Introduction to Communication Systems

Chapter 2
Electronic Fundamentals for Communications

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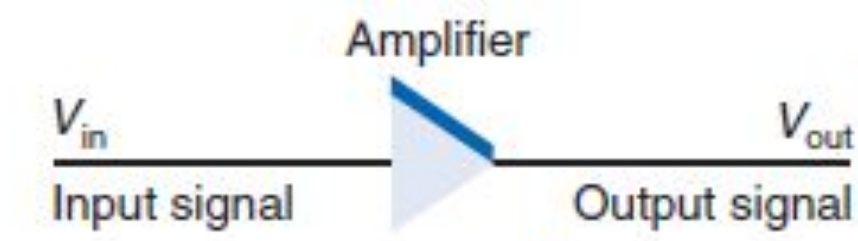
Text Book

- Principles of Electronic Communication Systems
  - L. E. Frenzel
  - 4th edition

Gain

- *Gain means amplification. If a signal is applied to a circuit such as the amplifier* and the output of the circuit has a greater amplitude than the input signal, the circuit has gain.
- Gain is simply the ratio of the output to the input. For input (V_{in}) and output (V_{out}) *voltages, voltage gain A_V is expressed as follows:*



$$A_V = \frac{\text{output}}{\text{input}} = \frac{V_{out}}{V_{in}}$$

Example 2-1

What is the voltage gain of an amplifier that produces an output of 750 mV for a 30-μV input?

$$A_V = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{750 \times 10^{-3}}{30 \times 10^{-6}} = 25{,}000$$

Power gain

- power gain A_p :

$$A_P = \frac{P_{\text{out}}}{P_{\text{in}}}$$

where P_{in} *is the power input and* P_{out} *is the power output.*

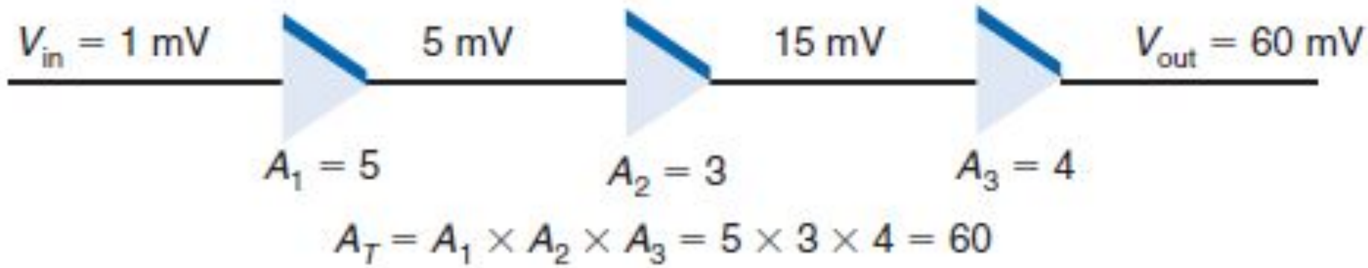
Example 2-2

The power output of an amplifier is 6 watts (W). The power gain is 80. What is the input power?

$$A_P = \frac{P_{\text{out}}}{P_{\text{in}}} \qquad \text{therefore} \qquad P_{\text{in}} = \frac{P_{\text{out}}}{A_P}$$

$$P_{\text{in}} = \frac{6}{80} = 0.075 \text{ W} = 75 \text{ mW}$$

Total gain of cascaded circuits is the product of individual stage gains.



Gain of cascaded amplifier

Example 2-3

Three cascaded amplifiers have power gains of 5, 2, and 17. The input power is 40 mW. What is the output power?

$$A_P = A_1 \times A_2 \times A_3 = 5 \times 2 \times 17 = 170$$

$$A_P = \frac{P_{\text{out}}}{P_{\text{in}}} \qquad \text{therefore} \qquad P_{\text{out}} = A_P P_{\text{in}}$$

$$P_{\text{out}} = 170(40 \times 10^{-3}) = 6.8 \text{ W}$$

Example 2-4

A two-stage amplifier has an input power of 25 μW and an output power of 1.5 mW. One stage has a gain of 3. What is the gain of the second stage?

$$A_P = \frac{P_{out}}{P_{in}} = \frac{1.5 \times 10^{-3}}{25 \times 10^{-6}} = 60$$

$$A_P = A_1 \times A_2$$

If $A_1 = 3$, then $60 = 3 \times A_2$ and $A_2 = 60/3 = 20$.

Attenuation

- *Attenuation refers to a loss introduced by a circuit or component.*
- *Many electronic circuits,* sometimes called stages, reduce the amplitude of a signal rather than increase it.
- If the output signal is lower in amplitude than the input, the signal is said to be attenuated.
- Like gain, attenuation is simply the ratio of the output to the input. The letter *A is used to* represent attenuation as well as gain:

$$\text{Attenuation } A = \frac{\text{output}}{\text{input}} = \frac{V_{\text{out}}}{V_{\text{in}}}$$

A voltage divider introduces attenuation.

