$

$$R = \frac{1}{\omega_c C}$$

$$R = \frac{1}{2\pi f_c C}$$

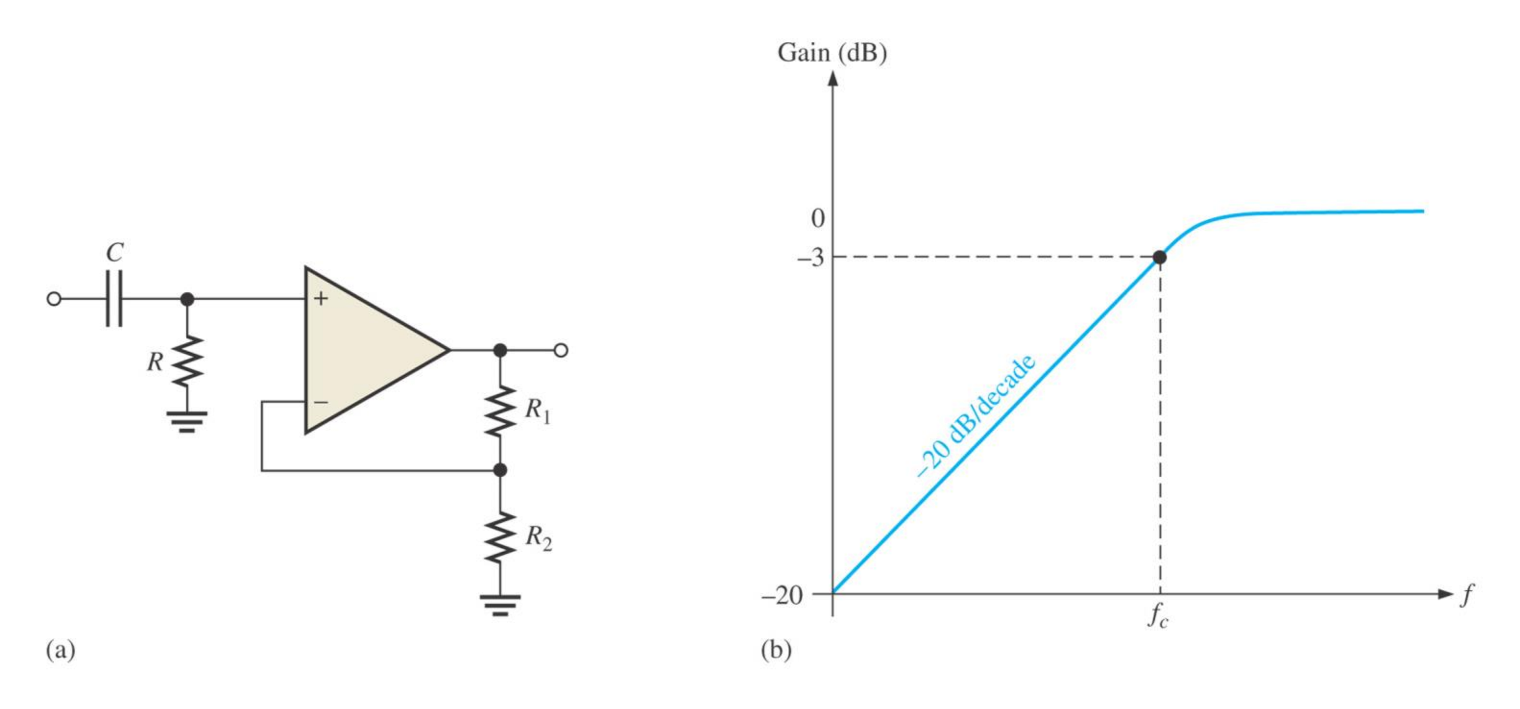
So, critical frequency ;

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

Single-Pole Filter

➢ In high-pass filters, the roles of the capacitor and resistor are reversed in the RC circuits as shown from Figure (a). The negative feedback circuit is the same as for the low-pass filters.

