Philadelphia University
Faculty of Engineering
Communication and Electronics Engineering

Amplifier Circuits-II
BJT and FET Frequency Response Characteristics:

- *Logarithms and Decibels:*

- Logarithms taken to the base 10 are referred to as *common logarithms*, while logarithms taken to the base *e* are referred to as *natural logarithms*. In summary:

$$\text{Common logarithm:} \quad x = \log_{10} a$$

$$\text{Natural logarithm:} \quad y = \log_e a$$

The two are related by

$$\log_e a = 2.3 \log_{10} a$$

- Some relationships hold true for logarithms to any base

$$\log_{10} 1 = 0$$

$$\log_{10} \frac{a}{b} = \log_{10} a - \log_{10} b$$

$$\log_{10} \frac{1}{b} = -\log_{10} b$$

$$\log_{10} ab = \log_{10} a + \log_{10} b$$

- The background surrounding the term *decibel* (dB) has its origin in the established fact that power and audio levels are related on a logarithmic basis.
- That is, an increase in power level, say 4 to 16 W, does not result in an audio level increase by a factor of 16/4 = 4. It will increase by a factor of 2 as derived from the power of 4 in the following manner: $(4)^2 = 16$.
- The term *bel* was derived from the surname of Alexander Graham Bell. For standardization, the bel (B) was defined by the following equation to relate power levels P_1 and P_2:

$$G = \log_{10} \frac{P_2}{P_1} \qquad \text{bel}$$

- It was found, however, that the bel was too large a unit of measurement for practical purposes, so the decibel (dB) was defined such that 10 decibels=1 bel. Therefore,

$$G_{dB} = 10 \log_{10} \frac{P_2}{P_1} \quad \text{dB}$$

- There exists a second equation for decibels that is applied frequently. It can be best described through the system with *Ri*, as an input resistance.

$$G_{dB} = 10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{V_2^2/R_i}{V_1^2/R_i} = 10 \log_{10}\left(\frac{V_2}{V_1}\right)^2$$

and

$$G_{dB} = 20 \log_{10} \frac{V_2}{V_1} \quad \text{dB}$$

- One of the advantages of the logarithmic relationship is the manner in which it can be applied to cascaded stages. In words, the equation states that the decibel gain of a cascaded system is simply the sum of the decibel gains of each stage.

- *General Frequency Considerations:*

- The frequency of the applied signal can have a pronounced effect on the response of a single-stage or multistage network. The analysis thus far has been for the midfrequency spectrum.
- At low frequencies, we shall find that the coupling and bypass capacitors can no longer be replaced by the short-circuit approximation because of the increase in reactance of these elements.
- The frequency-dependent parameters of the small-signal equivalent circuits and the stray capacitive elements associated with the active device and the network will limit the high-frequency response of the system.
- An increase in the number of stages of a cascaded system will also limit both the high- and low-frequency responses.
- For any system, there is a band of frequencies in which the magnitude of the gain is either equal or relatively close to the midband value.
- To fix the frequency boundaries of relatively high gain, $0.707A_{v\text{mid}}$ was chosen to be the gain at the cutoff levels. The corresponding frequencies f_1 and f_2 are generally called the *corner, cutoff, band, break*, or *half-power frequencies.* The multiplier 0.707 was chosen because at this level the output power is half the midband power output, that is, at midfrequencies.

- The bandwidth (or passband) of each system is determined by f_1 and f_2, that is,

$$\text{bandwidth (BW)} = f_2 - f_1$$

- For applications of a communications nature (audio, video), a decibel plot of the voltage gain versus frequency is more useful.

- Before obtaining the logarithmic plot, however, the curve is generally normalized as shown in Fig. 9.6. In this figure, the gain at each frequency is divided by the midband value. Obviously, the midband value is then 1 as indicated. At the half-power frequencies, the resulting level is $0.707 = 1/\sqrt{2}$.

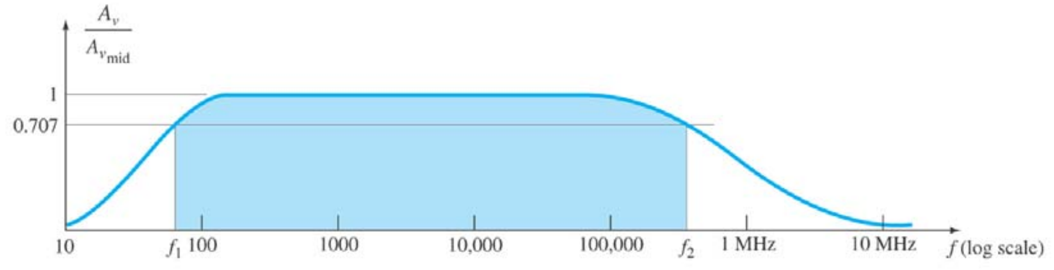


Fig. 9.6 Normalized gain versus frequency plot.

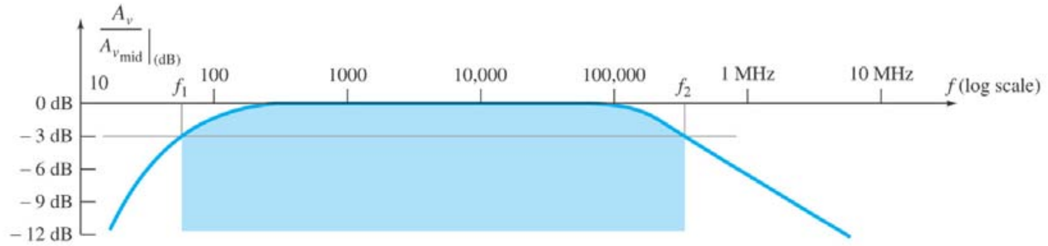
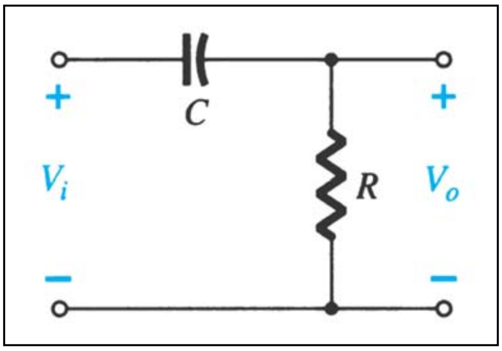


Fig. 9.7 Decibel plot of the normalized gain versus frequency plot of Fig. 9.6.

- *Low Frequency Analysis:*

- In the low-frequency region of the single-stage amplifier, it is the *R-C* combinations formed by the network capacitors C_C, C_E, and C_S and the network resistive parameters that determine the cutoff frequencies.

- The analysis, therefore, will begin with the series *R-C* combination of the given Fig. and the development of a procedure that will result in a plot of the frequency response with a minimum of time and effort.



1) At very high frequencies,

$$X_C = \frac{1}{2\pi f C} \cong 0\ \Omega$$

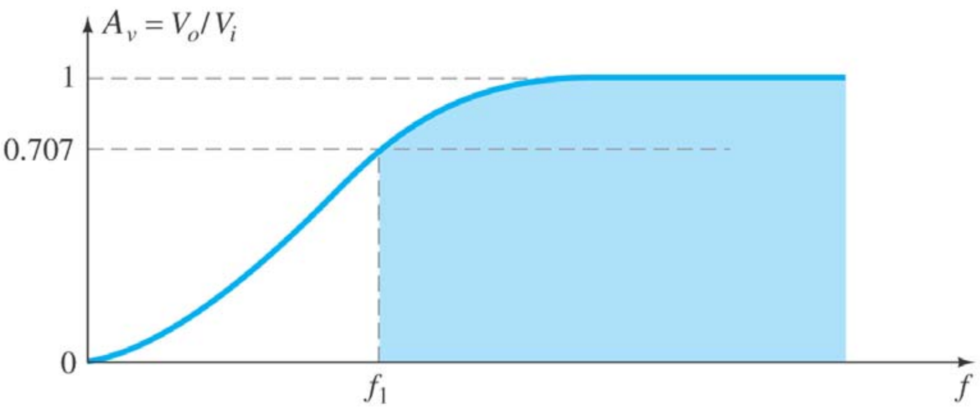
A short-circuit equivalent can be substituted for the capacitor. The result is that $V_o = V_i$ at high frequencies.