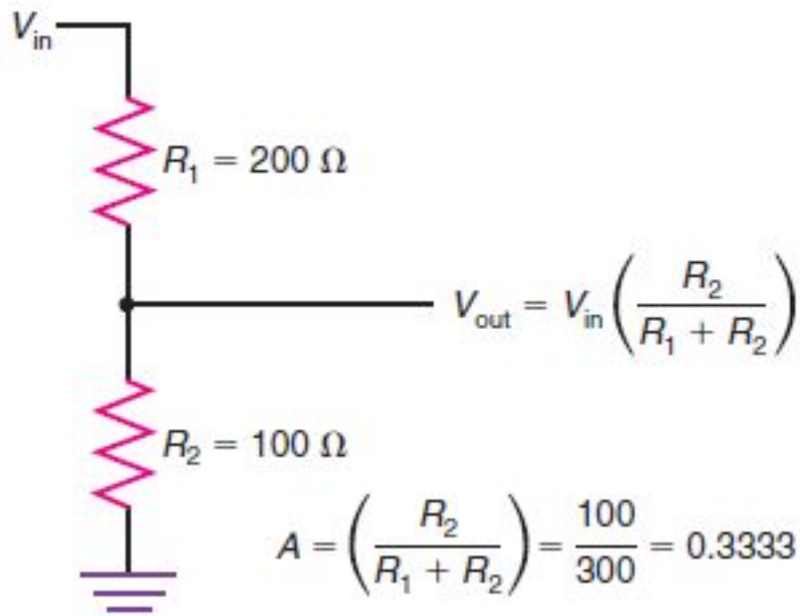
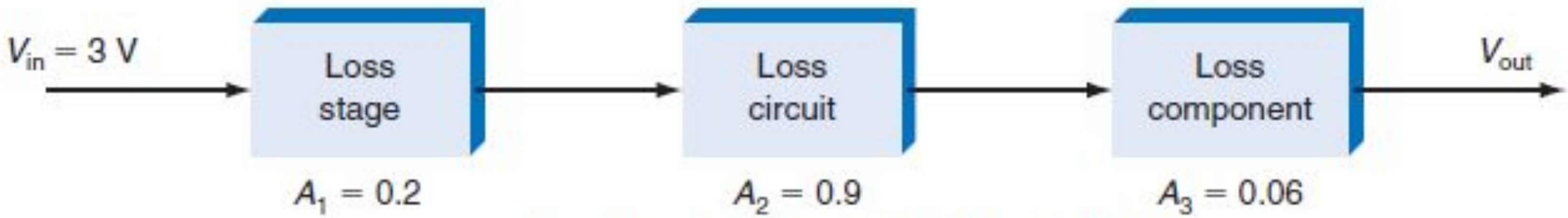


Figure 2-4 Total attenuation is the product of individual attenuations of each cascaded circuit.

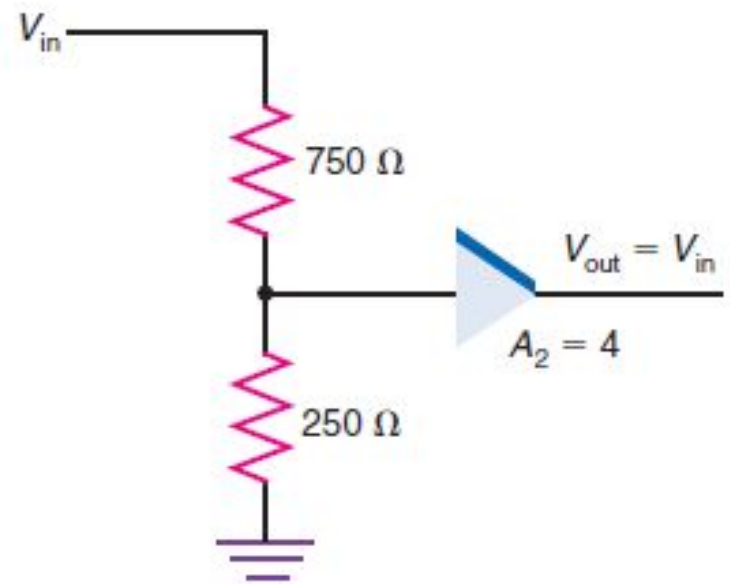


$$A_T = A_1 \times A_2 \times A_3 = 0.2 \times 0.9 \times 0.06 = 0.0108$$

$$V_{out} = A_T V_{in} = 0.0324 = 32.4 \text{ mV}$$

Attenuator and Amplifier

Figure 2-5 Gain exactly offsets the attenuation.



$$A_1 = \frac{250}{750 + 250} \qquad A_T = A_1 A_2 = 0.25(4) = 1$$

$$A_1 = \frac{250}{1000} = 0.25$$

Example 2-5

A voltage divider such as that shown in Fig. 2-5 has values of $R_1 = 10\ \text{k}\Omega$ and $R_2 = 470\ \Omega$.

a. What is the attenuation?

$$A_1 = \frac{R_2}{R_1 + R_2} = \frac{470}{10{,}470} \qquad A_1 = 0.045$$

b. What amplifier gain would you need to offset the loss for an overall gain of 1?

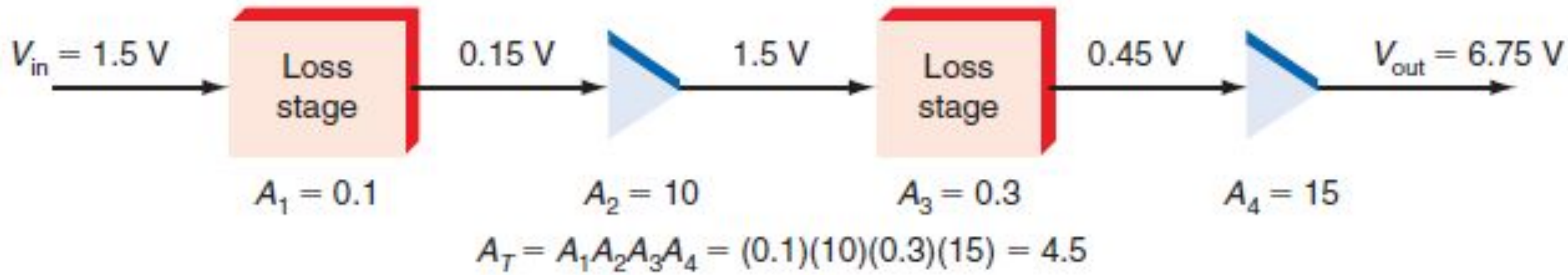
$$A_T = A_1 A_2$$

where A_1 is the attenuation and A_2 is the amplifier gain.

$$1 = 0.045 A_2 \qquad A_2 = \frac{1}{0.045} = 22.3$$

Note: To find the gain that will offset the loss for unity gain, just take the reciprocal of attenuation: $A_2 = 1/A_1$.

Figure 2-6 The total gain is the product of the individual stage gains and attenuations.



