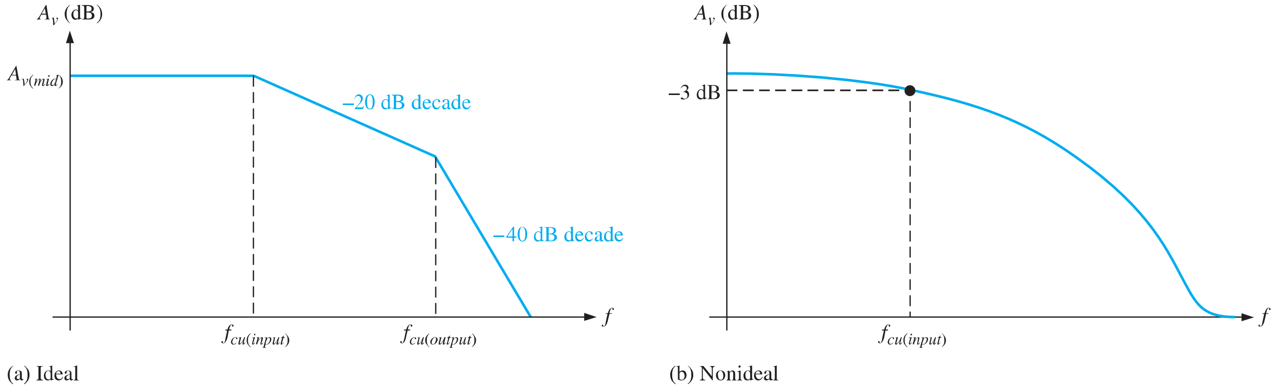
increases and reaches the high end of its midrange values, one of the *RC* circuits will cause the amplifier's gain to begin dropping off. The frequency at which this occurs is the dominant upper critical frequency; it is the lower of the two upper critical high frequencies. An ideal high-frequency Bode plot is shown in Figure 10–44(a). It shows the first break point at $f_{cu(input)}$ where the voltage gain begins to roll off at −20 dB/decade. At $f_{cu(output)}$, the gain begins dropping at −40 dB/decade because each *RC* circuit is providing a −20 dB/decade roll-off. Figure 10–44(b) shows a nonideal Bode plot where the voltage gain is actually −3 dB/decade below midrange at $f_{cu(input)}$. Other possibilities are that the output *RC* circuit is dominant or that both circuits have the same critical frequency.



(a) Ideal (b) Nonideal

▲ **FIGURE 10–44**

High-frequency Bode plots.

SECTION 10–4 CHECKUP

1. What determines the high-frequency response of an amplifier?
2. If an amplifier has a midrange voltage gain of 80, the transistor's C_{bc} is 4 pF, and C_{be} = 8 pF, what is the total input capacitance?
3. A certain amplifier has $f_{cu(input)}$ = 3.5 MHz and $f_{cu(output)}$ = 8.2 MHz. Which circuit dominates the high-frequency response?
4. What are the capacitances that are usually specified on a FET datasheet?
5. If C_{gs} = 4 pF and C_{gd} = 3 pF, what is the total input capacitance of a FET amplifier whose voltage gain is 25?

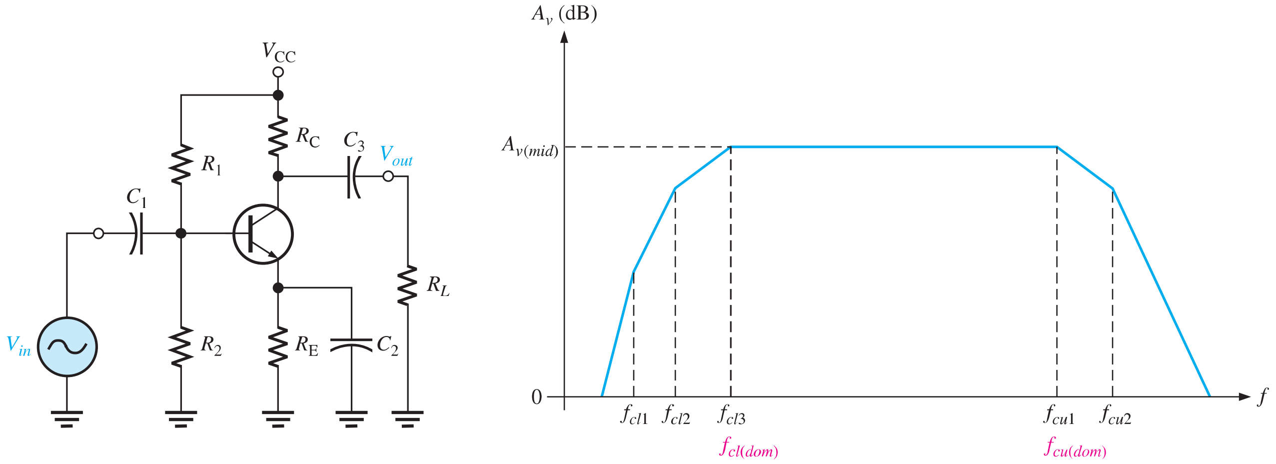
10–5 TOTAL AMPLIFIER FREQUENCY RESPONSE

In the previous sections, you learned how each *RC* circuit in an amplifier affects the frequency response. In this section, we will bring these concepts together and examine the total response of typical amplifiers and the specifications relating to their performance.