2) At $f = 0$ Hz,

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi (0) C} = \infty\ \Omega$$

An open-circuit approximation can be applied, with the result that $V_o = 0$ V.

3) Between the two extremes, the ratio $A_v = V_o/V_i$ will vary as shown below. As the frequency increases, the capacitive reactance decreases and more of the input voltage appears across the output terminals.



- The output and input voltages are related by the voltage-divider rule in the following manner:

$$\mathbf{V_o} = \frac{\mathbf{RV_i}}{\mathbf{R + X_C}}$$

- The magnitude of V_o determined by

$$V_o = \frac{RV_i}{\sqrt{R^2 + X_C^2}}$$

- For the special case where $X_C = R$,

$$V_o = \frac{RV_i}{\sqrt{R^2 + X_C^2}} = \frac{RV_i}{\sqrt{R^2 + R^2}} = \frac{1}{\sqrt{2}} V_i$$

$$\Rightarrow |A_v| = \frac{V_o}{V_i} = \frac{1}{\sqrt{2}} = 0.707 = -3dB$$

- The frequency of which $X_C = R$ (***<u>the output will be 70.7% of the input</u>***) is determined as:

$$X_C = \frac{1}{2\pi f_1 C} = R \Rightarrow f_1 = \frac{1}{2\pi CR}$$

$$A_v = \frac{R}{R - jX_C} = \frac{1}{1 - j\left(\frac{X_C}{R}\right)} = \frac{1}{1 - j\left(\frac{1}{\omega CR}\right)} = \frac{1}{1 - j\left(\frac{1}{2\pi f CR}\right)}$$

$$\Rightarrow A_v = \frac{1}{1 - j\left(\frac{f_1}{f}\right)} = \underbrace{\frac{1}{\sqrt{1 + \left(\frac{f_1}{f}\right)^2}}}_{\text{magnitude of } A_v} \underbrace{\angle \tan^{-1}(f_1 / f)}_{\text{phase by which } Vo \text{ leads } Vi} = -10\log\left[1 + \left(\frac{f_1}{f}\right)^2\right] dB$$

- For frequencies where $f << f_1$ or $(f_1/f)^2 >> 1$, the equation above can be approximated as

$$A_v = -10\log\left[\left(\frac{f_1}{f}\right)^2\right] dB = -20\log\left(\frac{f_1}{f}\right) dB$$

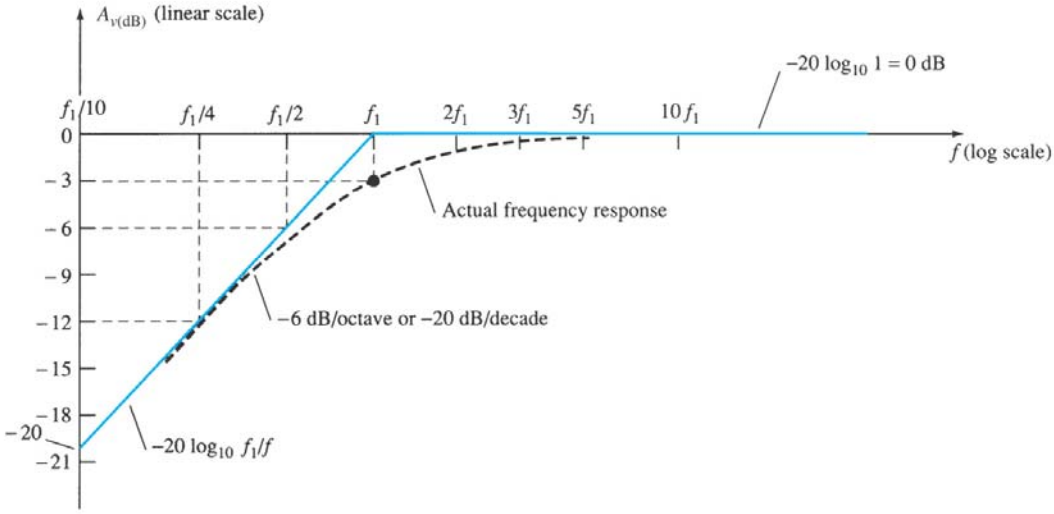
- Ignoring the previous condition for a moment, a plot on a frequency log scale will yield a result of a very useful nature for future decibel plots.

$$\text{At } f = f_1 \Rightarrow -20\log(1) = 0dB$$

$$\text{At } f = \frac{f_1}{2} \Rightarrow -20\log(2) \cong -6dB$$

$$\text{At } f = \frac{f_1}{4} \Rightarrow -20\log(4) \cong -12dB$$

$$\text{At } f = \frac{f_1}{10} \Rightarrow -20\log(10) = -20dB$$

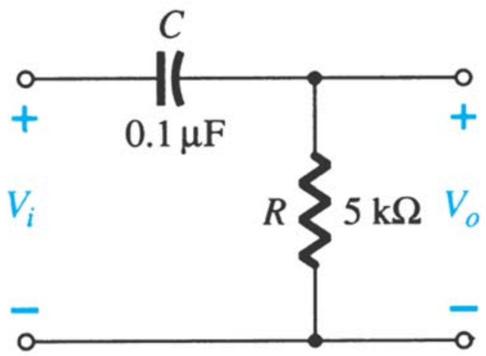


-A change in frequency by a factor of 2, equivalent to 1 octave, results in a 6-dB change in the ratio as noted by the change in gain from $f_1/2$ to f_1.

-For a 10:1 change in frequency, equivalent to 1 decade, there is a 20-dB change in the ratio as demonstrated between the frequencies of

Ex. For the given network:

(a) Determine the break frequency.
(b) Sketch the asymptotes and locate the -3-dB point.
(c) Sketch the frequency response curve.



Solution:

(a) $f_1 = \dfrac{1}{2\pi RC} = \dfrac{1}{2\pi\left(5\times10^3\,\Omega\right)\left(0.1\times10^{-6}\,\text{F}\right)} \cong 318.5\text{Hz}$

(b) See Figure below

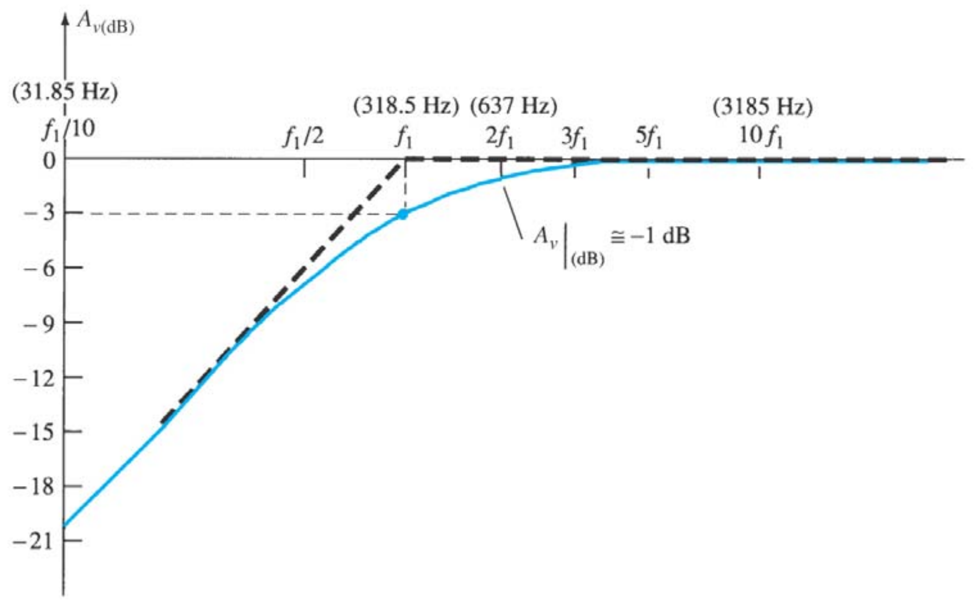
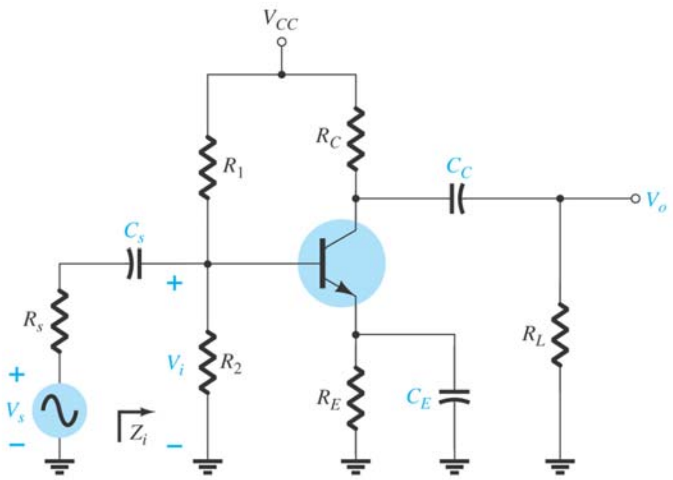


