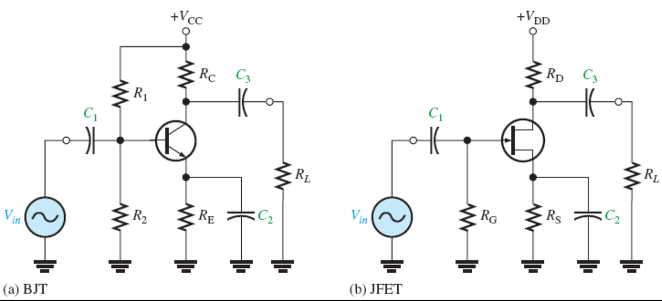
Chapter 10: Amplifiers Frequency Response

10-1: Basic Concepts

- **frequency response** of an amplifier is the change in gain or phase shift over a specified range of input signal frequencies
- In amplifiers, the coupling and bypass capacitors appear to be shorts to ac at the midband frequencies. At low frequencies the capacitive reactance, X_C, of these capacitors affect the gain and phase shift of signals, so they must be taken into account.

Effect of Coupling Capacitors

$X_C = 1/(2\pi f C)$ → At lower f (10Hz for example) the X_C is higher, and it decreases as f increases → more signal voltage is dropped across C_1 and C_3 in amplifiers circuits → less voltage gain

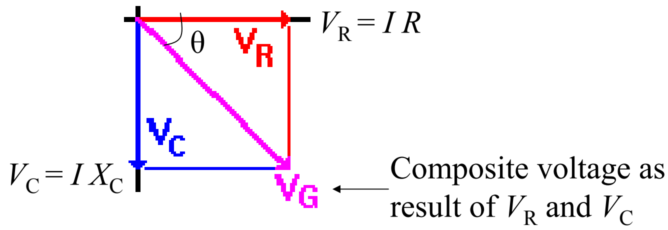


10-1: Basic Concepts

Also, a phase shift is introduced by the coupling capacitors because C_1 forms a **lead circuit** with the R_{in} of the amplifier and C_3 forms a lead circuit with R_L in series with R_C or R_D.

- *lead circuit* is an *RC* circuit in which the output voltage across *R* leads the input voltage in phase ; ac voltage signal will be divided between *C* and *R*.
  - *C* makes a phase difference of 90° between current and voltage across
  - no phase difference between current and *R*

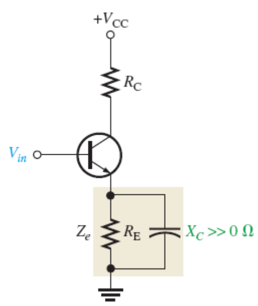
- → we will have $V_R \perp V_C$ → this will cause a phase shift (some where between 0° and 90°) between input voltage and output voltage of the *RC* circuit



10-1: Basic Concepts

Effect of Bypass Capacitors

- At lower *f*, the X_{C2} becomes significant large and the emitter (or FET source terminal) is no longer at ac ground.
- X_{C2} in parallel with R_E (or R_S) creates an impedance that reduces the gain.



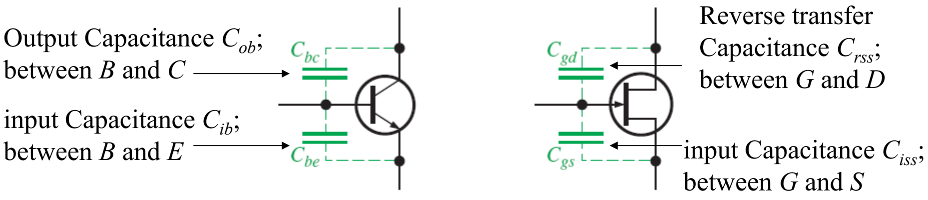
→ $A_v = R_C/(r'_e + Z_e)$. At $X_C >> 0$

Instead of $A_v = R_C/r'_e$ At $X_C \approx 0$

10-1: Basic Concepts

Effect of Internal Transistor Capacitances

- At lower *f*, the internal capacitances have a very high X_C → like opens and have no effect on the transistor's performance.
- However, as the frequency goes up (at high *f*), the internal capacitive reactances go down → they have a significant effect on the transistor's gain and also it introduces a phase shift; it has the inverse effect to the coupling capacitors

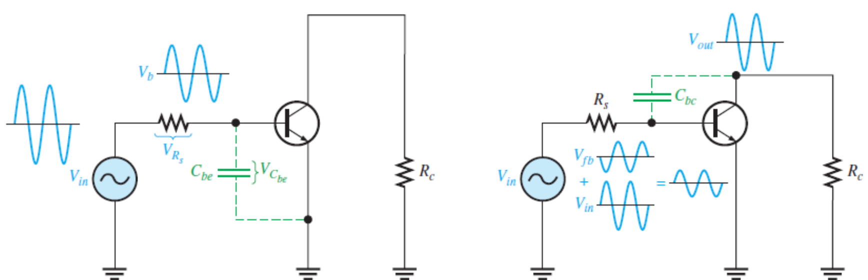


(a) BJT (b) JFET

10-1: Basic Concepts

Effect of Internal Transistor Capacitances

- When the reactance of C_{be} (or C_{gs}) becomes small enough, a significant amount of the signal voltage is lost due to a voltage-divider effect of the signal source resistance and the reactance of C_{be}.
- When the reactance of C_{bc} (or C_{gd}) becomes small enough, a significant amount of output signal voltage (V_{fb}) is fed back out of phase with the input (negative feedback) → reducing the voltage gain.

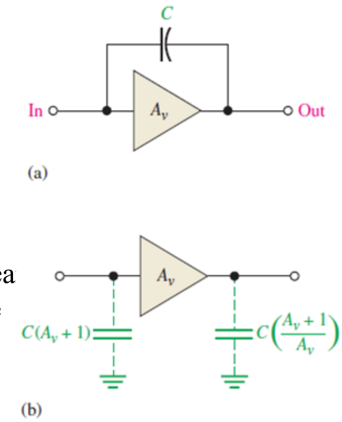


10-1: Basic Concepts

Miller's Theorem

■ is used to simplify the analysis of inverting amplifiers ***at high frequencies***, where the internal transistor capacitances are important

■ The capacitance C_{bc} in BJTs (C_{gd} in FETs) between the input and the output is shown in Figure (a) in a generalized form. Where Av is the absolute voltage gain of the inverting amplifier at midrange frequencies, and C represents either C_{bc} or C_{gd}



■ Miller's theorem states that C effectively appears as a capacitance from input to ground, as shown in Figure (b), that can be expressed as follows:

$$C_{in(Miller)} = C(A_v + 1)$$

Miller's theorem also states that C effectively appea as a capacitance from output to ground, that can be expressed as follows:

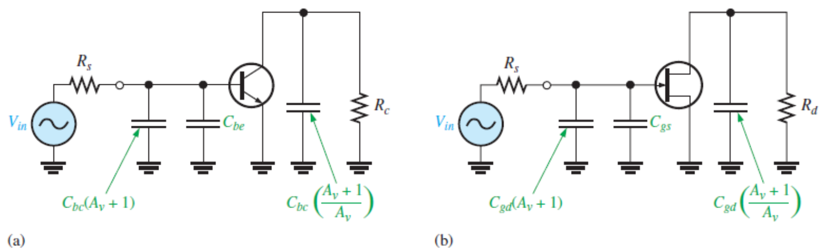
$$C_{out(Miller)} = C\left(\frac{A_v + 1}{A_v}\right)$$

10-1: Basic Concepts

Miller's Theorem

■ The figure below shows the effective input and output capacitance appears in the actual ac equivalent circuitin parallel with C_{be} (or C_{gs}).