➢ Figure (b) shows a high-pass active filter with a -20dB/decade roll-off



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

- The op-amp in single-pole filter is connected as a noninverting amplifier with the closed-loop voltage gain in the passband is set by the values of R_1 and R_2 :

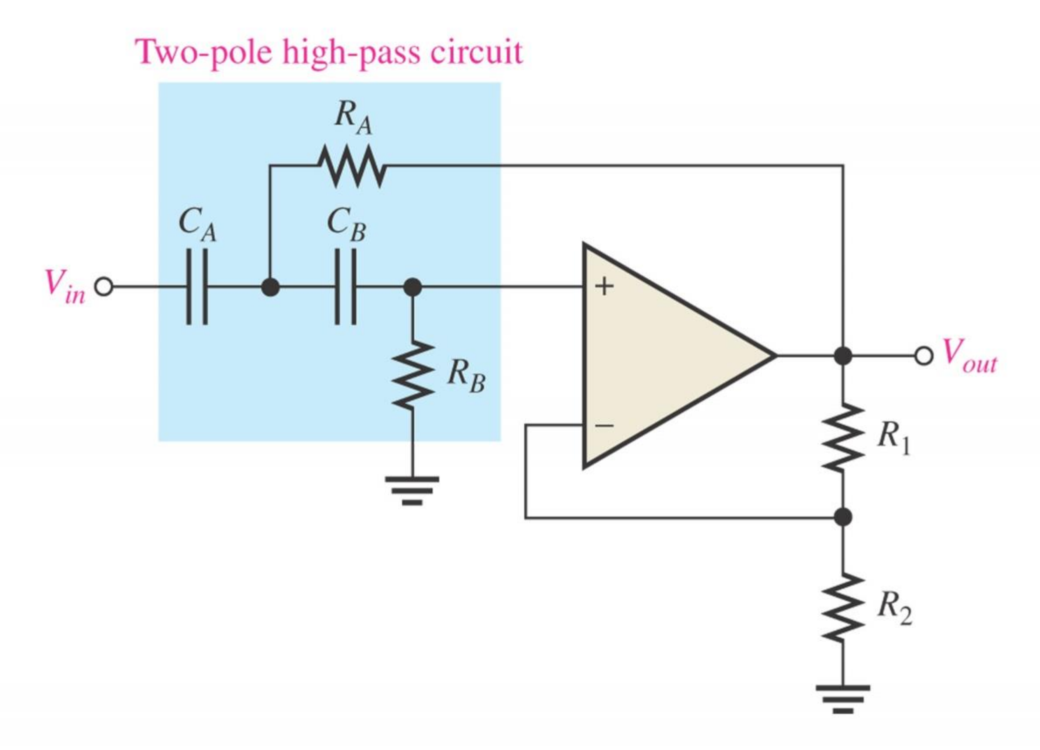
$$A_{cl(NI)} = \frac{R_1}{R_2} + 1$$

- The critical frequency of the single-pole filter is :

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

Sallen-Key High-Pass Filter

- Components R_A, C_A, R_B, and C_B form the second order (two-pole) frequency-selective circuit.
- The position of the resistors and capacitors in the frequency-selective circuit are opposite in low pass configuration.
- There are two high-pass RC circuits that provide a roll-off of -40 dB/decade above fc
- The response characteristics can be optimized by proper selection of the feedback resistors, R_1 and R_2.



Basic Sallen-Key high-pass filter.

- The critical frequency for the Sallen-Key filter is :