Fig. 11.14 Frequency response for the RC circuit of the Ex.

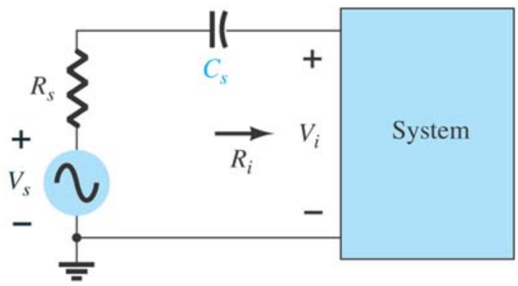
- *Low Frequency Analysis-BJT Amplifiers:*

- The analysis of this section will employ the loaded voltage-divider BJT bias configuration, but the results can be applied to any BJT configuration.
- It will simply be necessary to find the appropriate equivalent resistance for the *R-C* combination (*<u>for the capacitors C_S, C_C, and C_E, which will determine the low-frequency response</u>*).



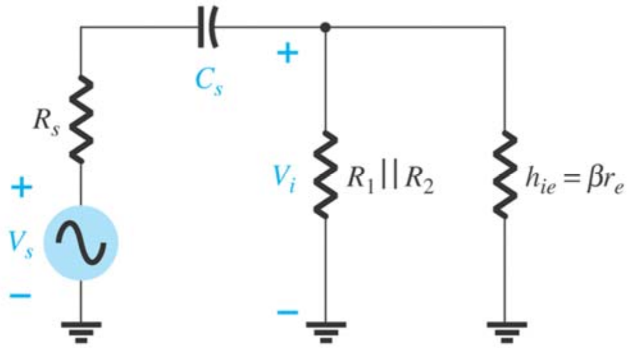
1) *The effect of C_S:*

- Since C_S is normally connected between the applied source and the active device, the total resistance is now $R_s + R_i$, and the cutoff frequency will be modified to be as:



$$f_{Ls} = \frac{1}{2\pi(R_s + R_i)C_s}$$

- At mid or high frequencies, the reactance of the capacitor will be sufficiently small to permit a short-circuit approximation for the element. The voltage V_i will then be related to V_s by



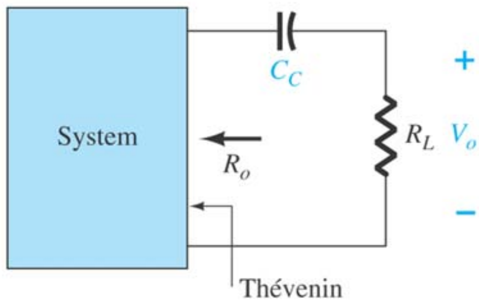
$$V_i\,|_{mid} = Vs\frac{Ri}{Ri + Rs}$$

- The voltage $\mathbf{V}_i$ applied to the input of the active device can be calculated using the voltage-divider rule:

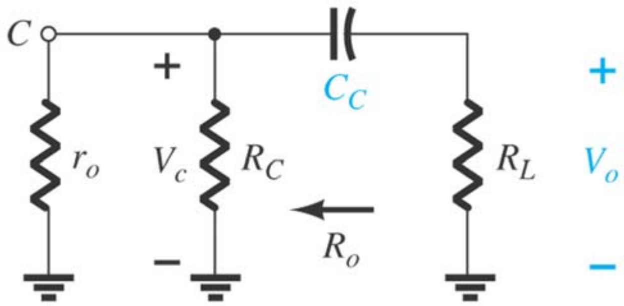
$$\mathbf{V}_i = \mathbf{V}_s\frac{R_i}{R_s + R_i - jX_{Cs}}$$

2) *The effect of C_C:*

- Since Cc the coupling capacitor is normally connected between the output of the active device and the applied load, the total resistance is now $R_o + R_L$, and the cutoff frequency will be modified to be as:

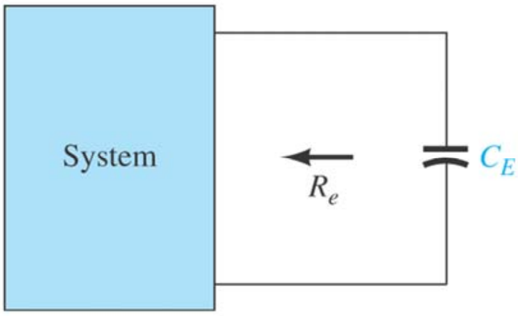


$$f_{LC} = \frac{1}{2\pi(R_o + R_L)C_C}$$

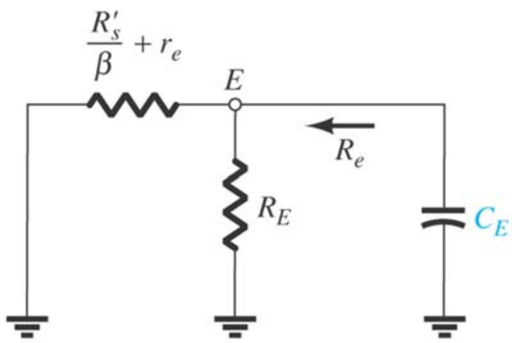


3) The effect of C_E:

- To determine f_{LE}, the network "seen" by C_E must be determined as shown in the Fig. below. Once the level of R_e is established, the cutoff frequency due to C_E can be determined using the following equation:



$$f_{LE} = \frac{1}{2\pi(R_e)C_E}$$



where R_e could be calculated as:

$$R_e = R_E // \left(\frac{R_S // R_1 // R_2}{\beta} + r_e \right)$$

where $R_S // R_1 // R_2 = R'_S$

Ex. (a) Determine the lower cutoff frequency for the voltage-divider BJT bias configuration network using the following parameters:
C_s =10μF, C_E =20μF, C_C =1μF, R_s =1kΩ, R_1 =40kΩ, R_2 =10kΩ, R_E =2kΩ, R_C =4kΩ, R_L = 2.2 kΩ, β= 100, r_o=∞, V_{CC} =20V.

(b) Sketch the frequency response using a Bode plot.