Example 2-6

An amplifier has a gain of 45,000, which is too much for the application. With an input voltage of 20 μV, what attenuation factor is needed to keep the output voltage from exceeding 100 mV? Let A_1 = amplifier gain = 45,000; A_2 = attenuation factor; A_T = total gain.

$$A_T = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{100 \times 10^{-3}}{20 \times 10^{-6}} = 5000$$

$$A_T = A_1 A_2 \qquad \text{therefore} \qquad A_2 = \frac{A_T}{A_1} = \frac{5000}{45{,}000} = 0.1111$$

Decibels (dB)

- The gain or loss of a circuit is usually expressed in *decibels (dB)*

Decibel Calculations. The formulas for computing the decibel gain or loss of a circuit are

$$\mathrm{dB} = 20 \log \frac{V_{\mathrm{out}}}{V_{\mathrm{in}}} \tag{1}$$

$$\mathrm{dB} = 20 \log \frac{I_{\mathrm{out}}}{I_{\mathrm{in}}} \tag{2}$$

$$\mathrm{dB} = 10 \log \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \tag{3}$$

Example 2-7

a. An amplifier has an input of 3 mV and an output of 5 V. What is the gain in decibels?

$$\text{dB} = 20 \log \frac{5}{0.003} = 20 \log 1666.67 = 20(3.22) = 64.4$$

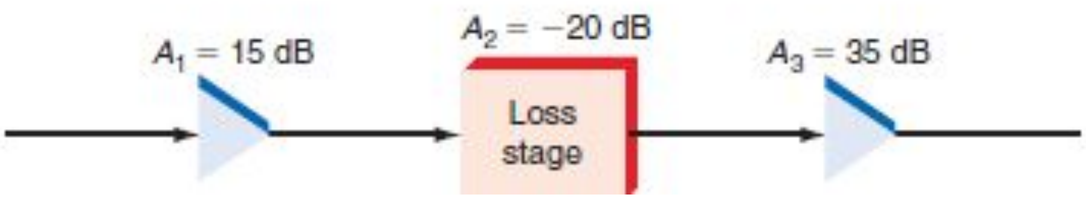
b. A filter has a power input of 50 mW and an output of 2 mW. What is the gain or attenuation?

$$\text{dB} = 10 \log \frac{2}{50} = 10 \log 0.04 = 10(-1.398) = -13.98$$

- To calculate the overall gain or attenuation of a circuit or system, simply add the decibel gain and attenuation factors of each circuit.
- An example is shown in Fig. 2-7, where there are two gain stages and an attenuation block. The overall gain of this circuit is

$$A_T = A_1 + A_2 + A_3 = 15 - 20 + 35 = 30\ \text{dB}$$

Figure 2-7 Total gain or attenuation is the algebraic sum of the individual stage gains in decibels.



	dB GAIN OR ATTENUATION	
Ratio (Power or Voltage)	Power	Voltage
0.000001	−60	−120
0.00001	−50	−100
0.0001	−40	−80
0.001	−30	−60
0.01	−20	−40
0.1	−10	−20
0.5	−3	−6
1	0	0
2	3	6
10	10	20
100	20	40
1000	30	60
10,000	40	80
100,000	50	100

Example 2-8

A power amplifier with a 40-dB gain has an output power of 100 W. What is the input power?

$$\text{dB} = 10 \log \frac{P_{out}}{P_{in}} \qquad \text{antilog} = \log^{-1}$$

$$\frac{\text{dB}}{10} = \log \frac{P_{out}}{P_{in}}$$

$$\frac{40}{10} = \log \frac{P_{out}}{P_{in}}$$

$$4 = \log \frac{P_{out}}{P_{in}}$$

$$\text{antilog } 4 = \text{antilog}\left(\log \frac{P_{out}}{P_{in}}\right)$$

$$\log^{-1} 4 = \frac{P_{out}}{P_{in}}$$

$$\frac{P_{out}}{P_{in}} = 10^4 = 10{,}000$$

$$P_{in} = \frac{P_{out}}{10{,}000} = \frac{100}{10{,}000} = 0.01 \text{ W} = 10 \text{ mW}$$

Example 2-9

An amplifier has a gain of 60 dB. If the input voltage is 50 μV, what is the output voltage?

Since

$$\text{dB} = 20 \log \frac{V_{\text{out}}}{V_{\text{in}}}$$

$$\frac{\text{dB}}{20} = \log \frac{V_{\text{out}}}{V_{\text{in}}}$$

Therefore

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \log^{-1} \frac{\text{dB}}{20} = 10^{\text{dB}/20}$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = 10^{60/20} = 10^3$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = 10^3 = 1000$$

$$V_{\text{out}} = 1000V_{\text{in}} = 1000(50 \times 10^{-6}) = 0.05 \text{ V} = 50 \text{ mV}$$

dBm

$$\text{dBm} = 10 \log \frac{P_{\text{out}}(\text{W})}{0.001(\text{W})}$$

The output of a 1-W amplifier expressed in dBm is, e.g.,

$$\text{dBm} = 10 \log \frac{1}{0.001} = 10 \log 1000 = 10(3) = 30 \text{ dBm}$$

Example 2-10

A power amplifier has an input of 90 mV across 10 kΩ. The output is 7.8 V across an 8-Ω speaker. What is the power gain, in decibels? You must compute the input and output power levels first.

$$P = \frac{V^2}{R}$$

$$P_{in} = \frac{(90 \times 10^{-3})^2}{10^4} = 8.1 \times 10^{-7}\ \text{W}$$

$$P_{out} = \frac{(7.8)^2}{8} = 7.605\ \text{W}$$

$$A_P = \frac{P_{out}}{P_{in}} = \frac{7.605}{8.1 \times 10^{-7}} = 9.39 \times 10^6$$

$$A_P(\text{dB}) = 10 \log A_P = 10 \log 9.39 \times 10^6 = 69.7\ \text{dB}$$

dBc

dBc. This is a decibel gain attenuation figure where the reference is the carrier. The carrier is the base communication signal, a sine wave that is modulated. Often the amplitude's sidebands, spurious or interfering signals, are referenced to the carrier. For example, if the spurious signal is 1 mW compared to the 10-W carrier, the dBc is

$$\text{dBc} = 10 \log \frac{P_{\text{signal}}}{P_{\text{carrier}}}$$

$$\text{dBc} = 10 \log \frac{0.001}{10} = 10(-4) = -40$$

Example 2-11

An amplifier has a power gain of 28 dB. The input power is 36 mW. What is the output power?

$$\frac{P_{\text{out}}}{P_{\text{in}}} = 10^{\text{dB}/10} = 10^{2.8} = 630.96$$

$$P_{\text{out}} = 630.96 P_{\text{in}} = 630.96(36 \times 10^{-3}) = 22.71 \text{ W}$$

Example 2-12

A circuit consists of two amplifiers with gains of 6.8 and 14.3 dB and two filters with attenuations of −16.4 and −2.9 dB. If the output voltage is 800 mV, what is the input voltage?