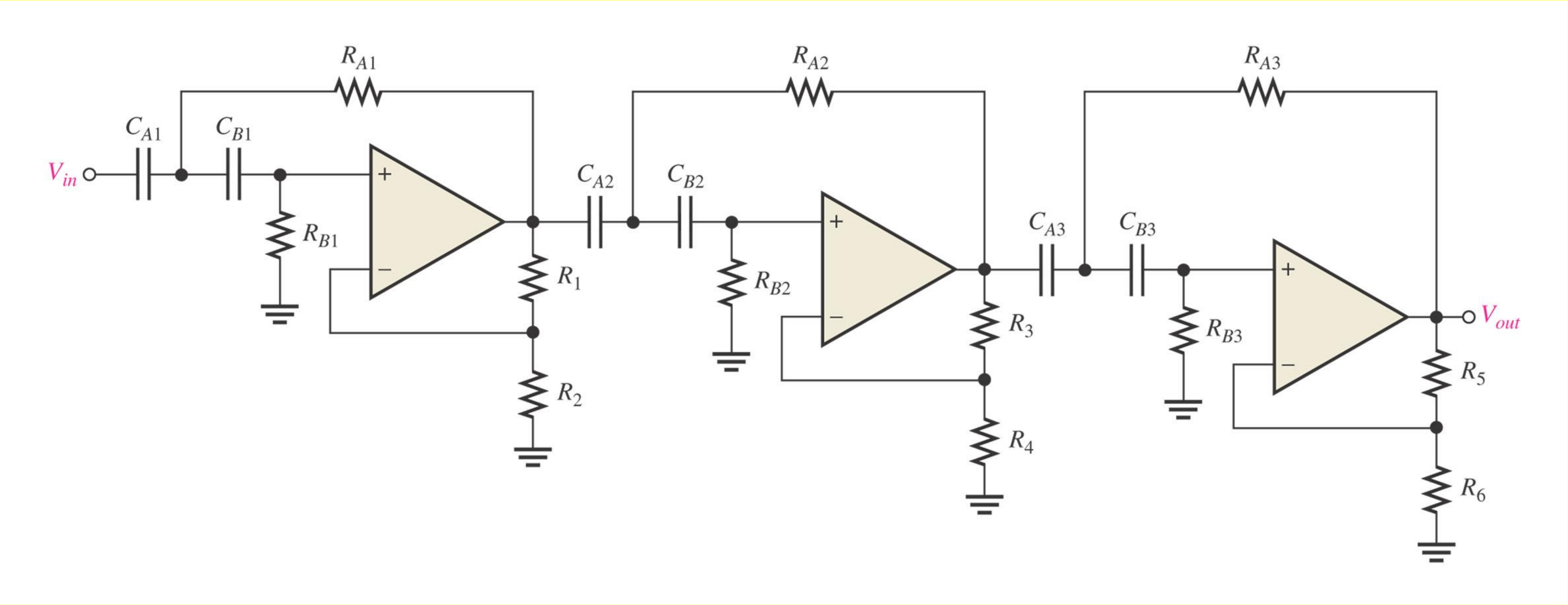
$$f_c = \frac{1}{2\pi\sqrt{R_A R_B C_A C_B}}$$

- For $R_A = R_B = R$ and $C_A = C_B = C$, thus the critical frequency :

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

Cascading High-Pass Filter

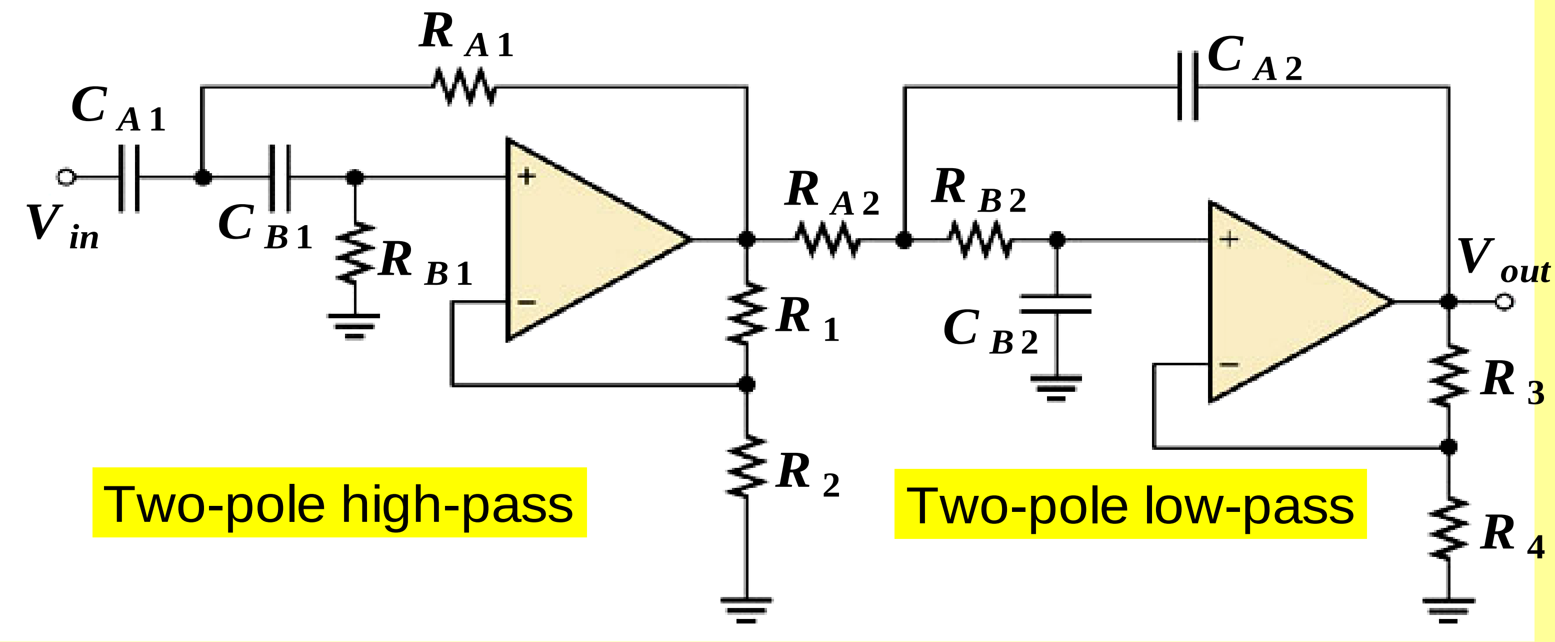
- As with the low-pass filter, first- and second-order high-pass filters can be cascaded to provide three or more poles and thereby create faster roll-off rates.
- A six-pole high-pass filter consisting of three Sallen-Key two-pole stages with the roll-off rate of -120 dB/decade.