After completing this section, you should be able to

- ❑ **Analyze an amplifier for total frequency response**
- ❑ Discuss bandwidth
  - ◆ Define the dominant critical frequencies
- ❑ Explain gain-bandwidth product
  - ◆ Define *unity-gain frequency*

Figure 10–45(b) shows a generalized ideal response curve (Bode plot) for the BJT amplifier shown in Figure 10–45(a). As previously discussed, the three break points at the lower critical frequencies (f_{cl1}, f_{cl2}, and f_{cl3}) are produced by the three low-frequency *RC* circuits formed by the coupling and bypass capacitors. The break points at the upper critical frequencies, f_{cu1} and f_{cu2}, are produced by the two high-frequency *RC* circuits formed by the transistor's internal capacitances.



(a)

(b)

▲ FIGURE 10–45

A BJT amplifier and its generalized ideal response curve (Bode plot).

Of particular interest are the two dominant critical frequencies, f_{cl3} and f_{cu1}, in Figure 10–45(b). These two frequencies are where the voltage gain of the amplifier is 3 dB below its midrange value. These dominant frequencies are designated $f_{cl(dom)}$ and $f_{cu(dom)}$.

The upper and lower dominant critical frequencies are sometimes called the *half-power frequencies.* This term is derived from the fact that the output power of an amplifier at its critical frequencies is one-half of its midrange power, as previously mentioned. This can be shown as follows, starting with the fact that the output voltage is 0.707 of its midrange value at the dominant critical frequencies.

$$V_{out(f_c)} = 0.707V_{out(mid)}$$

$$P_{out(f_c)} = \frac{V^2_{out(f_c)}}{R_{out}} = \frac{(0.707V_{out(mid)})^2}{R_{out}} = \frac{0.5V^2_{out(mid)}}{R_{out}} = 0.5P_{out(mid)}$$

Bandwidth

An amplifier normally operates with signal frequencies between $f_{cl(dom)}$ and $f_{cu(dom)}$. As you know, when the input signal frequency is at $f_{cl(dom)}$ or $f_{cu(dom)}$, the output signal voltage level is 70.7% of its midrange value or −3 dB. If the signal frequency drops below $f_{cl(dom)}$, the gain and thus the output signal level drops at 20 dB/decade until the next critical frequency is reached. The same occurs when the signal frequency goes above $f_{cu(dom)}$.

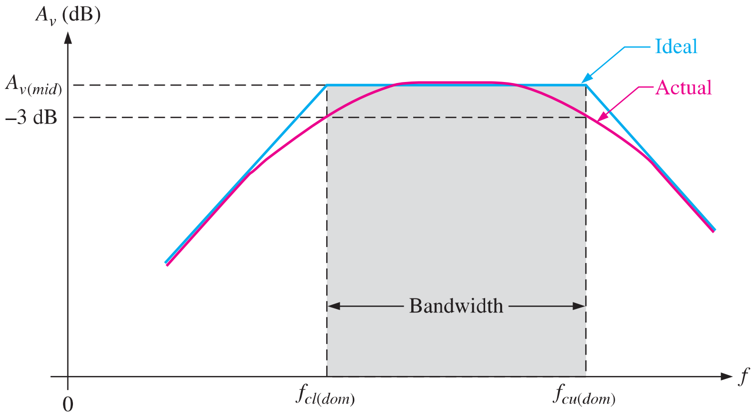
The range (band) of frequencies lying between $f_{cl(dom)}$ and $f_{cu(dom)}$ is defined as the **bandwidth** of the amplifier, as illustrated in Figure 10–46. Only the dominant critical frequencies appear in the response curve because they determine the bandwidth. Also, sometimes the other critical frequencies are far enough away from the dominant frequencies that they play no significant role in the total amplifier response and can be neglected. The amplifier's bandwidth is expressed in units of hertz as

$$BW = f_{cu(dom)} - f_{cl(dom)}$$

Equation 10–27

FIGURE 10–46

Response curve illustrating the bandwidth of an amplifier.



Ideally, all signal frequencies lying in an amplifier's bandwidth are amplified equally. For example, if a 10 mV rms signal is applied to an amplifier with a voltage gain of 20, it is amplified to 200 mV rms for all frequencies in the bandwidth. Actually, the gain is down 3 dB at $f_{cl(dom)}$ and $f_{cu(dom)}$.

EXAMPLE 10–16

What is the bandwidth of an amplifier having an $f_{cl(dom)}$ of 200 Hz and an $f_{cu(dom)}$ of 2 kHz?