$$A_T = A_1 + A_2 + A_3 + A_4 = 6.8 + 14.3 - 16.4 - 2.9 = 1.8 \text{ dB}$$

$$A_T = \frac{V_{\text{out}}}{V_{\text{in}}} = 10^{\text{dB}/20} = 10^{1.8/20} = 10^{0.09}$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = 10^{0.09} = 1.23$$

$$V_{\text{in}} = \frac{V_{\text{out}}}{1.23} = \frac{800}{1.23} = 650.4 \text{ mV}$$

Example 2-13

Express $P_{out} = 12.3$ dBm in watts.

$$\frac{P_{out}}{0.001} = 10^{dBm/10} = 10^{12.3/10} = 10^{1.23} = 17$$

$$P_{out} = 0.001 \times 17 = 17 \text{ mW}$$

Tuned circuits

- *Tuned circuits are made up of* inductors and capacitors that resonate at specific frequencies

Reactive components

- Capacitors: A *capacitor used in an ac circuit continually charges and discharges.* A capacitor tends to oppose voltage changes across it. This translates to an opposition to alternating current known as *capacitive reactance* X_C.

$$X_C = \frac{1}{2\pi f C}$$

$$f = \frac{1}{2\pi X_C C} \qquad \text{and} \qquad C = \frac{1}{2\pi f X_C}$$

The reactance of a 100-pF capacitor at 2 MHz is

$$X_C = \frac{1}{6.28(2 \times 10^6)(100 \times 10^{-12})} = 796.2\ \Omega$$

- Inductors: An *inductor, also called a coil or choke, is simply a winding of multiple* turns of wire. When current is passed through a coil, a magnetic field is produced around the coil. If the applied voltage and current are varying, the magnetic field alternately expands and collapses. This causes a voltage to be self-induced into the coil winding, which has the effect of opposing current changes in the coil. This effect is known as *inductance.*

$$X_L = 2\pi f L$$

For example, the inductive reactance of a 40-μH coil at 18 MHz is

$$X_L = 6.28(18 \times 10^6)(40 \times 10^{-6}) = 4522\ \Omega$$

Quality factor (Q factor) of L

- The quality factor (or Q) of an inductor is the ratio of its inductive reactance to its resistance at a given **frequency**, and is a measure of its efficiency.
- The higher the Q factor of the inductor, the closer it approaches the behavior of an ideal inductor.

$$Q = \frac{I^2 X_L}{I^2 R} = \frac{X_L}{R}$$

- the *Q of a 3-μH inductor with a total resistance of 45 Ω* at 90 MHz is calculated as follows:

$$Q = \frac{2\pi f L}{R} = \frac{6.28(90 \times 10^6)(3 \times 10^{-6})}{45} = \frac{1695.6}{45} = 37.68$$

Series resonant circuit

- A *series resonant circuit is made up of inductance,* capacitance, and resistance.
- Such circuits are often referred to as *LCR circuits or RLC circuits.*
- *The inductive and capacitive reactances depend upon the* frequency of the applied voltage.
- Resonance occurs when the inductive and capacitive reactances are equal.

Figure 2-13 Series *RLC* circuit.

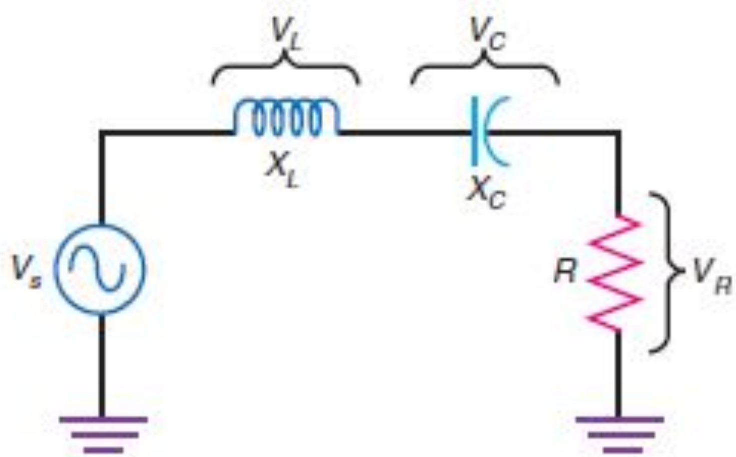


Figure 2-14 Variation of reactance with frequency.