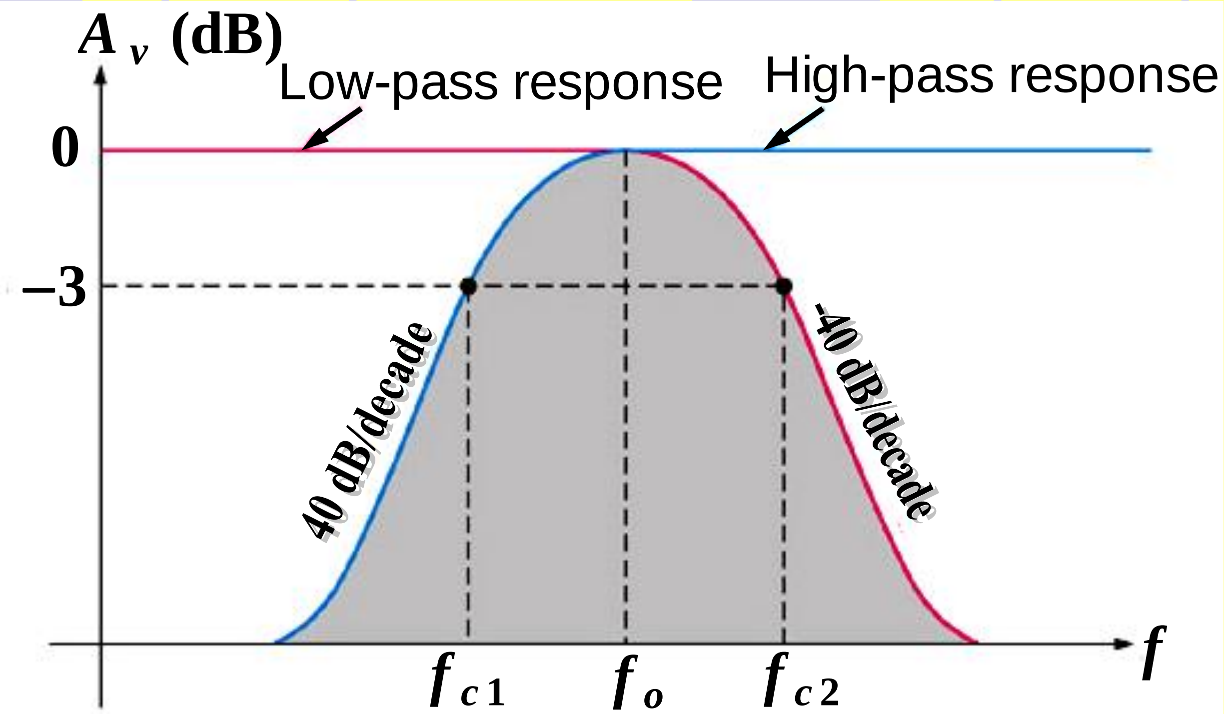
Sixth-order high-pass filter

ACTIVE BAND-PASS FILTERS

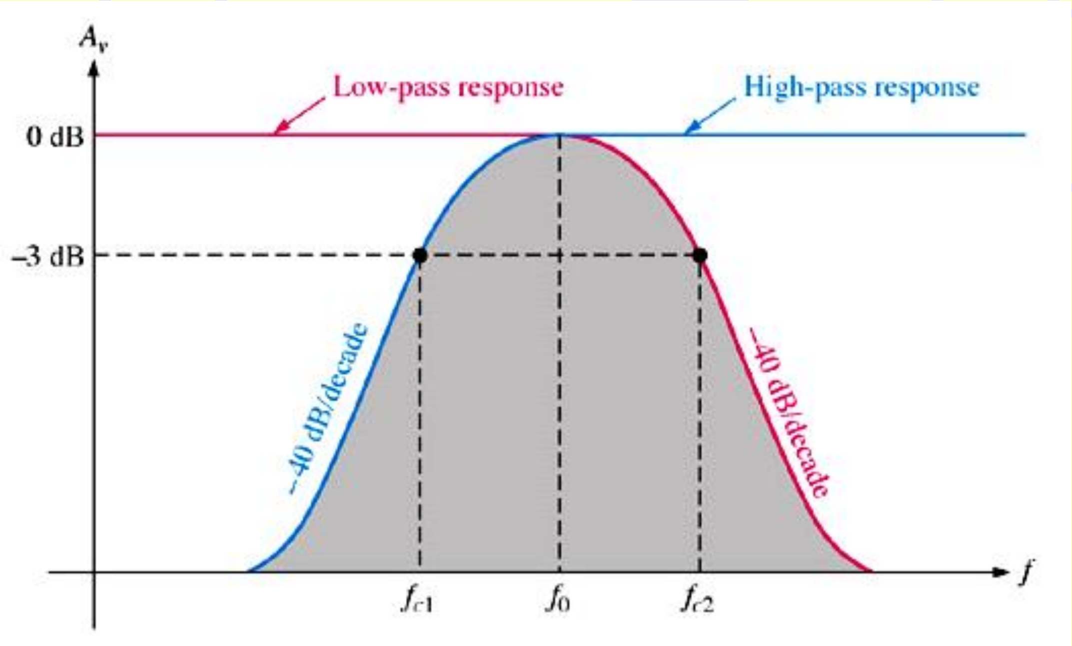
Cascaded Low-Pass and High-Pass Filters



- Band-pass filter is formed by cascading a two-pole high-pass and two pole low-pass filter.
- Each of the filters shown is Sallen-Key Butterworth configuration, so that the roll-off rate are -40dB/decade.



- The lower frequency f_{c1} of the passband is the critical frequency of the high-pass filter.
- The upper frequency f_{c2} of the passband is the critical frequency of the low-pass filter.



- The following formulas express the three frequencies of the band-pass filter.