■ $C_{in(Miller)}$ formula shows that C_{bc} (or C_{gd}) has a much greater impact on input capacitance than its actual value. For example, if C_{bc} 6 pF and the amplifier gain is 50, then $C_{in(Miller)} = C(A_v{+}1) = 306$ pF.



■ $C_{out(Miller)}$ indicates that if the voltage gain is 10 or greater

→ $C_{out(Miller)} \approx C_{bc}$ or C_{gd} because $(Av{+}1)\,/Av \approx 1$

10-2: The Decibel

- As stated before, The decibel (dB) is a unit of logarithmic gain measurement and is commonly used to express amplifier response.
- The **decibel** is a measurement of the ratio of one power to another or one voltage to another.

The power gain in dB is: $A_{p(\mathrm{dB})} = 10 \log A_p$ where $A_p = P_{out}/P_{in}$

The voltage gain in dB is: $A_{v(\mathrm{dB})} = 20 \log A_v$ where $A_v = V_{out}/V_{in}$

- If $Av > 1$ → dB gain is positive.
- If $Av < 1$ → dB gain is negative (*attenuation*).

Example: Express each of the following ratios in dB:

(a) $\frac{P_{out}}{P_{in}} = 250$ **(b)** $\frac{P_{out}}{P_{in}} = 100$ **(c)** $A_v = 10$ **(d)** $A_p = 0.5$ **(e)** $\frac{V_{out}}{V_{in}} = 0.707$

solution

(a) $A_{p(\mathrm{dB})} = 10 \log (250) = \mathbf{24\ dB}$ **(b)** $A_{p(\mathrm{dB})} = 10 \log (100) = \mathbf{20\ dB}$

(c) $A_{v(\mathrm{dB})} = 20 \log (10) = \mathbf{20\ dB}$ **(d)** $A_{p(\mathrm{dB})} = 10 \log (0.5) = \mathbf{-3\ dB}$

(e) $A_{v(\mathrm{dB})} = 20 \log (0.707) = \mathbf{-3\ dB}$

10-2: The Decibel

0 dB Reference

- Many amplifiers exhibit a maximum gain (often called **midrange gain** $A_{v(mid)}$), over a certain range of frequencies and a reduced gain at frequencies below and above this range.
- We can assign this maximum gain at midrange to a ***zero*** dB reference by setting this maximum gain to 1 into the log by using a ratio with respect to midrange gain (20 log $A_v/A_{v(mid)}$):

For $A_{v(mid)}$ → the ratio $A_{v(\mathrm{mid})}/A_{v(\mathrm{mid})} = 1$ → 20 log 1 = 0 dB (reference 0 dB).

- Any other voltage gain below $A_{v(mid)}$ (for same input voltage) will have a –ve value. → reduction of voltage gain with respect to the maximum (log $A_v/A_{v(mid)}$ is -ve)
- On the other hand, Any other voltage gain above $A_{v(mid)}$ (for same input voltage) will have a +ve value. → increase of voltage gain with respect to the maximum (log $A_v/A_{v(mid)}$ is +ve)

10-2: The Decibel

0 dB Reference

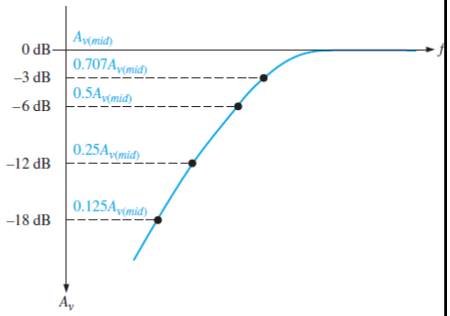
For example if $A_{v(mid)} = 100$
→20 log 100/100 = 0 dB is the reference

If $A_v = 50$ ($A_v = 0.5\ A_{v(mid)}$)
→ 20 log 50/100 = -6 dB

If $Av = 25$($Av = 0.25\ A_{v(mid)}$)
→ 20 log 25/100 = -12 dB

If $Av = 12.5$ ($A_v = 0.125\ A_{v(mid)}$)
→ 20 log 12.5/100 = -18 dB

- As you can see (also from table), Halving the output voltage for a steady input voltage is always a 6 dB *reduction* (-6 dB) in the gain. Correspondingly, a doubling of the output voltage is always a 6 dB *increase* (+6 dB) in the gain



VOLTAGE GAIN (A_v)	DECIBEL VALUE*
32	20 log (32) = 30 dB
16	20 log (16) = 24 dB
8	20 log (8) = 18 dB
4	20 log (4) = 12 dB
2	20 log (2) = 6 dB
1	20 log (1) = 0 dB
0.707	20 log (0.707) = −3 dB
0.5	20 log (0.5) = −6 dB
0.25	20 log (0.25) = −12 dB
0.125	20 log (0.125) = −18 dB
0.0625	20 log (0.0625) = −24 dB
0.03125	20 log (0.03125) = −30 dB

*Decibel values are with respect to zero reference.