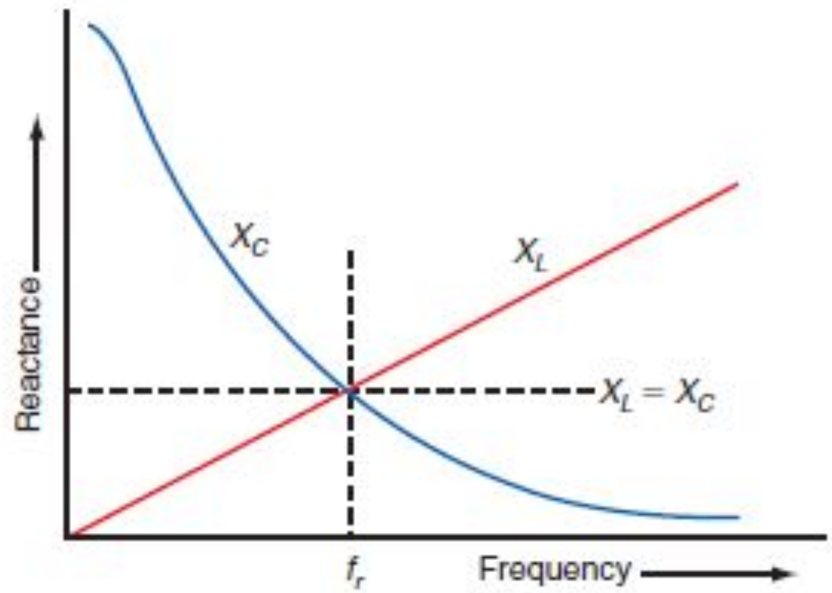
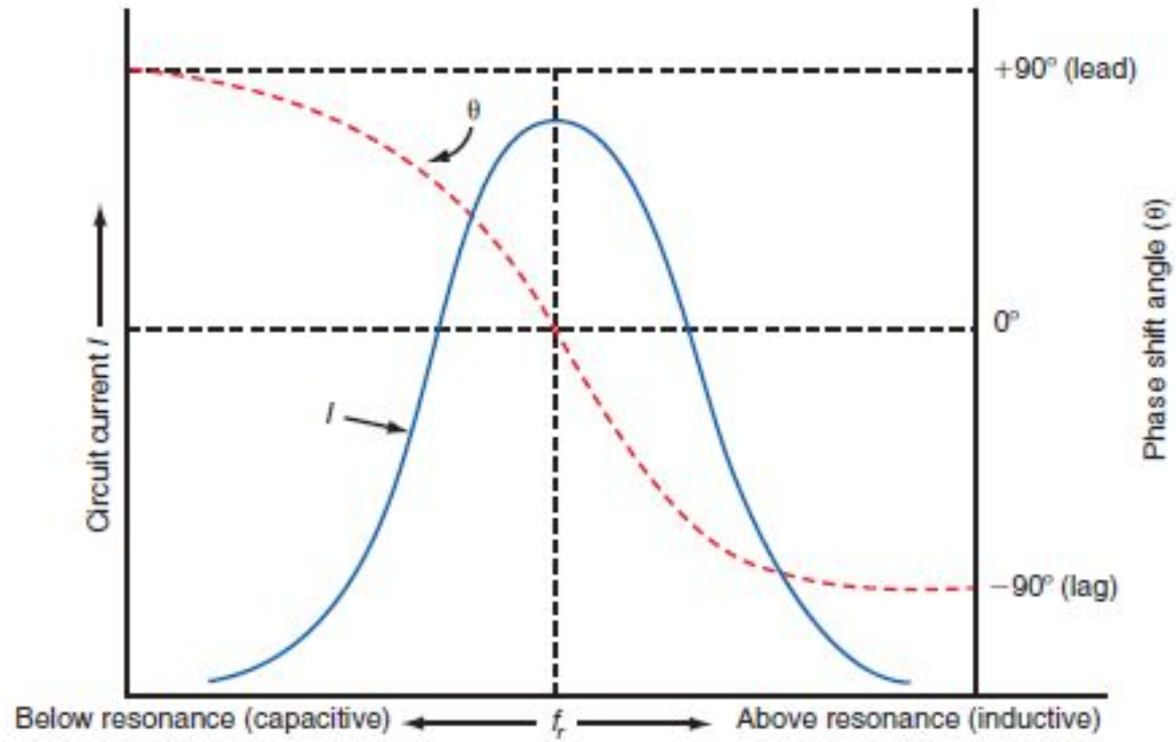


Figure 2-15 Frequency and phase response curves of a series resonant circuit.



The total impedance of the circuit is given by the expression

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The resonant frequency can be expressed in terms of inductance and capacitance. A formula for resonant frequency can be easily derived. First, express X_L and X_C as an equivalence: $X_L = X_C$. Since

$$X_L = 2\pi f_r L \qquad \text{and} \qquad X_C = \frac{1}{2\pi f_r C}$$

we have

$$2\pi f_r L = \frac{1}{2\pi f_r C}$$

Solving for f_r gives

$$f_r = \frac{1}{2\pi\sqrt{LC}}$$

Example 2-14

What is the resonant frequency of a 2.7-pF capacitor and a 33-nH inductor?

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{6.28\sqrt{33 \times 10^{-9} \times 2.7 \times 10^{-12}}}$$
$$= 5.33 \times 10^8 \text{ Hz or } 533 \text{ MHz}$$

Example 2-15

What value of inductance will resonate with a 12-pF capacitor at 49 MHz?

$$L = \frac{1}{4\pi^2 f_r^{\,2} C} = \frac{1}{39.478(49 \times 10^6)^2(12 \times 10^{-12})}$$

$$= 8.79 \times 10^{-7} \text{ H or } 879 \text{ nH}$$

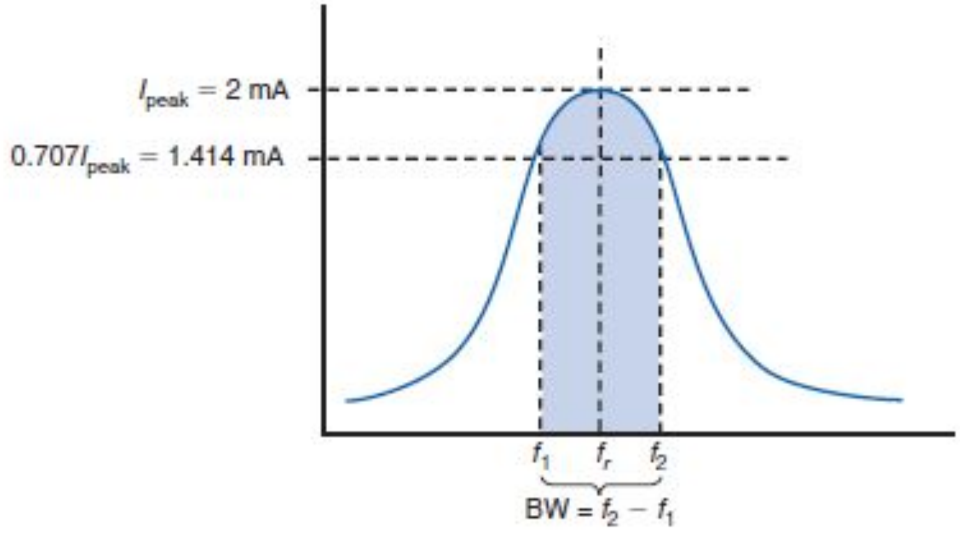
BW of a tuned circuit

The bandwidth BW of the tuned circuit is defined as the difference between the upper and lower cutoff frequencies:

$$BW = f_2 - f_1$$

For example, assuming a resonant frequency of 75 kHz and upper and lower cutoff frequencies of 76.5 and 73.5 kHz, respectively, the bandwidth is BW = 76.5 − 73.5 = 3 kHz.

Figure 2-16 Bandwidth of a series resonant circuit.



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

If the Q of a circuit resonant at 18 MHz is 50, then the bandwidth is BW = 18/50 = 0.36 MHz = 360 kHz.