Solution:

(a) Determining r_e for dc conditions:

$$\beta R_E = (100)(2\text{ k}\Omega) = 200\text{ k}\Omega \gg 10R_2 = 100\text{ k}\Omega$$

The result is:

$$V_B \cong \frac{R_2 V_{CC}}{R_2 + R_1} = \frac{10\text{ k}\Omega(20\text{ V})}{10\text{ k}\Omega + 40\text{ k}\Omega} = \frac{200\text{ V}}{50} = 4\text{ V}$$

with
$$I_E = \frac{V_E}{R_E} = \frac{4\text{ V} - 0.7\text{ V}}{2\text{ k}\Omega} = \frac{3.3\text{ V}}{2\text{ k}\Omega} = 1.65\text{ mA}$$

so that
$$r_e = \frac{26\text{ mV}}{1.65\text{ mA}} \cong \mathbf{15.76\ \Omega}$$

and
$$\beta r_e = 100(15.76\ \Omega) = 1576\ \Omega = \mathbf{1.576\ k\Omega}$$

Midband Gain $A_v = \frac{V_o}{V_i} = \frac{-R_C \| R_L}{r_e} = -\frac{(4\text{ k}\Omega) \| (2.2\text{ k}\Omega)}{15.76\ \Omega} \cong -90$

The input impedance
$$Z_i = R_i = R_1 \| R_2 \| \beta r_e$$
$$= 40\text{ k}\Omega \| 10\text{ k}\Omega \| 1.576\text{ k}\Omega$$
$$\cong 1.32\text{ k}\Omega$$

and
$$V_i = \frac{R_i V_s}{R_i + R_s}$$

or
$$\frac{V_i}{V_s} = \frac{R_i}{R_i + R_s} = \frac{1.32\text{ k}\Omega}{1.32\text{ k}\Omega + 1\text{ k}\Omega} = 0.569$$

so that
$$A_{v_s} = \frac{V_o}{V_s} = \frac{V_o}{V_i}\frac{V_i}{V_s} = (-90)(0.569)$$
$$= \mathbf{-51.21}$$

C_s

$$R_i = R_1 \| R_2 \| \beta r_e = 40\text{ k}\Omega \| 10\text{ k}\Omega \| 1.576\text{ k}\Omega \cong 1.32\text{ k}\Omega$$

$$f_{L_S} = \frac{1}{2\pi\,(R_s + R_i)C_s} = \frac{1}{(6.28)(1\text{ k}\Omega + 1.32\text{ k}\Omega)(10\ \mu\text{F})}$$
$$f_{L_S} \cong \mathbf{6.86\ Hz}$$

C_C

$$f_{L_C} = \frac{1}{2\pi(R_C + R_L)C_C}$$
$$= \frac{1}{(6.28)(4\text{ k}\Omega + 2.2\text{ k}\Omega)(1\ \mu\text{F})}$$
$$\cong \mathbf{25.68\ Hz}$$

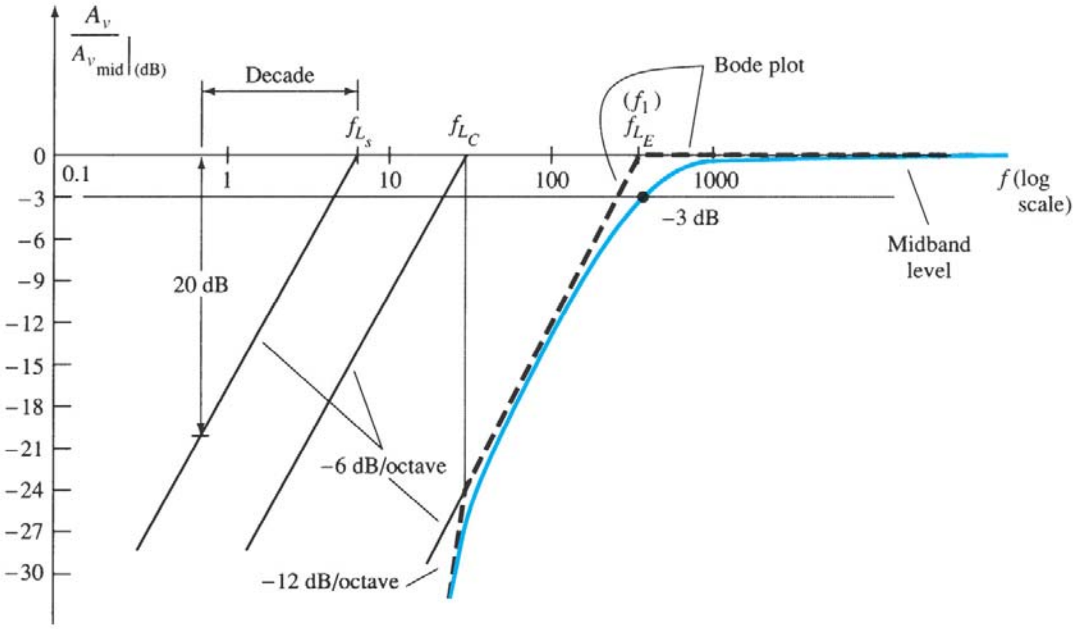
C_E

$$R_s' = R_s \| R_1 \| R_2 = 1\text{ k}\Omega \| 40\text{ k}\Omega \| 10\text{ k}\Omega \cong 0.889\text{ k}\Omega$$

$$R_e = R_E \Big\| \left(\frac{R'_s}{\beta} + r_e\right) = 2\text{ k}\Omega \Big\| \left(\frac{0.889\text{ k}\Omega}{100} + 15.76\ \Omega\right)$$
$$= 2\text{ k}\Omega \| (8.89\ \Omega + 15.76\ \Omega) = 2\text{ k}\Omega \| 24.65\ \Omega \cong 24.35\ \Omega$$

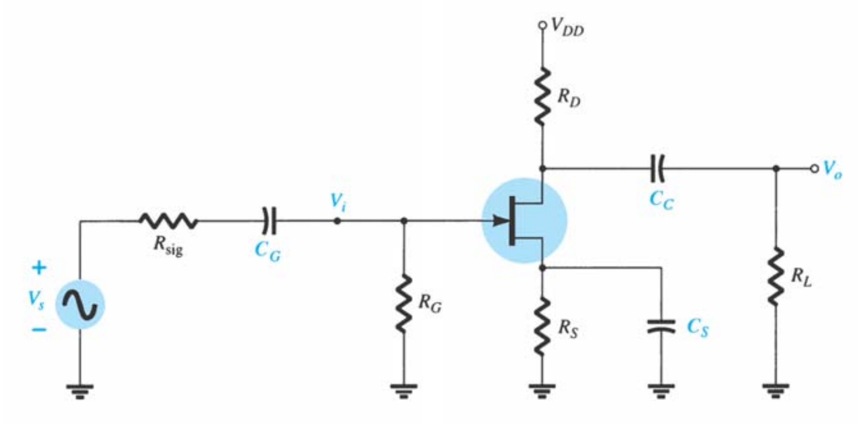
$$f_{L_E} = \frac{1}{2\pi R_e C_E} = \frac{1}{(6.28)(24.35\ \Omega)(20\ \mu\text{F})} = \frac{10^6}{3058.36} \cong \mathbf{327\ Hz}$$

(b)



- ***Low Frequency Analysis-FET Amplifiers:***

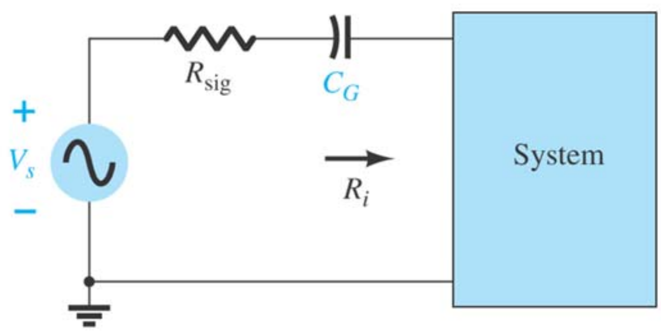
  - The analysis of the analysis of the FET amplifier in the low-frequency region will be quite similar to that of the BJT amplifier. There are again three capacitors of primary concern as appearing in the given network: C_G, C_C, and C_S.