10-2: The Decibel

Critical Frequency

- A **critical frequency** (also known as **cutoff frequency** or *corner frequency*) is a frequency at which P_{out} drops to one-half (50%) of its $P_{(mid)}$ →

$$A_{p(\text{dB})} = 10 \log (0.5) = -3 \text{ dB}$$ (at 3 dB reduction in the power gain)

- Also, at the critical frequencies the voltage gain is 70.7% of its midrange value and is expressed in dB as

$$\mathbf{A_{v(dB)} = 20 \log (0.707) = -3 \text{ dB}}$$ (at 3 dB reduction in the voltage gain)

Example: A certain amplifier has a midrange rms output voltage of 10 V. What is the rms output voltage for each of the following dB gain reductions with a constant rms input voltage? **(a)** 3 dB **(b)** 6 dB **(c)** 12 dB **(d)** 24 dB

$$a)\ at -3dB \Rightarrow -3dB = 20\log(V_{out}/V_{(mid)})$$

$$\rightarrow -3/20 = \log(V_{out}/V_{(mid)})$$

$$\rightarrow 10^{-3/20} = V_{out}/V_{(mid)} = 0.707$$

$$\rightarrow V_{out} = 0.707V_{(mid)} = 7.07V$$

Also you can have dB values from table or figure before

(b) At −6 dB, $V_{out} = 0.5(10\text{ V}) = \mathbf{5\ V}$

(c) At −12 dB, $V_{out} = 0.25(10\text{ V}) = \mathbf{2.5\ V}$

(d) At −24 dB, $V_{out} = 0.0625(10\text{ V}) = \mathbf{0.625\ V}$

10-2: The Decibel

Power Measurement in dBm

- The **dBm** is a unit for measuring power levels referenced to 1 mW (0 dBm)

→ For +ve dBm → power levels above 1 mW
→ For –ve dBm → power levelsbelow 1 mW.

- the table shows the dBm values when halved or doubled:
- As you can see from table, Halving the output power for a steady input voltage is always a 3 dBm *reduction* (-3 dBm) in the gain. Correspondingly, a doubling of the output power is always a 3 dBm *increase* (+3 dB) in the gain

POWER	dBm
32 mW	15 dBm
16 mW	12 dBm
8 mW	9 dBm
4 mW	6 dBm
2 mW	3 dBm
1 mW	0 dBm
0.5 mW	−3 dBm
0.25 mW	−6 dBm
0.125 mW	−9 dBm
0.0625 mW	−12 dBm
0.03125 mW	−15 dBm

10-3: Low Frequency Amplifier Response

- As descriped before, The voltage gain and phase shift (reduction in voltage gain and an increase in phase shift) of capacitively coupled amplifiers are affected when the signal frequency is below a critical value.

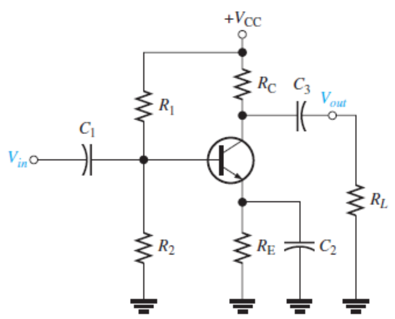
BJT Amplifiers: A typical capacitively coupled CE amplifier is shown

At midrange frequency, the midrange voltage gain

$$A_{v(mid)} = \frac{R_c}{r'_e}$$

If a swamping resistor (R_{E1}) is used

$$A_{v(mid)} = \frac{R_c}{r'_e + R_{E1}}$$



10-3: Low Frequency Amplifier Response

BJT Amplifiers:

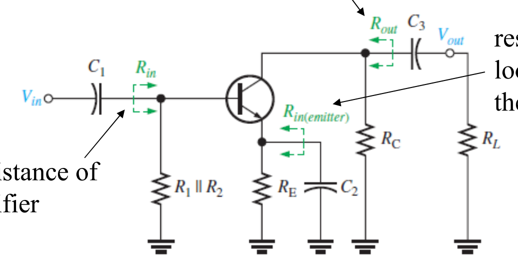
- For frequency below midrange frequency → low frequency ac equivalent circuit will contain the capacitors C_1, C_2, and C_3
- There are three high-pass *RC* circuits that affect its gain;

A **high-pass RC circuit** an RC circuit passes high-frequency signals but attenuates reduces the amplitude of signals with frequencies lower than the cutoff frequency (midrange frequency)

- The three high-pass RC circuits are:

$R_{in}C_1$, $R_{in(emitter)}C_2$, and $R_{out}C_3$

Resistance looking at the collector



resistance looking in at the emitter

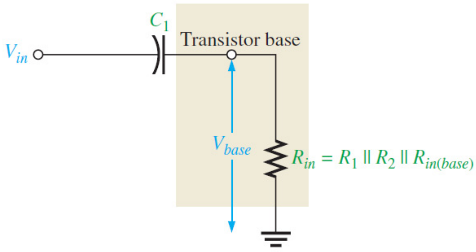
input resistance of the amplifier

10-3: Low Frequency Amplifier Response

BJT Amplifier: The Input *RC* Circuit

$$V_{base} = \left(\frac{R_{in}}{\sqrt{R_{in}^2 + X_{C1}^2}}\right)V_{in}$$

due to X_{C1}, V_{base} is less than voltage at midrange frequency ($V_{base} = V_{in}$ when $X_{C1} \approx 0$)



Lower Critical Frequency

- Critical point in the amplifier's response occurs when the V_{out} is 70.7% of its midrange value. This may occurs at $V_{base} = 0.707\ V_{in}$ (when $R_{in} = X_{C1}$)

$$V_{base} = \left(\frac{R_{in}}{\sqrt{R_{in}^2 + R_{in}^2}}\right)V_{in} = \left(\frac{R_{in}}{\sqrt{2R_{in}^2}}\right)V_{in} = \left(\frac{R_{in}}{\sqrt{2}R_{in}}\right)V_{in} = \left(\frac{1}{\sqrt{2}}\right)V_{in} = 0.707V_{in}$$

$$\longrightarrow 20\log\left(\frac{V_{base}}{V_{in}}\right) = 20\log(0.707) = -3\text{ dB}$$ than at midrange

10-3: Low Frequency Amplifier Response

The Input *RC* Circuit: Lower Critical Frequency

■ → Input *lower critical frequency* (or *lower cutoff frequency*), can be calculated as follows:

$$X_{C1} = \frac{1}{2\pi f_{cl(input)} C_1} = R_{in} \longrightarrow f_{cl(input)} = \frac{1}{2\pi R_{in} C_1}$$

If the resistance of the input source (R_S) is taken into account

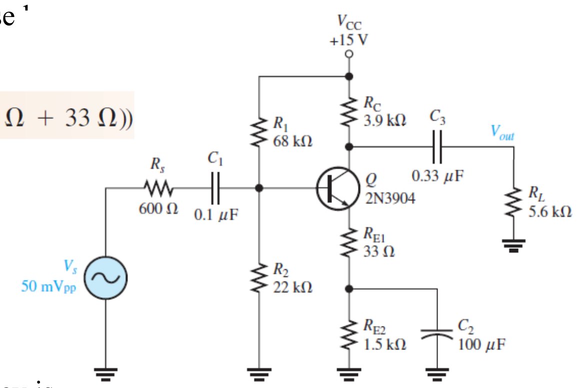
$$\longrightarrow f_{cl(input)} = \frac{1}{2\pi (R_s + R_{in}) C_1}$$