Since the bandwidth is approximately centered on the resonant frequency, f_1 is the same distance from f_r as f_2 is from f_r. This fact allows you to calculate the resonant frequency by knowing only the cutoff frequencies:

$$f_r = \sqrt{f_1 \times f_2}$$

For example, if $f_1 = 175$ kHz and $f_2 = 178$ kHz, the resonant frequency is

$$f_r = \sqrt{175 \times 10^3 \times 178 \times 10^3} = 176.5 \text{ kHz}$$

Example 2-17

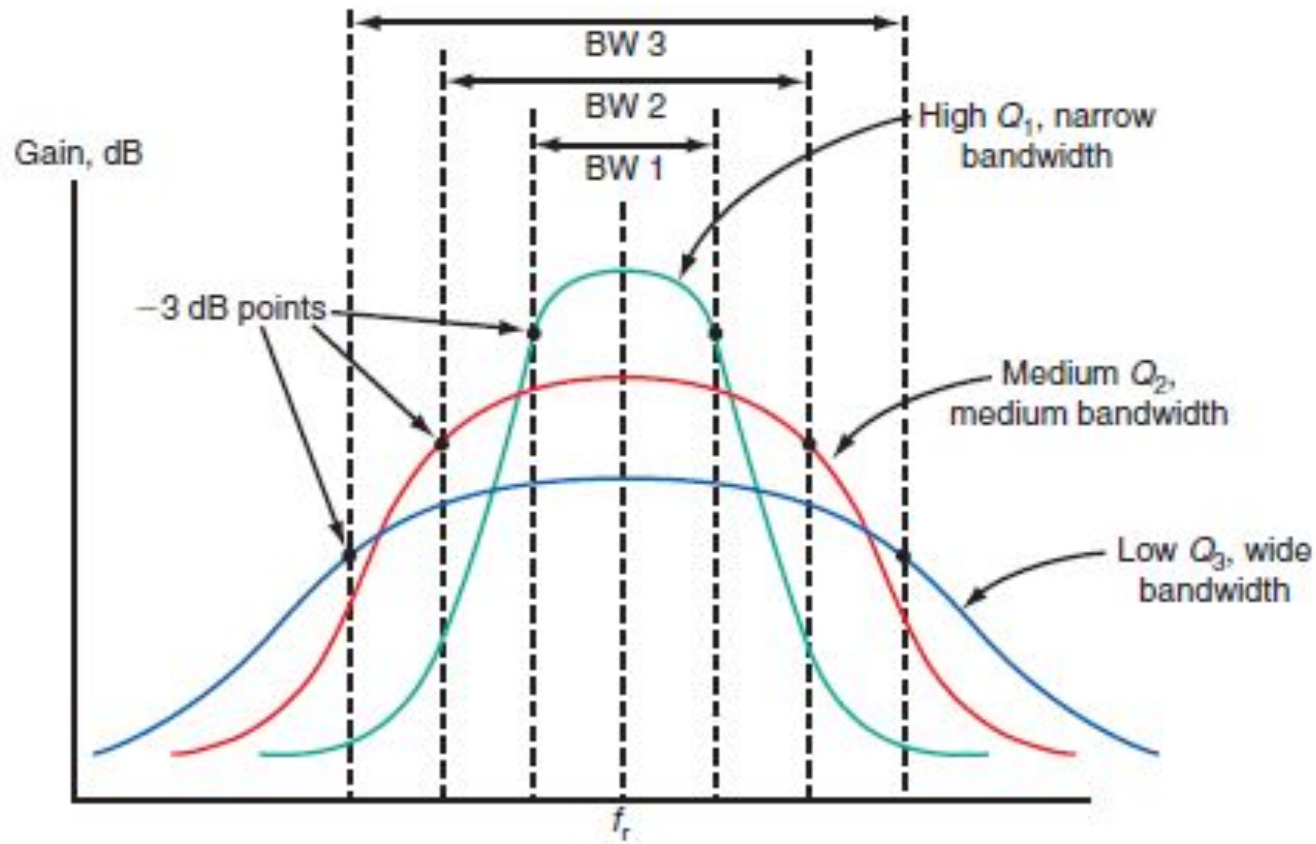
The upper and lower cutoff frequencies of a resonant circuit are found to be 8.07 and 7.93 MHz. Calculate (*a*) the bandwidth, (*b*) the approximate resonant frequency, and (*c*) Q.

a. $\mathrm{BW} = f_2 - f_1 = 8.07\ \mathrm{MHz} - 7.93\ \mathrm{MHz} = 0.14\ \mathrm{MHz} = 140\ \mathrm{kHz}$

b. $f_r = \sqrt{f_1 f_2} = \sqrt{(8.07 \times 10^6)(7.93 \times 10^6)} = 8\ \mathrm{MHz}$

c. $Q = \dfrac{f_r}{\mathrm{BW}} = \dfrac{8 \times 10^6}{140 \times 10^3} = 57.14$

Figure 2-17 The effect of Q on bandwidth and selectivity in a resonant circuit.



Filters

- A *filter is a frequency-selective circuit. Filters are designed to pass some frequencies and* reject others.

The five basic kinds of filter circuits are as follows:

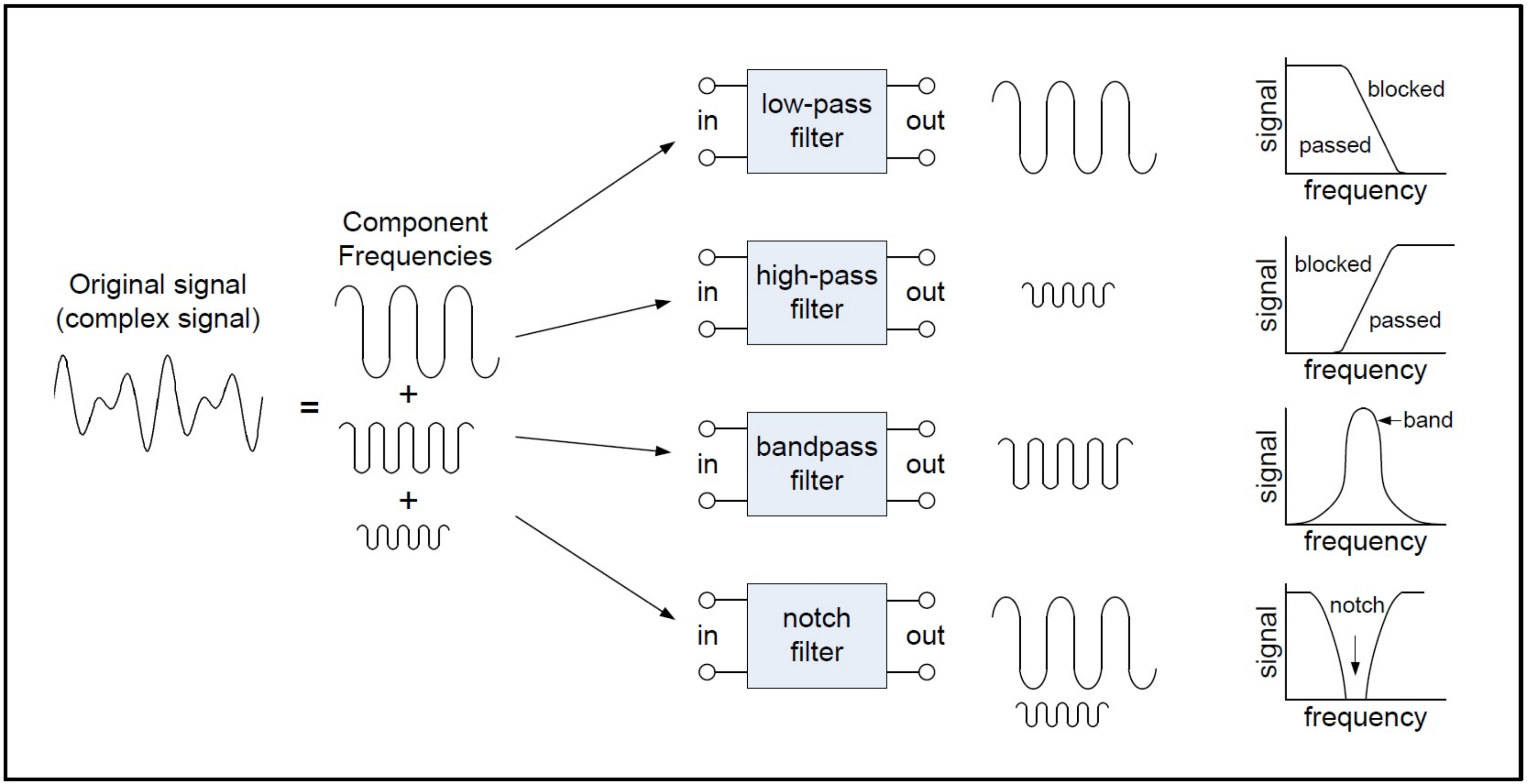
Low-pass filter. Passes frequencies below a critical frequency called the *cutoff frequency* and greatly attenuates those above the cutoff frequency.

High-pass filter. Passes frequencies above the cutoff but rejects those below it.

Bandpass filter. Passes frequencies over a narrow range between lower and upper cutoff frequencies.

Band-reject filter. Rejects or stops frequencies over a narrow range but allows frequencies above and below to pass.

All-pass filter. Passes all frequencies equally well over its design range but has a fixed or predictable phase shift characteristic.



Original signal
(complex signal)
=
Component
Frequencies
+
+
in
low-pass
filter
out
signal
blocked
passed
frequency
in
high-pass
filter
out
signal
blocked
passed
frequency
in
bandpass
filter
out
signal
band
frequency
in
notch
filter
out
signal
notch
frequency

RC low pass filter (LPF)

- *Low-pass filter is a circuit that introduces no attenuation at frequencies* below the cutoff frequency but completely eliminates all signals with frequencies above the cutoff.

Figure 2-23 Ideal response curve of a low-pass filter.

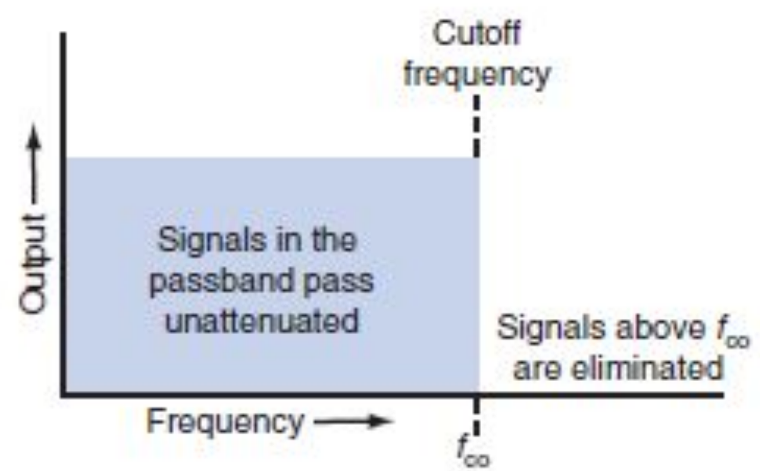
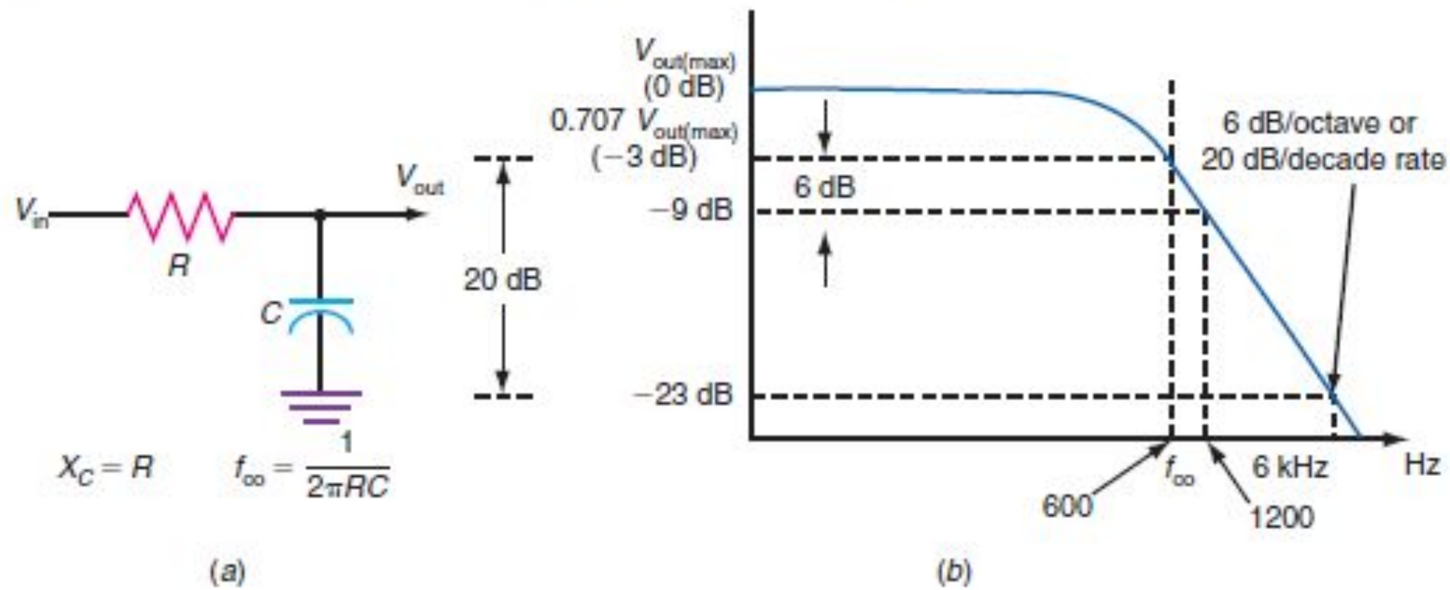