1) ***The effect of C_G:***

The cutoff frequency determined by C_G will then be

$$f_{LG} = \frac{1}{2\pi(R_G + R_{sig})C_G}$$

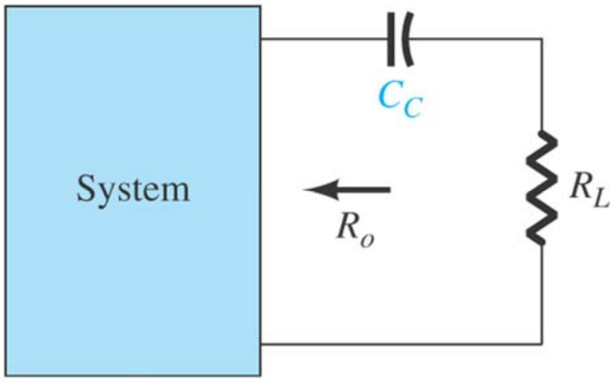


2) *The effect of C_C:*

The cutoff frequency determined by C_C will then be

$$f_{LC} = \frac{1}{2\pi(R_L + R_o)C_C}$$

where $R_o = R_D // r_d$



3) *The effect of C_S:*

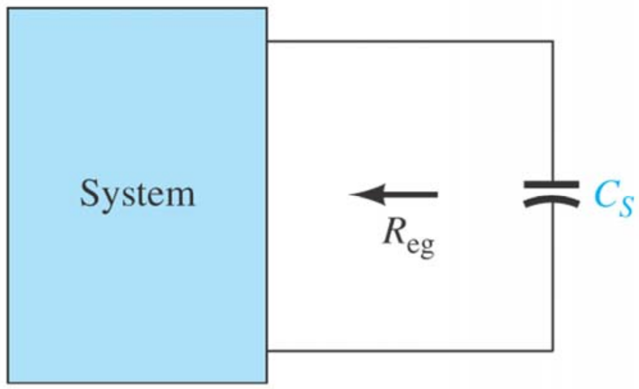
The cutoff frequency determined by C_S will then be

$$f_{LS} = \frac{1}{2\pi(R_{eg})C_S}$$

$$\text{where } R_{eg} = \frac{R_S}{1 + \left[\dfrac{R_S(1 + g_m r_d)}{(r_d + R_G // R_L)}\right]}$$

which for $r_d \cong \infty$ bcomes

$$R_{eg} = R_S // \left(\frac{1}{g_m}\right)$$



Ex. (a) Determine the lower cutoff frequency for the CS FET bias configuration network using the following parameters:
C_G =0.01μF, C_C =0.5μF, C_S =2μF, R_{sig} =10kΩ, R_G =1MΩ, R_D =4.7kΩ, R_S =1kΩ, R_L = 2.2 kΩ, I_{DSS}=8mA, V_p= -4V, r_d=∞, V_{DD} =20V.
(b) Sketch the frequency response using a Bode plot.

Solution:

(a) DC Analysis: Plotting the transfer curve of $I_D = I_{DSS}(1 - V_{GS}/V_P)^2$ and superimposing the curve defined by $V_{GS} = -I_D R_S$ will result in an intersection at $V_{GS_Q} = -2$ V and $I_{D_Q} = 2$ mA. In addition,

$$g_{m0} = \frac{2I_{DSS}}{|V_P|} = \frac{2(8\text{ mA})}{4\text{ V}} = 4\text{ mS}$$

$$g_m = g_{m0}\left(1 - \frac{V_{GS_Q}}{V_P}\right) = 4\text{ mS}\left(1 - \frac{-2\text{ V}}{-4\text{ V}}\right) = 2\text{ mS}$$

C_G $$f_{L_G} = \frac{1}{2\pi\,(10\text{ k}\Omega + 1\text{ M}\Omega)(0.01\ \mu\text{F})} \cong \mathbf{15.8\ Hz}$$

C_C $$f_{L_C} = \frac{1}{2\pi\,(4.7\text{ k}\Omega + 2.2\text{ k}\Omega)(0.5\ \mu\text{F})} \cong \mathbf{46.13\ Hz}$$

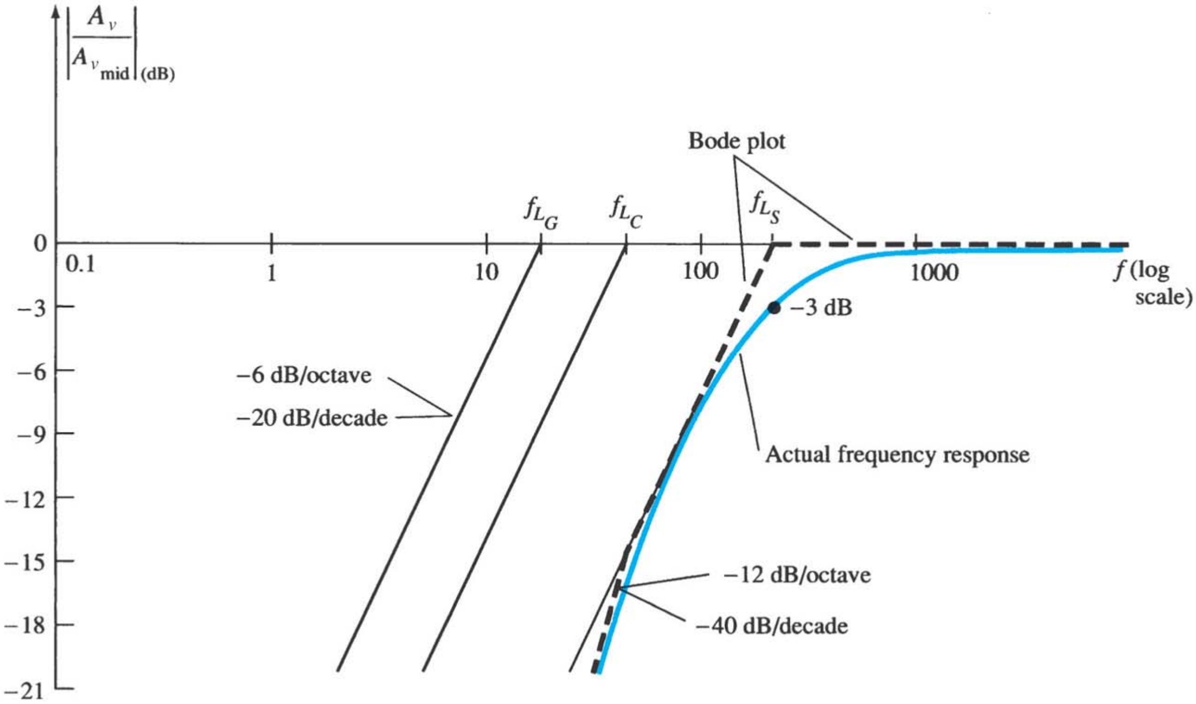
C_S $$R_{eq} = R_S \| \frac{1}{g_m} = 1\text{ k}\Omega \| \frac{1}{2\text{ mS}} = 1\text{ k}\Omega \| 0.5\text{ k}\Omega = 333.33\ \Omega$$

$$f_{L_S} = \frac{1}{2\pi\,(333.33\ \Omega)(2\ \mu\text{F})} = \mathbf{238.73\ Hz}$$

Since f_{L_S} is the largest of the three cutoff frequencies, it defines the low cutoff frequency for the network.

(b) The midband gain of the system is determined by

$$A_{v_{mid}} = \frac{V_o}{V_i} = -g_m(R_D \| R_L) = -(2\text{ mS})(4.7\text{ k}\Omega \| 2.2\text{ k}\Omega)$$
$$= -(2\text{ mS})(1.499\text{ k}\Omega)$$
$$\cong \mathbf{-3}$$



- *Miller Effect capacitance:*

In the high-frequency region, the capacitive elements of importance are the interelectrode (between terminals) capacitances internal to the active device and the wiring capacitance between leads of the network. The large capacitors of the network that controlled the low-frequency response have all been replaced by their short-circuit equivalent due to their very low reactance levels.

- Miller input capacitance

$$C_{Mi} = (1 - A_v)C_f$$

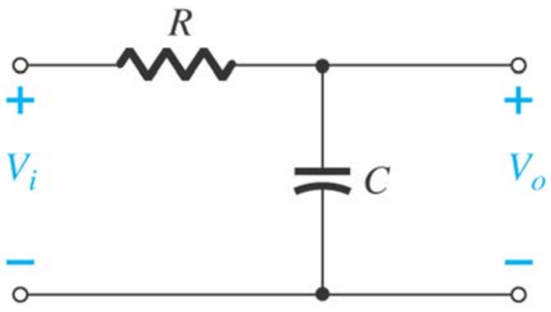
where C_f is the feedback capacitance.