10-3: Low Frequency Amplifier Response

The Input *RC* Circuit: Lower Critical Frequency

Example: For the circuit shown, calculate the lower critical frequency due to the input *RC* circuit. Assumed $r'_e = 9.6\Omega$ and $\beta = 200$. Notice that a swamping resistor, R_{E1}, is use '

$$R_{in} = R_1 \| R_2 \| (\beta(r'_e + R_{E1}))$$
$$= 68\ k\Omega \| 22\ k\Omega \| (200(9.6\ \Omega + 33\ \Omega))$$
$$= 5.63\ k\Omega$$



→ The lower critical frequency is

$$\longrightarrow f_{cl(input)} = \frac{1}{2\pi (R_s + R_{in}) C_1} = \frac{1}{2\pi (0.6\ k\Omega + 5.63\ k\Omega)(0.1\ \mu F)} = \mathbf{255\ Hz}$$

10-3: Low Frequency Amplifier Response

The Input *RC* Circuit: Voltage Gain Roll-Off at Low Frequencies

- When the frequency is reduced to the critical value f_c → A_v of an amplifier is reduced by 3 dB.
- As the frequency continues to decrease below f_c, A_v also continues to decrease. The rate of decrease A_v with frequency is called **roll-off**

For example at $f = 0.1 f_c$ → $X_{C1} = 10\ R_{in}$

$$\longrightarrow \text{Attenuation} = \frac{V_{base}}{V_{in}} = \frac{R_{in}}{\sqrt{R_{in}^2 + X_{C1}^2}} = \frac{R_{in}}{\sqrt{R_{in}^2 + (10R_{in})^2}} = \frac{R_{in}}{\sqrt{R_{in}^2 + 100R_{in}^2}}$$

$$= \frac{R_{in}}{\sqrt{R_{in}^2(1 + 100)}} = \frac{R_{in}}{R_{in}\sqrt{101}} = \frac{1}{\sqrt{101}} \cong \frac{1}{10} = 0.1$$

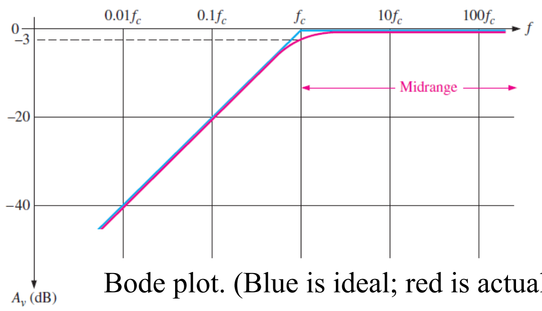
→ V_{base} decrease by 10 times with respect to V_{in} when f decrease by a decade (10 time)

Which corresponds to $20 \log\left(\frac{V_{base}}{V_{in}}\right) = 20 \log(0.1) = -20\ \text{dB}$ attenuation

10-3: Low Frequency Amplifier Response

The Input *RC* Circuit: Voltage Gain Roll-Off at Low Frequencies

→ For every 10 times change in frequency f (decade), there is a 20dB decrease in the voltage gain as shown in the following Bode plot



Bode plot. (Blue is ideal; red is actual.)

Example: The midrange voltage gain of a certain amplifier is 100. The input *RC* circuit has a lower critical frequency of 1 kHz. Determine the actual voltage gain at f 1 kHz, f 100 Hz, and f 10 Hz.

at $f = f_c$ =1kHz → $A_v = 0.707\ A_{v(mid)} = 70.7$

at $f = 0.1\ f_c$ =100 Hz → $A_v = 0.1\ A_{v(mid)}$ =10

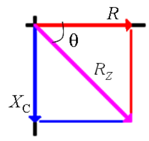
at $f = 0.01\ f_c$ =10 Hz → $A_v = 0.01\ A_{v(mid)}$ =1

10-3: Low Frequency Amplifier Response

The Input *RC* Circuit: Phase Shift in the Input RC Circuit

- the phase shift angle of the input *RC* circuit is expressed as

$$\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$$

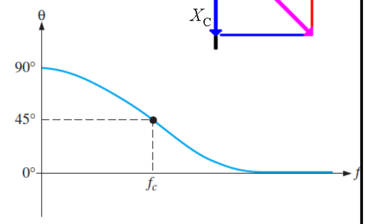


For midrange frequencies, $X_{C1} \cong 0\ \Omega$, so

$$\theta = \tan^{-1}\left(\frac{0\ \Omega}{R_{in}}\right) = \tan^{-1}(0) = 0°$$

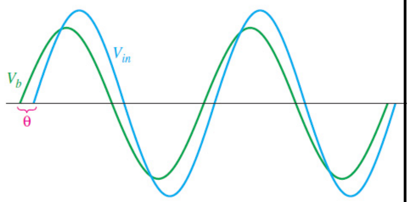
At the critical frequency, $X_{C1} = R_{in}$, so

$$\theta = \tan^{-1}\left(\frac{R_{in}}{R_{in}}\right) = \tan^{-1}(1) = 45°$$



At a decade below the critical frequency, $X_{C1} = 10R_{in}$, so

$$\theta = \tan^{-1}\left(\frac{10R_{in}}{R_{in}}\right) = \tan^{-1}(10) = 84.3°$$



- The result is that the voltage at the base of the transistor *leads* the input signal voltage in phase below midrange

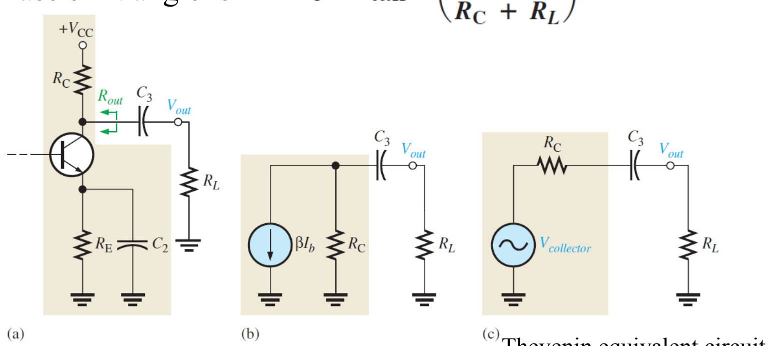
10-3: Low Frequency Amplifier Response

The Output *RC* Circuit

- The second high-pass *RC* circuit in the BJT amplifier is formed by the coupling capacitor C_3, the resistance looking in at the collector, and the load resistance R_L, as shown below

The critical frequency is $$f_{cl(output)} = \frac{1}{2\pi(R_C + R_L)C_3}$$

The phase shift angle is $$\theta = \tan^{-1}\left(\frac{X_{C3}}{R_C + R_L}\right)$$



Source transformation →

Thevenin equivalent circuit

10-3: Low Frequency Amplifier Response

The output *RC* Circuit: Lower Critical Frequency

Example: For the circuit shown (same in the previous example), calculate the lower critical frequency due to the output *RC* circuit.