Figure 2-24 *RC* low-pass filter. (*a*) Circuit. (*b*) Low-pass filter.



Design of LPF

- The cutoff frequency of this filter is that point where *R and* X_C *are equal. The cutoff frequency, also known as the critical frequency, is determined* by the expression

$$X_C = R$$

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

$$f_{co} = \frac{1}{2\pi RC}$$

For example, if $R = 4.7\ \text{k}\Omega$ and $C = 560\ \text{pF}$, the cutoff frequency is

$$f_{co} = \frac{1}{2\pi(4700)(560 \times 10^{-12})} = 60{,}469\ \text{Hz} \quad \text{or} \quad 60.5\ \text{kHz}$$

Example 2-23

What is the cutoff frequency of a single-section *RC* low-pass filter with $R = 8.2\ \mathrm{k}\Omega$ and $C = 0.0033\ \mu\mathrm{F}$?

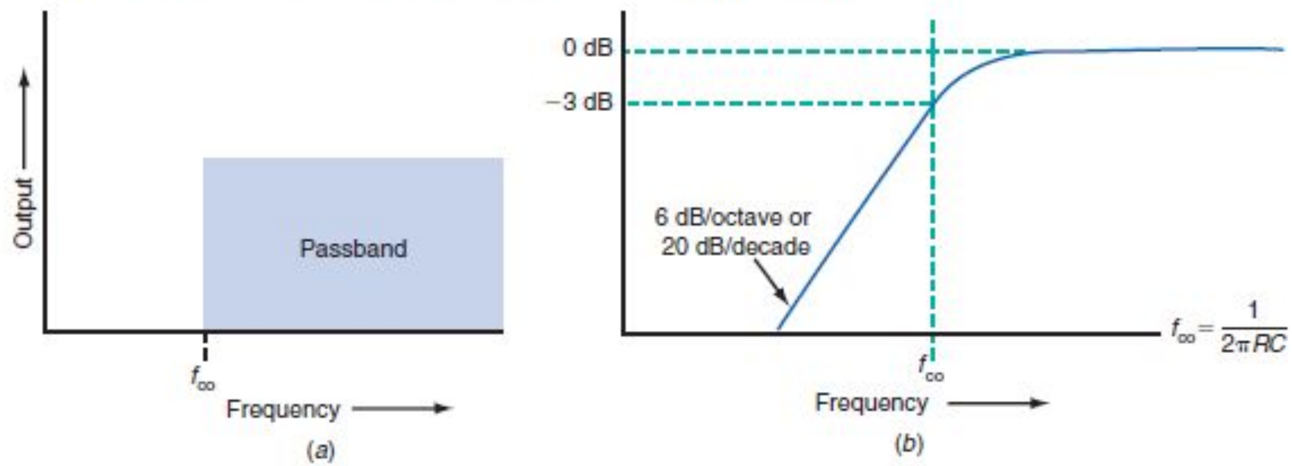
$$f_{co} = \frac{1}{2\pi RC} = \frac{1}{2\pi(8.2 \times 10^{3})(0.0033 \times 10^{-6})}$$

$$f_{co} = 5881.56\ \mathrm{Hz} \quad \text{or} \quad 5.88\ \mathrm{kHz}$$

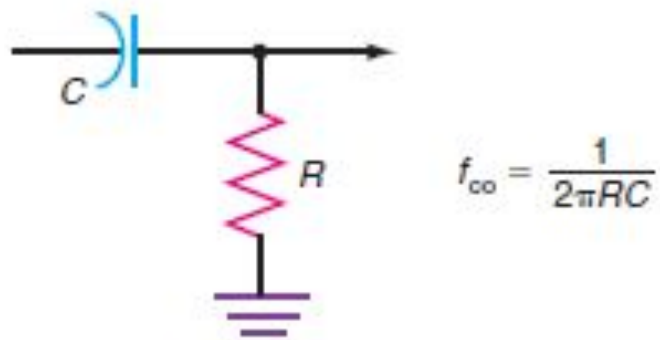
High pass filter (HPF)

- A *high-pass filter passes frequencies above the cutoff frequency with* little or no attenuation but greatly attenuates those signals below the cutoff.

Figure 2-27 Frequency response curve of a high-pass filter. (*a*) Ideal. (*b*) Practical.



RC HPF



(a)

The cutoff frequency for this filter is the same as that for the low-pass circuit and is derived from setting X_C equal to R and solving for frequency:

$$f_{co} = \frac{1}{2\pi RC}$$

Example 2-24

What is the closest standard EIA resistor value that will produce a cutoff frequency of 3.4 kHz with a 0.047-μF capacitor in a high-pass RC filter?

$$f_{co} = \frac{1}{2\pi RC}$$

$$R = \frac{1}{2\pi f_{co} C} = \frac{1}{2\pi(3.4 \times 10^3)(0.047 \times 10^{-6})} = 996\ \Omega$$

The closest standard values are 910 and 1000 Ω, with 1000 being the closest.