- Miller output capacitance

$$C_{Mo} = \left(1 - \frac{1}{A_v}\right)C_f \cong_{|A_v>>1} C_f$$

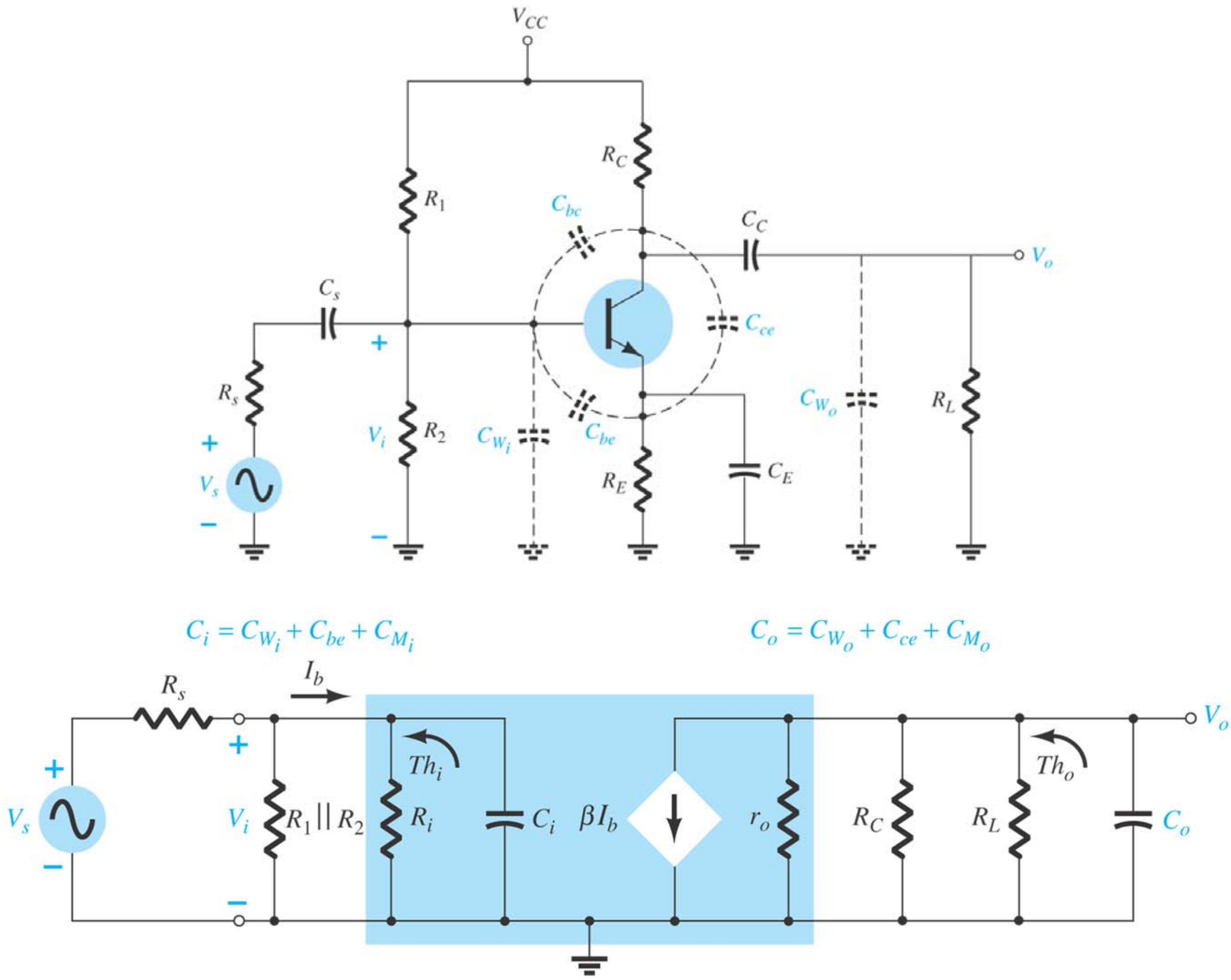
where C_f is the feedback capacitance.

- *High Frequency Analysis-BJT Amplifiers:*



In the high-frequency region, the *RC* network of concern has the configuration appearing in given Fig. At increasing frequencies, the reactance X_C will decrease in magnitude, resulting in a shorting effect across the output and a decrease in gain.
The derivation leading to the corner frequency for this *RC* configuration follows along similar lines to that encountered for the low-frequency region. The most significant difference is in the general form of A_v appearing below:

$$A_v = \frac{1}{1 + j\left(\frac{f}{f_2}\right)}$$



- In the above Fig., the various parasitic capacitances (C_{be}, C_{bc}, C_{ce}) of the transistor have been included with the wiring capacitances (C_{W_i}, C_{W_o}) introduced during construction.
- In the high-frequency equivalent model for the network, note the absence of the capacitors C_s, C_C, and C_E, which are all assumed to be in the short-circuit state at these frequencies.
- The capacitance C_i includes the input wiring capacitance C_{W_i}, the transition capacitance C_{be}, and the Miller capacitance C_{M_i}.
- The capacitance C_o includes the output wiring capacitance C_{W_o}, the parasitic capacitance C_{ce}, and the output Miller capacitance C_{M_o}.
- In general, the capacitance C_{be} is the largest of the parasitic capacitances, with C_{ce} the smallest. In fact, most specification sheets simply provide the levels of C_{be} and C_{bc} and do not include C_{ce} unless it will affect the response of a particular type of transistor in a specific area of application.

1) For the input network, C_i:

For the input network, the -3-dB frequency is defined by

$$f_{Hi} = \frac{1}{2\pi R_{Thi} C_i}$$

where

$$R_{Th_1} = R_s \| R_1 \| R_2 \| R_i$$

$$C_i = C_{W_i} + C_{be} + C_{M_i} = C_{W_i} + C_{be} + (1 - A_v) C_{bc}$$

2) For the output network, C_o:

$$f_{H_o} = \frac{1}{2\pi R_{Th_2} C_o}$$

$$R_{Th_2} = R_C \| R_L \| r_o$$

$$C_o = C_{W_o} + C_{ce} + C_{M_o}$$

Ex. For the given network, with the following parameters:
C_s =10μF, C_E =20μF, C_C =1μF, R_s =1kΩ, R_1 =40kΩ, R_2 =10kΩ, R_E =2kΩ, R_C =4kΩ, R_L = 2.2 kΩ, β= 100, r_o=∞, V_{CC} =20V.
with the addition of
C_{be} =36pF, C_{bc} =4pF, C_{ce} = 1pF, C_{W_i} =6pF, C_{W_o} =8pF

(a) Determine f_{Hi} and f_{Ho}.

(b) Sketch the total frequency response for the low- and high-frequency regions.