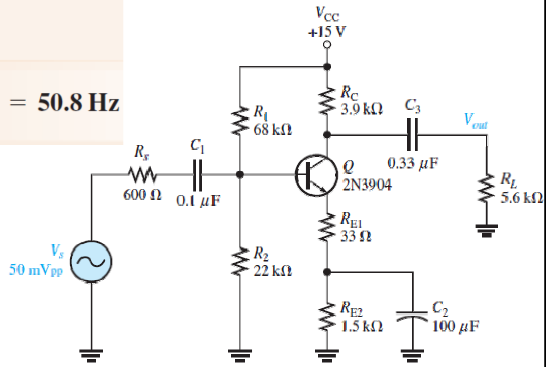
The resistance in the output *RC* circuit is

$$R_C + R_L = 3.9\,k\Omega + 5.6\,k\Omega = 9.5\,k\Omega$$

The lower critical frequency is

$$f_{cl(output)} = \frac{1}{2\pi(R_C + R_L)C_3}$$

$$= \frac{1}{2\pi(9.5\,k\Omega)(0.33\,\mu F)} = \mathbf{50.8\ Hz}$$



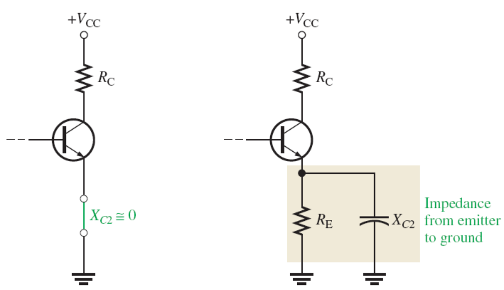
10-3: Low Frequency Amplifier Response

The Bypass *RC* circuit: Lower Critical Frequency

As the frequency reduced below midrange → the X_{C2} for Bypass capacitor increase → voltage gain reduced

$$\Rightarrow A_v = \frac{R_c}{r_r^{'} + R_e}$$

Where $R_e = R_E // X_{C2}$ is the impedance between emitter and ground



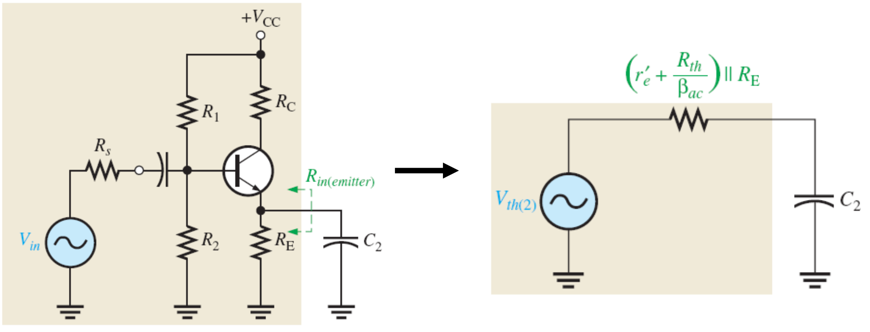
(a) For midrange frequencies, C_2 effectively shorts the emitter to ground.

(b) Below f_c, X_{C2} and R_E form an impedance between the emitter and ground.

10-3: Low Frequency Amplifier Response

The Bypass *RC* circuit: Lower Critical Frequency

The bypass *RC* circuit is formed by C_2 and the resistance looking in at the emitter, $R_{in(emitter)}$,



(a)

$$R_{in(emitter)} = r'_e + \frac{R_{th}}{\beta_{ac}}$$ → The resistance R in the RC_2 circuit becomes $R_{in(emitter)}//R_E$

10-3: Low Frequency Amplifier Response

The Bypass *RC* circuit: Lower Critical Frequency

→ The lower critical frequency of the bypass equivalent RC circuit is

$$f_{cl(bypass)} = \frac{1}{2\pi[(r'_e + R_{th}/\beta_{ac}) \| R_E]C_2}$$

If a swamping resistor is used, the equation for $R_{in(emitter)}$ becomes

$$R_{in(emitter)} = r'_e + R_{E1} + \frac{R_{th}}{\beta_{ac}}$$

Example: for same circuit in the previous example, calculate the lower critical frequency

$$R_{in(emitter)} = r'_e + R_{E1} + \frac{R_{th}}{\beta_{ac}} = 9.6\ \Omega + 33\ \Omega + \frac{68\text{ k}\Omega \| 22\text{ k}\Omega \| 600\ \Omega}{200} = 45.5\ \Omega$$

The lower critical frequency is

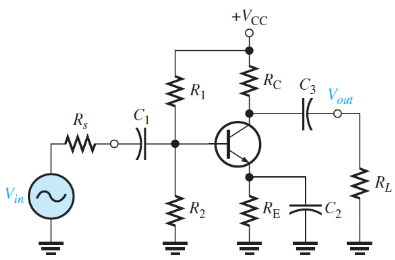
$$f_{cl(bypass)} = \frac{1}{2\pi(R_{in(emitter)} \| R_{E2})C_2} = \frac{1}{2\pi(45.5\ \Omega \| 1.5\text{ k}\Omega)(100\ \mu\text{F})} = \mathbf{36.0\ Hz}$$

10-4: High Frequency Amplifier Response

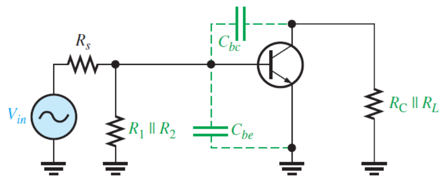
- At midrange frequency of an amplifier, the effects of the coupling and transistor internal capacitors are minimal and can be neglected.
- If the frequency is increased sufficiently, a point is reached where the transistor's internal capacitances begin to have a significant effect on the gain.

BJT Amplifiers

The high frequency ac equivalent circuit of BJT amplifier with transistor internal capacitance is shown below. Note that coupling capacitors and bypass capacitor equivalents are short at high frequency



(a) Capacitively coupled amplifier



(b) High-frequency equivalent circuit

10-4: High Frequency Amplifier Response

- By applying Miller's theorem to the inverting amplifier

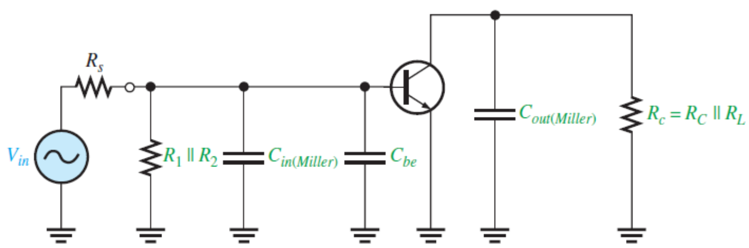
→ Looking in from the signal source, the capacitance C_{bc} appears in the Miller input capacitance from base to ground.