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

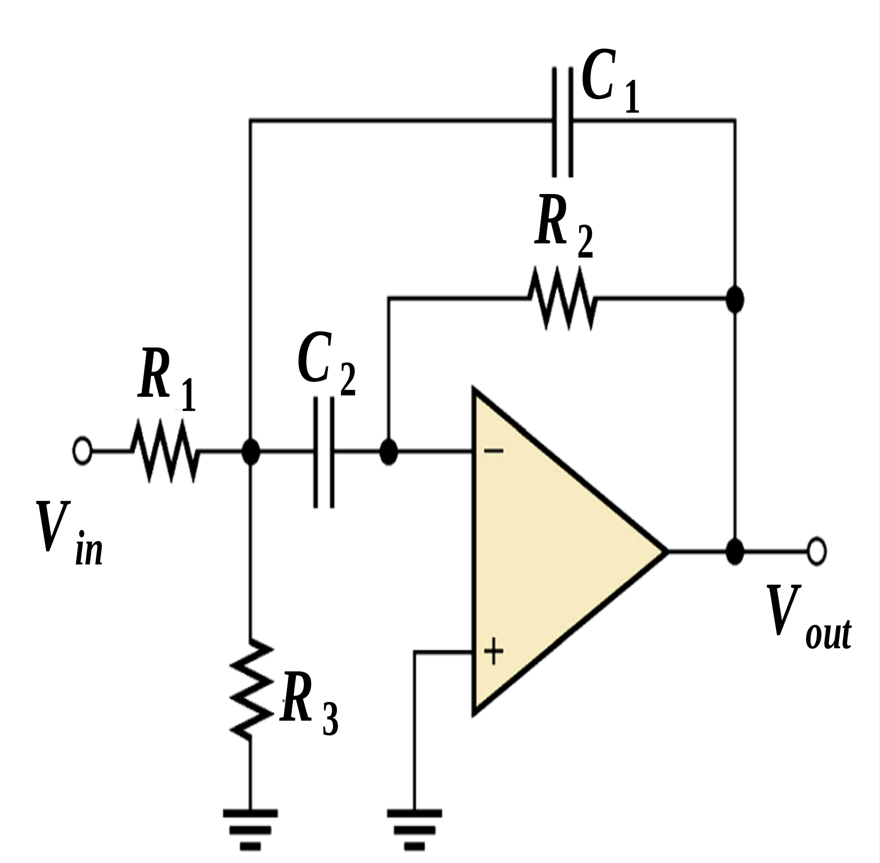
$$f_{c2} = \frac{1}{2\pi\sqrt{R_{A2}R_{B2}C_{A2}C_{B2}}}$$

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

- If equal-value components are used in implementing each filter,

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

Multiple-Feedback Band-Pass Filter



- The low-pass circuit consists of $\boldsymbol{R_1}$ and $\boldsymbol{C_1}$.
- The high-pass circuit consists of $\boldsymbol{R_2}$ and $\boldsymbol{C_2}$.