Solution:

(a) from previous example

$$R_i = 1.32\ \text{k}\Omega, \qquad A_{v_{mid}}(\text{amplifier}) = -90$$

and
$$R_{Th_1} = R_s \| R_1 \| R_2 \| R_i = 1\ \text{k}\Omega \| 40\ \text{k}\Omega \| 10\ \text{k}\Omega \| 1.32\ \text{k}\Omega$$
$$\cong 0.531\ \text{k}\Omega$$

with
$$C_i = C_{W_i} + C_{be} + (1 - A_v)C_{be}$$
$$= 6 \text{ pF} + 36 \text{ pF} + [1 - (-90)]4 \text{ pF}$$
$$= 406 \text{ pF}$$

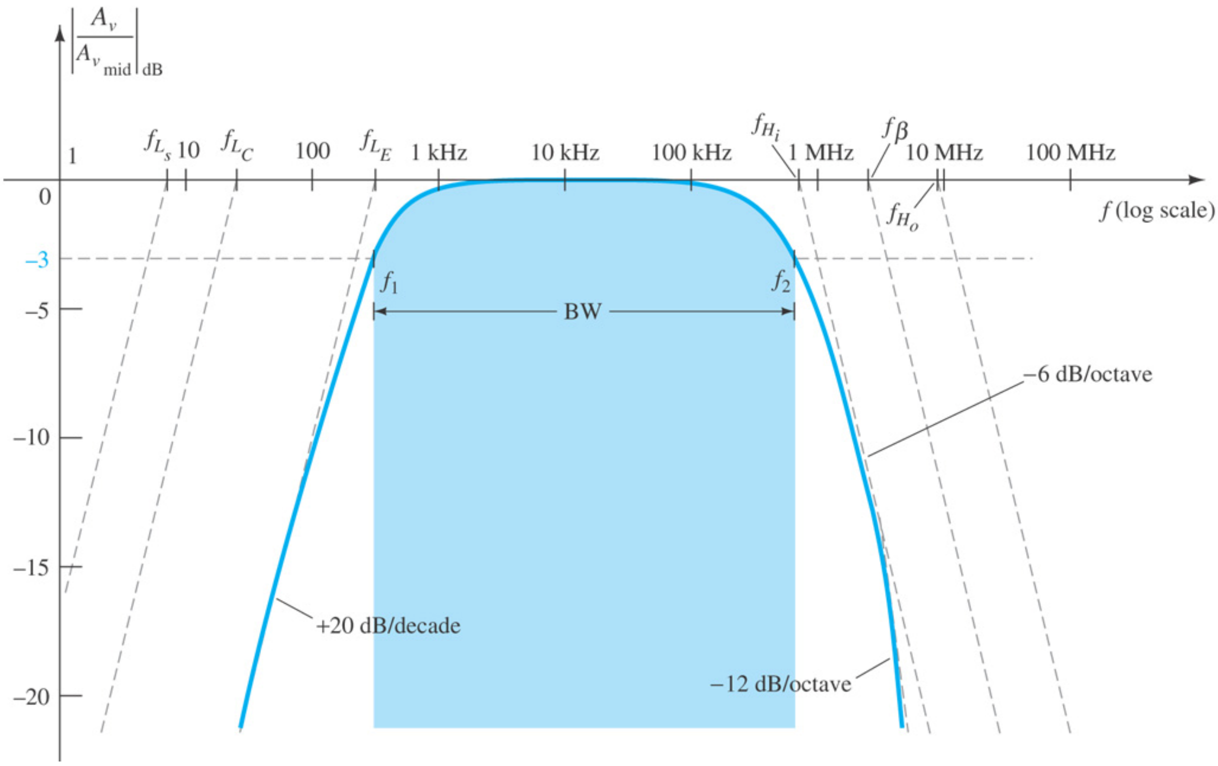
$$f_{H_i} = \frac{1}{2\pi R_{\text{Th}_1} C_i} = \frac{1}{2\pi(0.531 \text{ k}\Omega)(406 \text{ pF})}$$
$$= \mathbf{738.24 \text{ kHz}}$$

$$R_{\text{Th}_2} = R_C \| R_L = 4 \text{ k}\Omega \| 2.2 \text{ k}\Omega = 1.419 \text{ k}\Omega$$

$$C_o = C_{W_o} + C_{ce} + C_{M_o} = 8 \text{ pF} + 1 \text{ pF} + \left(1 - \frac{1}{-90}\right) 4 \text{ pF}$$
$$= 13.04 \text{ pF}$$

$$f_{H_o} = \frac{1}{2\pi R_{\text{Th}_2} C_o} = \frac{1}{2\pi(1.419 \text{ k}\Omega)(13.04 \text{ pF})}$$
$$= \mathbf{8.6 \text{ MHz}}$$

(b)

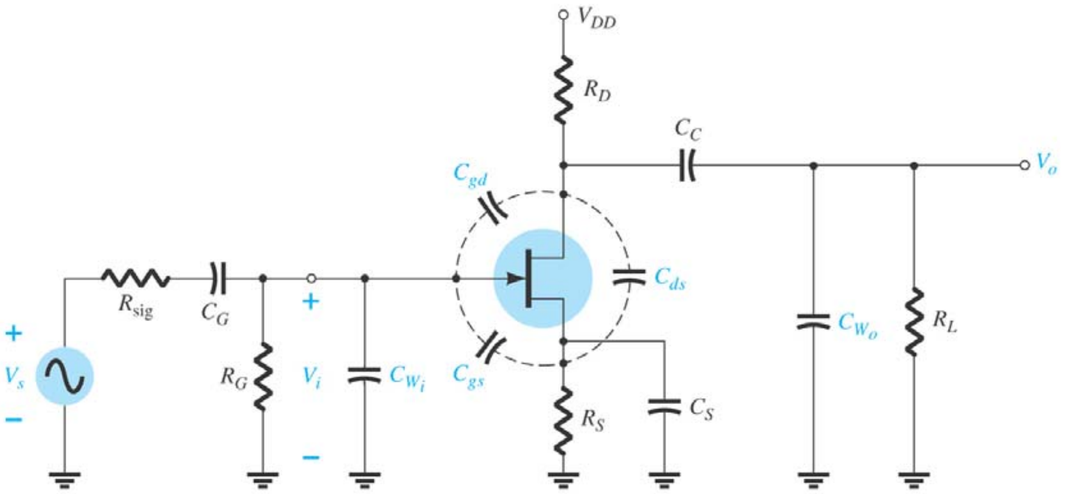


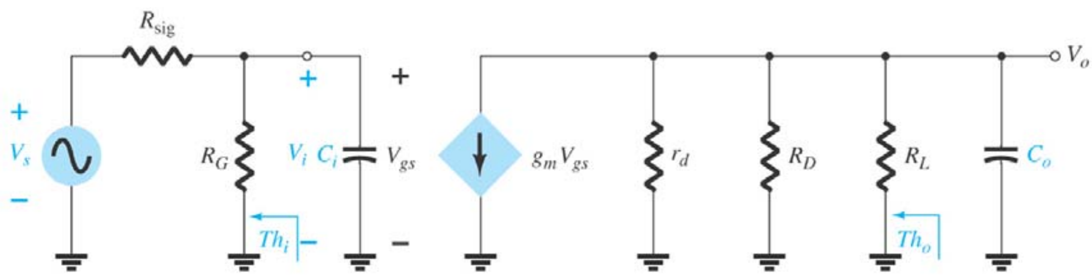
- ***High Frequency Analysis-FET Amplifiers:***

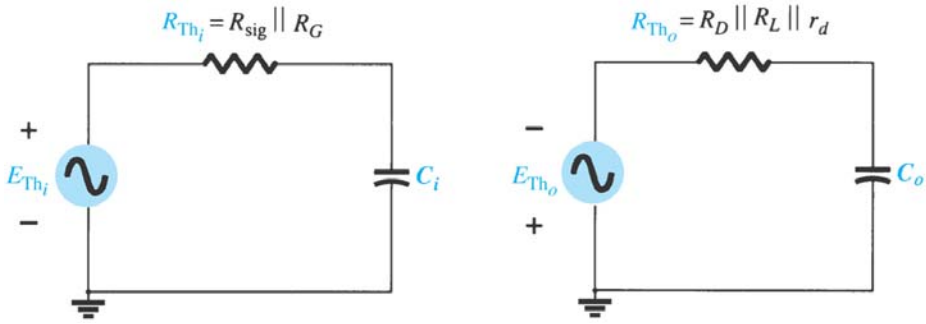
  - The analysis of the high-frequency response of the FET amplifier will proceed in a very similar manner to that encountered for the BJT amplifier. There are interelectrode and wiring capacitances that will determine the high-frequency characteristics of the amplifier.

  - The capacitors C_{gs} and C_{gd} typically vary from 1 to 10 pF, while the capacitance C_{ds} is usually quite a bit smaller, ranging from 0.1 to1 pF.