$$C_{in(Miller)} = C_{bc}(A_v + 1)$$

and the Miller output capacitance appears in parallel with R_c

$$C_{out(Miller)} = C_{bc}\left(\frac{A_v + 1}{A_v}\right)$$

where A_v is the voltage gain at midrange

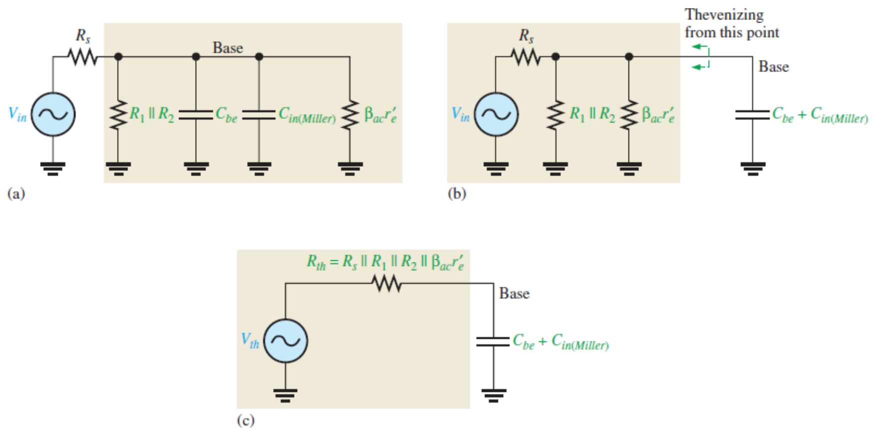


10-4: High Frequency Amplifier Response

BJT Amplifiers: input *RC* circuit

The input circuit shown below can be thevinized to have the equivalent input *RC* circuit

$C_{in(tot)} = C_{be} + C_{in(miller)}$ $\qquad$ $R_{in(tot)} = R_{th} = R_S // R_1 // R_2 // \beta_{ac} r'_e$



10-4: High Frequency Amplifier Response

BJT Amplifiers: input *RC* circuit

- At the critical frequency, the gain is 3 dB less than its midrange value.

→ upper critical high frequency of the input circuit, $f_{cu\,(input)}$, is the frequency at which $X_{Ctot} = R_{tot}$ → $X_{C_{tot}} = R_s \parallel R_1 \parallel R_2 \parallel \beta_{ac} r'_e$

$$\longrightarrow \quad \frac{1}{2\pi f_{cu\,(input)} C_{tot}} = R_s \parallel R_1 \parallel R_2 \parallel \beta_{ac} r'_e$$

Hence, $$f_{cu(input)} = \frac{1}{2\pi (R_s \parallel R_1 \parallel R_2 \parallel \beta_{ac} r'_e) C_{tot}}$$

- As the frequency goes above $f_{cu\,(input)}$, the input *RC* circuit causes the gain to roll off at a rate of -20 dB/decade just as with the low-frequency response.

- The phase shift angle is $$\theta = \tan^{-1}\left(\frac{R_s \parallel R_1 \parallel R_2 \parallel \beta_{ac} r'_e}{X_{C_{(tot)}}}\right)$$

10-4: High Frequency Amplifier Response

BJT Amplifiers: input *RC* circuit

Example: for the circuit shown, determine the lower and upper critical frequency. The transistor's datasheet provides the following: $\beta_{ac} = 125$, $C_{be} = 20$ pF, and $C_{bc} = 2.4$ pF.

$$A_{v(mid)} = \frac{R_c}{r'_e} = \frac{R_C \parallel R_L}{r'_e} \quad \text{but} \quad r'_e = \frac{25\text{ mV}}{I_E}$$

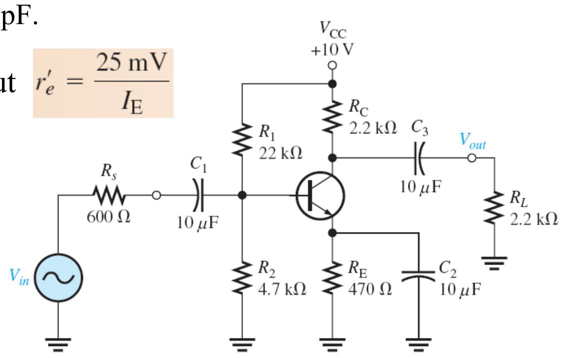
$$V_B = \left(\frac{R_2}{R_1 + R_2}\right)V_{CC}$$

$$= \left(\frac{4.7\text{ k}\Omega}{26.7\text{ k}\Omega}\right)10\text{ V} = 1.76\text{ V}$$

$$V_E = V_B - 0.7\text{ V} = 1.06\text{ V}$$

$$I_E = \frac{V_E}{R_E} = \frac{1.06\text{ V}}{470\ \Omega} = 2.26\text{ mA}$$

$$\rightarrow r'_e = \frac{25\text{ mV}}{I_E} = 11.1\ \Omega \rightarrow A_{v(mid)} = \frac{R_c}{r'_e} = \frac{R_C \parallel R_L}{r'_e} = \frac{1.1\text{ k}\Omega}{11.1\ \Omega} = 99$$



10-4: High Frequency Amplifier Response

BJT Amplifiers: input *RC* circuit: Example – continued from previous

$$R_{in} = R_1 \parallel R_2 \parallel \beta_{ac} r'_e = 22\text{ k}\Omega \parallel 4.7\text{ k}\Omega \parallel 125(11.1\ \Omega) = 1\text{k}\Omega$$

$$f_{cl(input)} = \frac{1}{2\pi(R_s + R_{in})C_1} = \frac{1}{2\pi(0.6k\Omega + 1k\Omega)10\mu C} = 10Hz$$

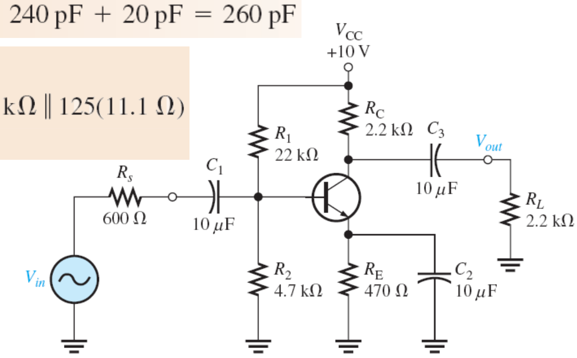
At high frequency we apply miller's theorem →

$$C_{in(Miller)} = C_{bc}(A_{v(mid)} + 1) = (2.4\text{ pF})(100) = 240\text{ pF}$$

$$\rightarrow C_{in(tot)} = C_{in(Miller)} + C_{be} = 240\text{ pF} + 20\text{ pF} = 260\text{ pF}$$

and
$$R_{in(tot)} = R_s \parallel R_1 \parallel R_2 \parallel \beta_{ac} r'_e$$
$$= 600\ \Omega \parallel 22\text{ k}\Omega \parallel 4.7\text{ k}\Omega \parallel 125(11.1\ \Omega)$$
$$= 378\ \Omega$$

$$f_{cu(input)} = \frac{1}{2\pi(R_{in(tot)})(C_{in(tot)})}$$
$$= \frac{1}{2\pi(378\ \Omega)(260\text{ pF})}$$
$$= \mathbf{1.62\ MHz}$$