- The feedback paths are through $\boldsymbol{C_1}$ and $\boldsymbol{R_2}$.
- Center frequency;

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

- By making C1 = C2 =C, yields

$$f_0 = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_3}{R_1 R_2 R_3}}$$

- The resistor values can be found by using following formula

$$R_1 = \frac{Q}{2\pi f_o C A_o}$$

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

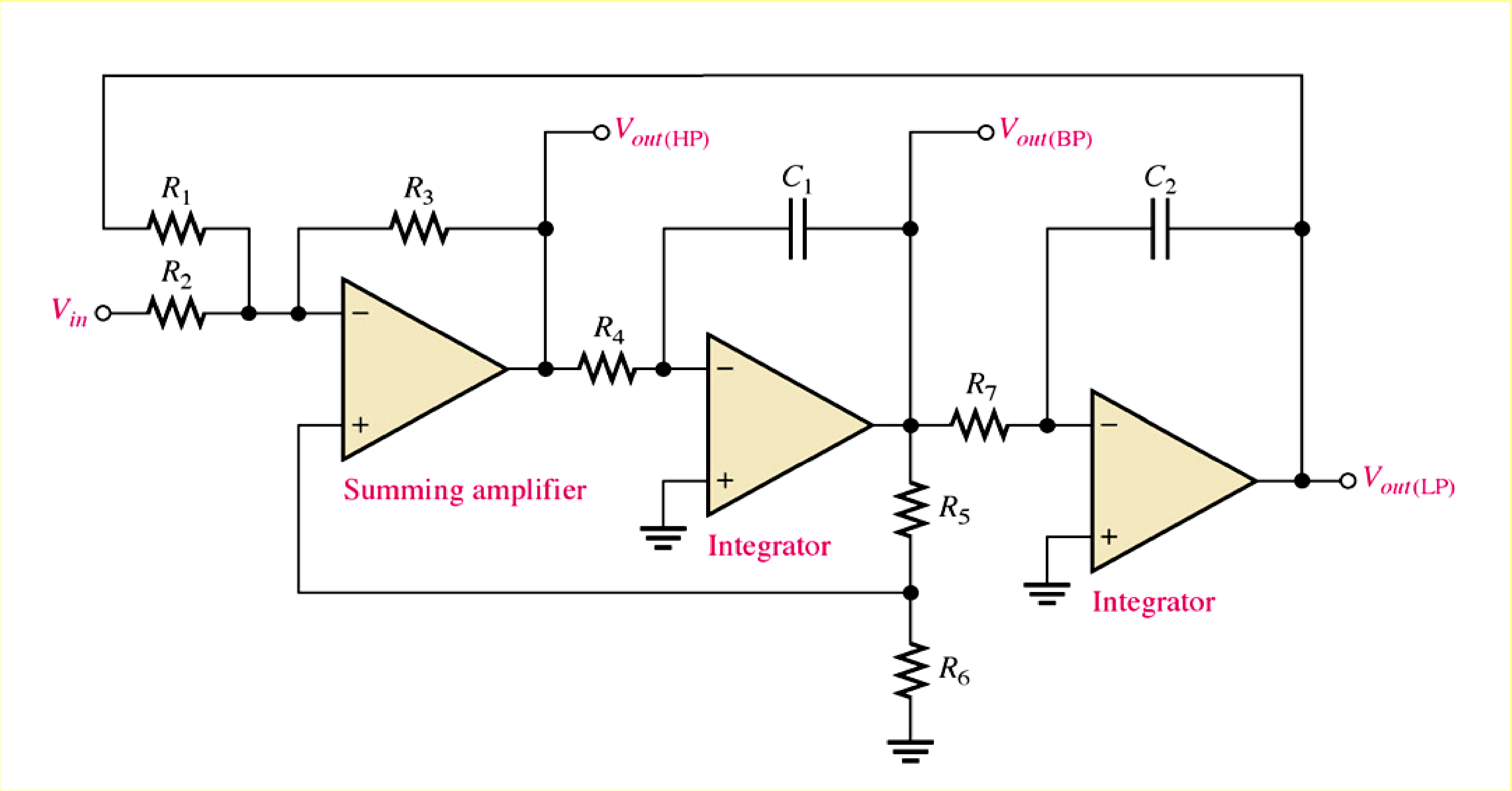
$$R_3 = \frac{Q}{2\pi f_o C(2Q^2 - A_o)}$$