Solution

$$BW = f_{cu(dom)} - f_{cl(dom)} = 2000\text{ Hz} - 200\text{ Hz} = \mathbf{1800\text{ Hz}}$$

Notice that bandwidth has the unit of hertz.

Related Problem If $f_{cl(dom)}$ is increased, does the bandwidth increase or decrease? If $f_{cu(dom)}$ is increased, does the bandwidth increase or decrease?

Gain-Bandwidth Product

One characteristic of amplifiers is that the product of the voltage gain and the bandwidth is always constant when the roll-off is −20 dB/decade. This characteristic is called the **gain-bandwidth product.** Let's assume that the dominant lower critical frequency of a particular amplifier is much less than the dominant upper critical frequency.

$$f_{cl(dom)} \ll f_{cu(dom)}$$

The bandwidth can then be approximated as

$$BW = f_{cu(dom)} - f_{cl(dom)} \cong f_{cu}$$

Unity-Gain Frequency The simplified Bode plot for this condition is shown in Figure 10–47. Notice that $f_{cl(dom)}$ is neglected because it is so much smaller than $f_{cu(dom)}$, and the bandwidth approximately equals $f_{cu(dom)}$. Beginning at $f_{cu(dom)}$, the gain rolls off until unity gain (0 dB) is reached. The frequency at which the amplifier's gain is 1 is called the *unity-gain frequency,* f_T. The significance of f_T is that it always equals the midrange voltage gain times the bandwidth and is constant for a given transistor.

Equation 10–28

$$\boldsymbol{f_T = A_{v(mid)}BW}$$

For the case shown in Figure 10–47, $f_T = A_{v(mid)}f_{cu(dom)}$. For example, if a transistor datasheet specifies $f_T = 100$ MHz, this means that the transistor is capable of producing a voltage gain of 1 up to 100 MHz, or a gain of 100 up to 1 MHz, or any combination of gain and bandwidth that produces a product of 100 MHz.

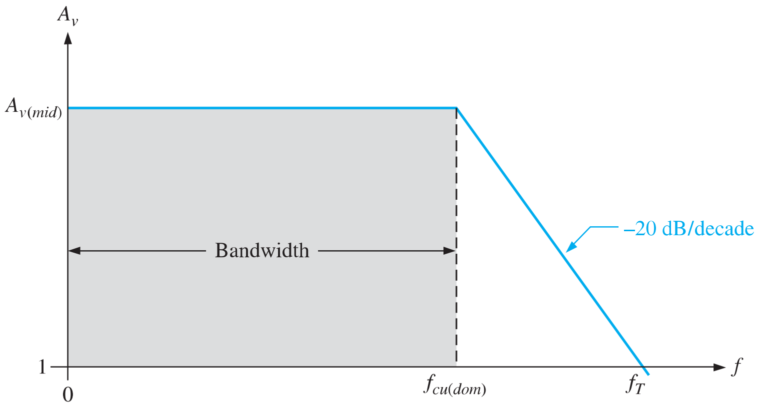


FIGURE 10–47

Simplified response curve where $f_{cl(dom)}$ is negligible (assumed to be zero) compared to $f_{cu(dom)}$.

EXAMPLE 10–17 A certain transistor has an f_T of 175 MHz. When this transistor is used in an amplifier with a midrange voltage gain of 50, what bandwidth can be achieved ideally?

Solution

$$f_T = A_{v(mid)}BW$$

$$BW = \frac{f_T}{A_{v(mid)}} = \frac{175\text{ MHz}}{50} = \mathbf{3.5\ MHz}$$

Related Problem An amplifier has a midrange voltage gain of 20 and a bandwidth of 1 MHz. What is the f_T of the transistor?

SECTION 10–5 CHECKUP

1. What is the voltage gain of an amplifier at f_T?
2. What is the bandwidth of an amplifier when $f_{cu(dom)} = 25$ kHz and $f_{cl(dom)} = 100$ Hz?
3. The f_T of a certain transistor is 130 MHz. What voltage gain can be achieved with a bandwidth of 50 MHz?

10–6 FREQUENCY RESPONSE OF MULTISTAGE AMPLIFIERS

To this point, you have seen how the voltage gain of a single-stage amplifier changes over frequency. When two or more stages are cascaded to form a multistage amplifier, the overall frequency response is determined by the frequency response of each stage depending on the relationships of the critical frequencies.

After completing this section, you should be able to

- **Analyze multistage amplifiers for frequency response**
- Analyze the case where the stages have different critical frequencies
  - Determine the overall bandwidth
- Analyze the case where the stages have equal critical frequencies
  - Determine the overall bandwidth
- Simulate a two-stage amplifier using Multisim

When amplifier stages are cascaded to form a multistage amplifier, the dominant frequency response is determined by the responses of the individual stages. There are two cases to consider:

1. Each stage has a different dominant lower critical frequency and a different dominant upper critical frequency.