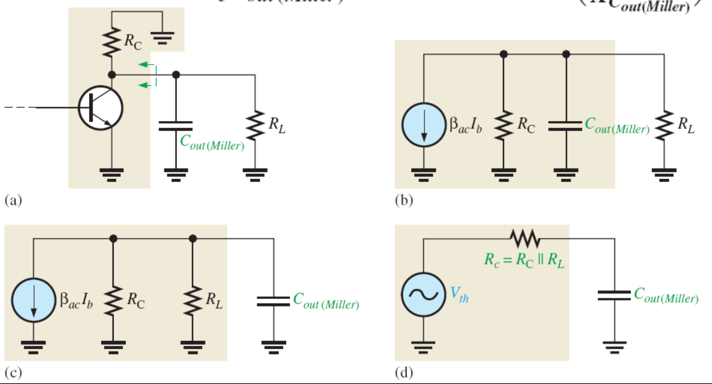
10-4: High Frequency Amplifier Response

BJT Amplifiers: output *RC* circuit

The output circuit shown below can be thevinized to have the equivalent output *RC* circuit ($C_{out(miller)}$ in series with R_c)

$$C_{out(Miller)} = C_{bc}\left(\frac{A_v + 1}{A_v}\right) \cong C_{bc} \quad \text{and} \quad R_c = R_C \parallel R_L$$

$$\rightarrow f_{cu(output)} = \frac{1}{2\pi R_c C_{out(Miller)}} \qquad \theta = \tan^{-1}\left(\frac{R_c}{X_{C_{out(Miller)}}}\right)$$



10-4: High Frequency Amplifier Response

BJT Amplifiers: output *RC* circuit

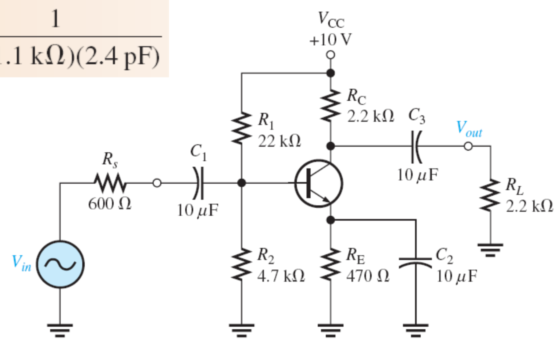
Example:Determine the upper critical frequency of the amplifier in previous Example due to its output *RC* circuit.

$$C_{out(Miller)} = C_{bc}\left(\frac{A_v + 1}{A_v}\right) = (2.4\text{ pF})\left(\frac{99 + 1}{99}\right) \cong 2.4\text{ pF}$$

$$R_c = R_C \parallel R_L = 2.2\text{ k}\Omega \parallel 2.2\text{ k}\Omega = 1.1\text{ k}\Omega$$

$$f_{cu(output)} = \frac{1}{2\pi R_c C_{bc}} = \frac{1}{2\pi(1.1\text{ k}\Omega)(2.4\text{ pF})}$$

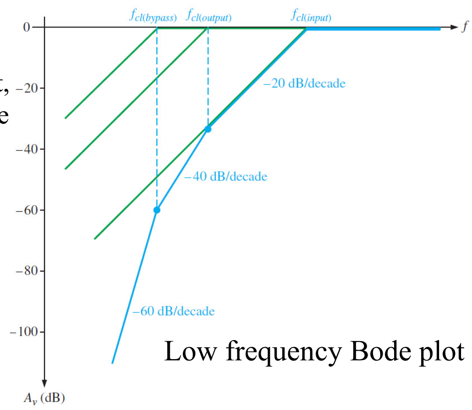
$$= \mathbf{60.3\text{ MHz}}$$



10-5: Total Amplifier Frequency Response

Total Low-Frequency Response

- We have note that each of the three *RC* circuits in a BJT amplifier has a critical frequency determined by the *R* and *C* values. The critical frequencies of the three *RC* circuits are not necessarily all equal.
- If one of the *RC* circuits has a critical frequency higher than the other two, then it is the *dominant RC* circuit and its critical frequency is the dominant frequency, $f_{cl(dom)}$.
- As the frequency is reduced from midrange, the first "break point" occurs at the critical frequency of the input *RC* circuit, $f_{cl(input)}$, → A_v begins to drop at -20dB/decade
- -20dB/decade continues until the $f_{cl(output)}$ is reached. → the output *RC* circuit adds another -20 dB/decade → total roll-off of -40 dB/decade
- -40 dB/decade also continue as *f* reduced until the *fcl*(*bypass*) is reached → the bypass *RC* circuit adds another -20 dB/decade→ a total gain roll-of of -60dB/decade

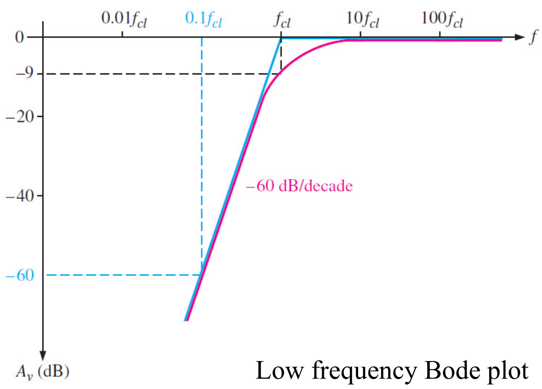


Low frequency Bode plot

10-5: Total Amplifier Frequency Response

Total Low-Frequency Response

- If all *RC* circuits have the same critical frequency, the response curve has one break point at that value of f_{cl}, and the voltage gain rolls off at -60 dB/decade below that value
- at critical point f_{cl}, A_v will be -9dB from the $A_{v(mid)}$ (-3dB for each *RC* circuit)

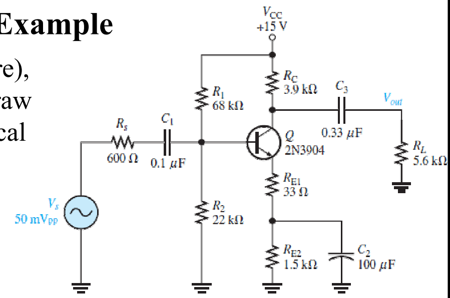


Low frequency Bode plot

10-5: Total Amplifier Frequency Response

Total Low-Frequency Response: Example

For the circuit from shown (same shown before), determine the midband gain in decibels and draw the Bode plot, showing each of the lower critical frequencies. Assume $r'_e = 9.6\Omega$