- The maximum gain, A_o occurs at the center frequency.

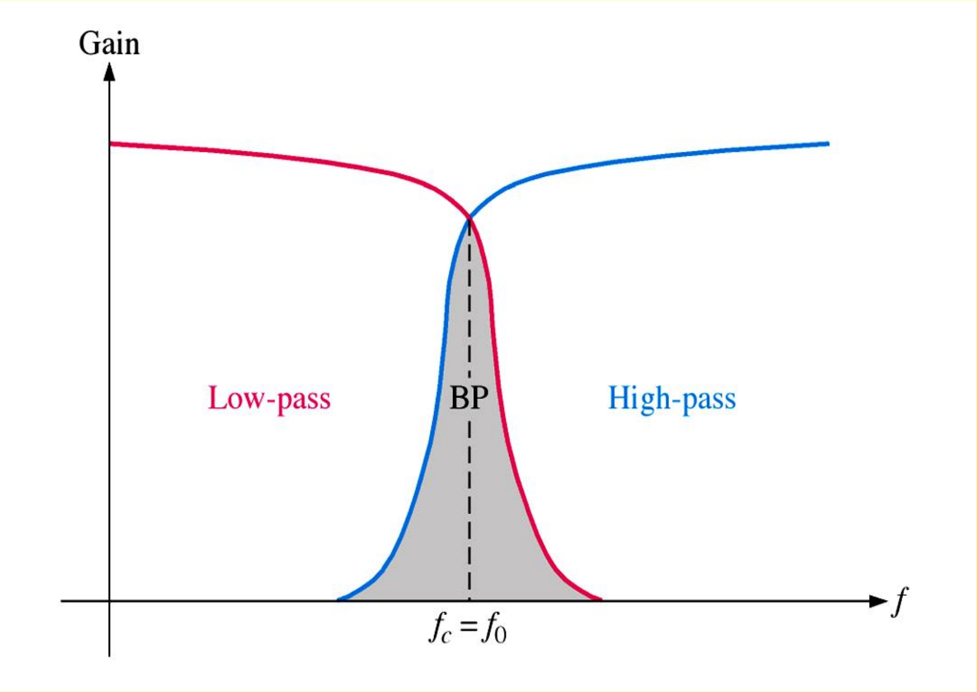
$$A_o = \frac{R_2}{2R_1}$$

State-Variable Filter

- State-Variable BPF is widely used for band-pass applications.