At mid range

$$A_v = \frac{R_C R_L}{r'_e + R_{E1}} = \frac{(3.9\ \text{k}\Omega)(5.6\ \text{k}\Omega)}{9.6\ \Omega + 33\ \Omega} = 54.0$$

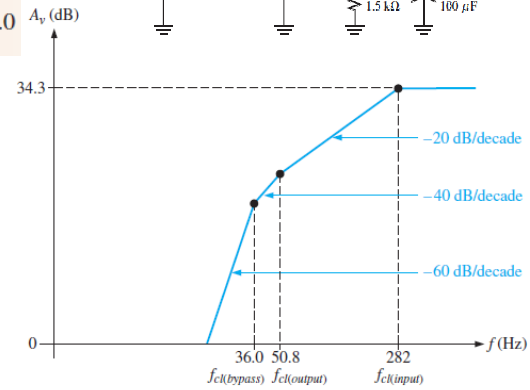
$$A_v = 20 \log (54.0) = \mathbf{34.3\ dB}$$

The lower critical frequencies was previously calculated:

$$f_{cl(input)} = \mathbf{255\ Hz}$$

$$f_{cl(output)} = \mathbf{50.8\ Hz}$$

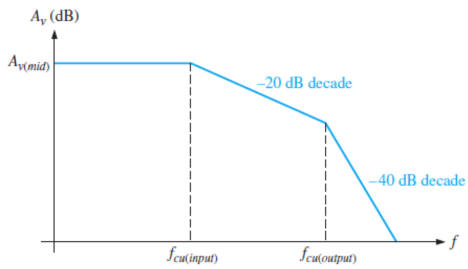
$$f_{cl(bypass)} = \mathbf{36.0\ Hz}$$



10-5: Total Amplifier Frequency Response

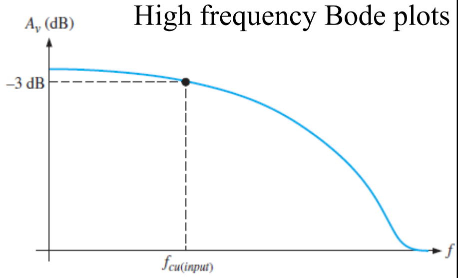
Total High-Frequency Response

- As you have seen, the two *RC* circuits created by the internal transistor capacitances influence the high-frequency response of BJT amplifier.
- If one of the *RC* circuits has a critical frequency lower than the other t, then it is the *dominant RC* circuit and its critical frequency is the dominant frequency, $f_{cu(dom)}$.
- As the frequency is increased from midrange, the first "break point" occurs at the critical frequency of the input *RC* circuit, $f_{cu(input)}$, → A_v begins to drop at -20dB/decade
- -20dB/decade continues until the $f_{cu(output)}$ is reached. → the output *RC* circuit adds another -20 dB/decade → total roll-off of -40 dB/decade



(a) Ideal

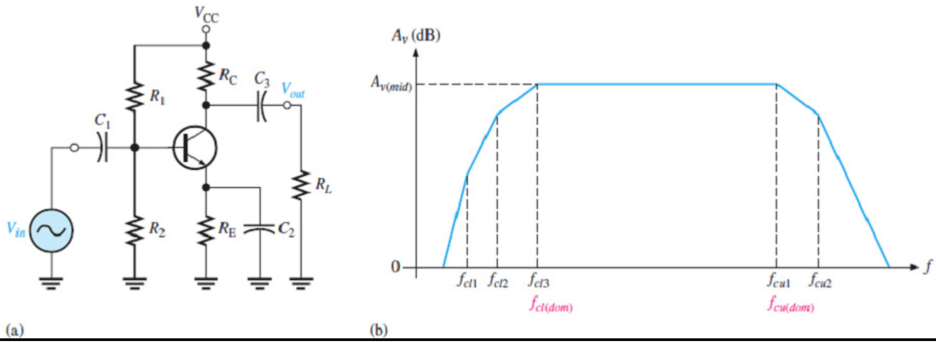
High frequency Bode plots



(b) Nonideal

10-5: Total Amplifier Frequency Response

- 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.
- ideal response curve (Bode plot) for the BJT amplifier of all frequencies can drawn as shown
- the two dominant critical frequencies, f_{cl3} and f_{cu1}, designated $f_{cl(dom)}$ and $f_{cu(dom)}$ are the frequencies where the voltage gain of the amplifier is 3 dB below its midrange value.



10-5: Total Amplifier Frequency Response

- $f_{cl(dom)}$ and $f_{cu(dom)}$ are sometimes called the *half-power frequencies* because the output power of an amplifier at its critical frequencies is one-half of its midrange power

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

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

Bandwidth

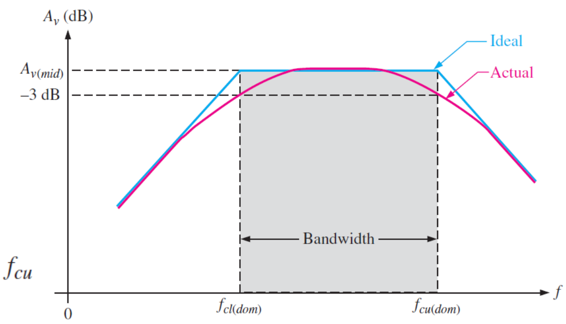
- The range (band) of frequencies lying between $f_{cl(dom)}$ and $f_{cu(dom)}$ is defined as the **bandwidth** of the amplifier →

$$BW = f_{cu(dom)} - f_{cl(dom)} \quad \text{(Hz)}$$

SEE EXAMPLE 10.16

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

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

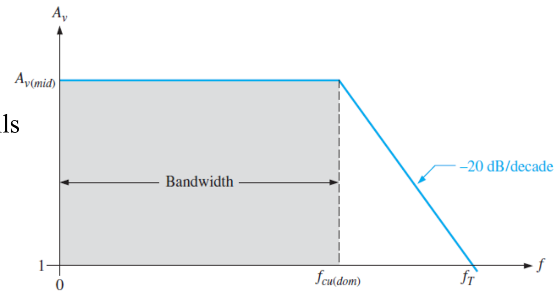


10-5: Total Amplifier Frequency Response

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

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

- Beginning at $f_{cu(dom)}$, the gain rolls off until unity gain (0 dB) is reached ($V_{out}/V_{in} = 1$). The frequency at which the amplifier's gain is 1 is called the *unity gain frequency*, f_T.



- When the roll-off is -20dB, f_T It can be found from $f_T = A_{v(mid)}BW$

Example:

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?

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

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