- It consists of a summing amplifier and two integrators.
- It has outputs for low-pass, high-pass, and band-pass.
- The center frequency is set by the integrator RC circuits.
- The critical frequency of the integrators usually made equal
- R_5 and R_6 set the Q (bandwidth).



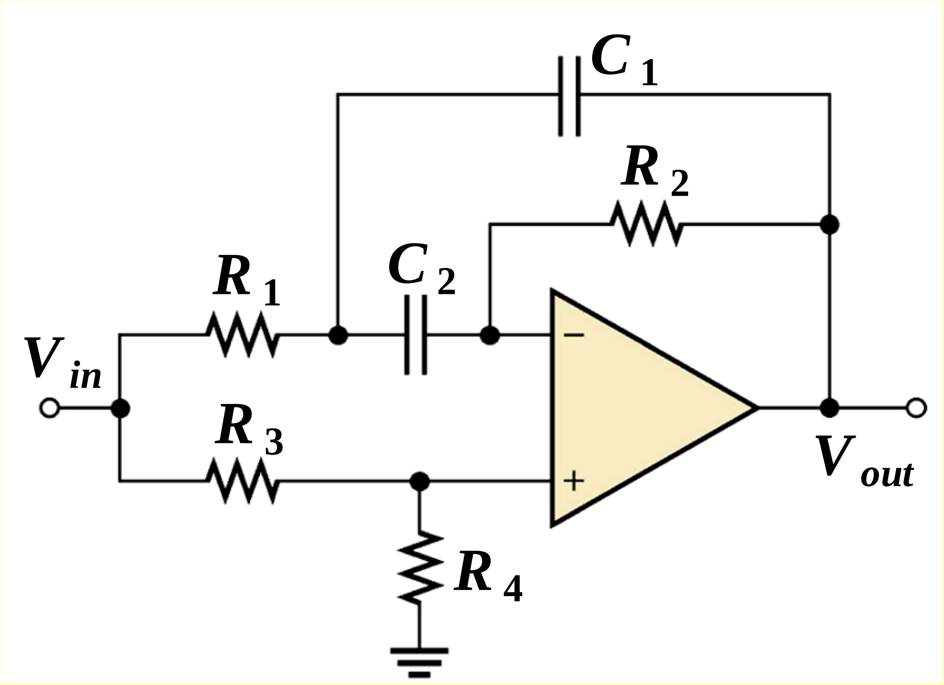
- The band-pass output peaks sharply the center frequency giving it a high Q.

- The Q is set by the feedback resistors R_5 and R_6 according to the following equations :

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

ACTIVE BAND-STOP FILTERS

Multiple-Feedback Band-Stop Filter



- The configuration is similar to the band-pass version BUT R_3 has been moved and R_4 has been added.
- The BSF is opposite of BPF in that it blocks a specific band of frequencies

FILTER RESPONSE MEASUREMENT

- Measuring frequency response can be performed with typical bench-type equipment.
- It is a process of setting and measuring frequencies both outside and inside the known cutoff points in predetermined steps.
- Use the output measurements to plot a graph.
- More accurate measurements can be performed with sweep generators along with an oscilloscope, a spectrum analyzer, or a scalar analyzer.

SUMMARY

- The bandwidth of a low-pass filter is the same as the upper critical frequency.
- The bandwidth of a high-pass filter extends from the lower critical frequency up to the inherent limits of the circuit.
- The band-pass passes frequencies between the lower critical frequency and the upper critical frequency.

- A band-stop filter rejects frequencies within the upper critical frequency and upper critical frequency.
- The Butterworth filter response is very flat and has a roll-off rate of –20 B
- The Chebyshev filter response has ripples and overshoot in the passband but can have roll-off rates greater than –20 dB

- The Bessel response exhibits a linear phase characteristic, and filters with the Bessel response are better for filtering pulse waveforms.
- A filter pole consists of one RC circuit. Each pole doubles the roll-off rate.
  The Q of a filter indicates a band-pass filter's selectivity. The higher the Q the narrower the bandwidth.
- The damping factor determines the filter response characteristic.