  - At high frequencies, C_i will approach a short-circuit equivalent and V_{gs} will drop in value and reduce the overall gain. At frequencies where C_o approaches its short circuit equivalent, the parallel output voltage V_o will drop in magnitude.







$$f_{H_i} = \frac{1}{2\pi R_{Th_1} C_i}$$

and $$R_{Th_1} = R_{sig} \| R_G$$

with $$C_i = C_{W_i} + C_{gs} + C_{M_i}$$

and $$C_{M_i} = (1 - A_v) C_{gd}$$

and for the output circuit,

$$f_{H_o} = \frac{1}{2\pi R_{Th_2} C_o}$$

with $$R_{Th_2} = R_D \| R_L \| r_d$$

and $$C_o = C_{W_o} + C_{ds} + C_{M_o}$$

and $$C_{M_o} = \left(1 - \frac{1}{Av}\right) C_{gd}$$

Ex. (a) Determine the high cutoff frequencies for the CS FET bias configuration network using the following parameters:
C_G =0.01µF, C_C =0.5µF, C_S =2µF, R_{sig} =10kΩ, R_G =1MΩ, R_D =4.7kΩ, R_S =1kΩ, R_L = 2.2 kΩ, I_{DSS}=8mA, V_p= -4V, r_d=∞, V_{DD} =20V.
C_{gd} = 2pF, C_{gs} =4pF, C_{ds} =0.5pF, C_{W_i} =5pF, C_{W_o} =6pF

Solution:

(a) From the previous example

$$R_{Th_1} = R_{sig} \| R_G = 10\text{ k}\Omega \| 1\text{ M}\Omega = 9.9\text{ k}\Omega$$
$$A_v = -3.$$

$$C_i = C_{W_i} + C_{gs} + (1 - A_v)C_{gd}$$
$$= 5\text{ pF} + 4\text{ pF} + (1 + 3)2\text{ pF}$$
$$= 9\text{ pF} + 8\text{ pF}$$
$$= 17\text{ pF}$$

$$f_{H_i} = \frac{1}{2\pi R_{Th_1} C_i}$$

$$= \frac{1}{2\pi(9.9\text{ k}\Omega)(17\text{ pF})} = \mathbf{945.67\text{ kHz}}$$

$$R_{Th_2} = R_D \| R_L$$
$$= 4.7\text{ k}\Omega \| 2.2\text{ k}\Omega$$
$$\cong 1.5\text{ k}\Omega$$

$$C_o = C_{W_o} + C_{ds} + C_{M_o} = 6\text{ pF} + 0.5\text{ pF} + \left(1 - \frac{1}{-3}\right)2\text{ pF} = 9.17\text{ pF}$$

$$f_{H_o} = \frac{1}{2\pi(1.5\text{ k}\Omega)(9.17\text{ pF})} = \mathbf{11.57\text{ MHz}}$$

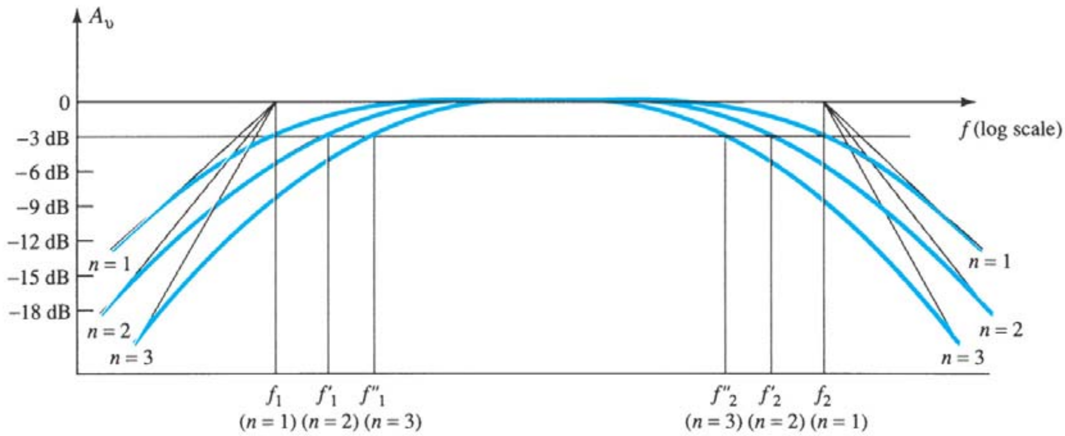
- ***Multistage Frequency Effect:***

  - **For Low Frequency region**

$$f_1' = \frac{f_1}{\sqrt{2^{\left(\frac{1}{n}\right)} - 1}}$$

  - **For High Frequency region**

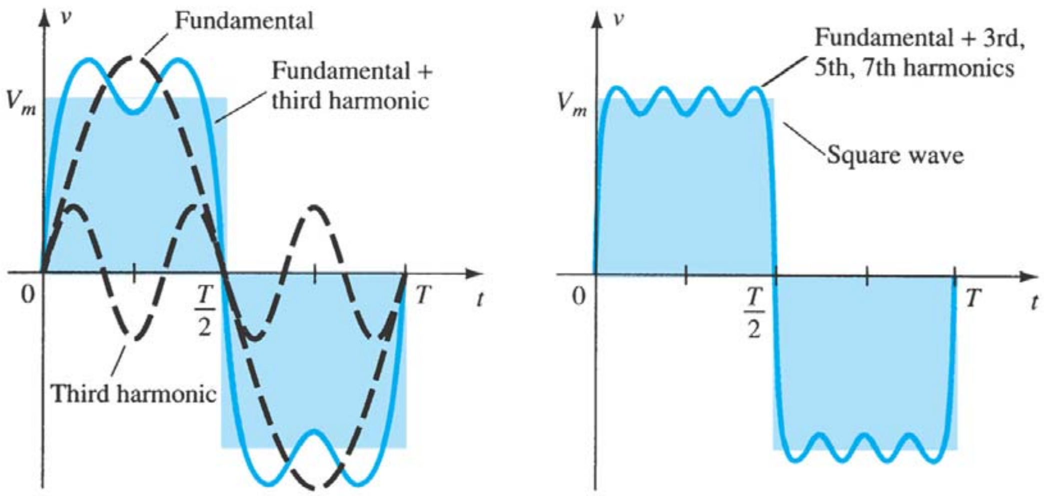
$$f_2' = \left(\sqrt{2^{\left(\frac{1}{n}\right)} - 1}\right) f_2$$



- ***Square wave Testing:***

  - Experimentally, the sense for the frequency response can be determined by applying a square wave signal to the amplifier and noting the output response.
  - The reason for choosing a square-wave signal for the testing process is best described by examining the Fourier series expansion of a square wave composed of a series of sinusoidal components of different magnitudes and frequencies. The summation of the terms of the series will result in the original waveform. In other words, even though a waveform may not be sinusoidal, it can be reproduced by a series of sinusoidal terms of different frequencies and magnitudes.

$$v = \frac{4}{\pi} V_m\left(\sin 2\pi f_s t + \frac{1}{3}\sin 2\pi(3f_s)t + \frac{1}{5}\sin 2\pi(5f_s)t + \frac{1}{7}\sin 2\pi(7f_s)t + \frac{1}{9}\sin 2\pi(9f_s)t + \cdots + \frac{1}{n}\sin 2\pi(nf_s)t\right)$$



  - Since the ninth harmonic has a magnitude greater than 10% of the fundamental term, the fundamental term through the ninth harmonic are the major contributors to the Fourier series expansion of the square-wave function.

<u>*Ex. For a specific application (Audio amplifier with 20*kHz *Bandwidth), what is the maximum frequency could be amplified?*</u>

$$\frac{20\text{kHz}}{9} = 2.2\text{kHz}$$

- If the response of an amplifier to an applied square wave is an undistorted replica of the input, the frequency response (or BW) of the amplifier is obviously sufficient for the applied frequency.

- If the response is as shown in Fig. 11.60a and b, the low frequencies are not being amplified properly and the low cutoff frequency has to be investigated.

- If the waveform has the appearance of Fig. 11.60c, the high-frequency components are not receiving sufficient amplification and the high cutoff frequency (or BW) has to be reviewed.

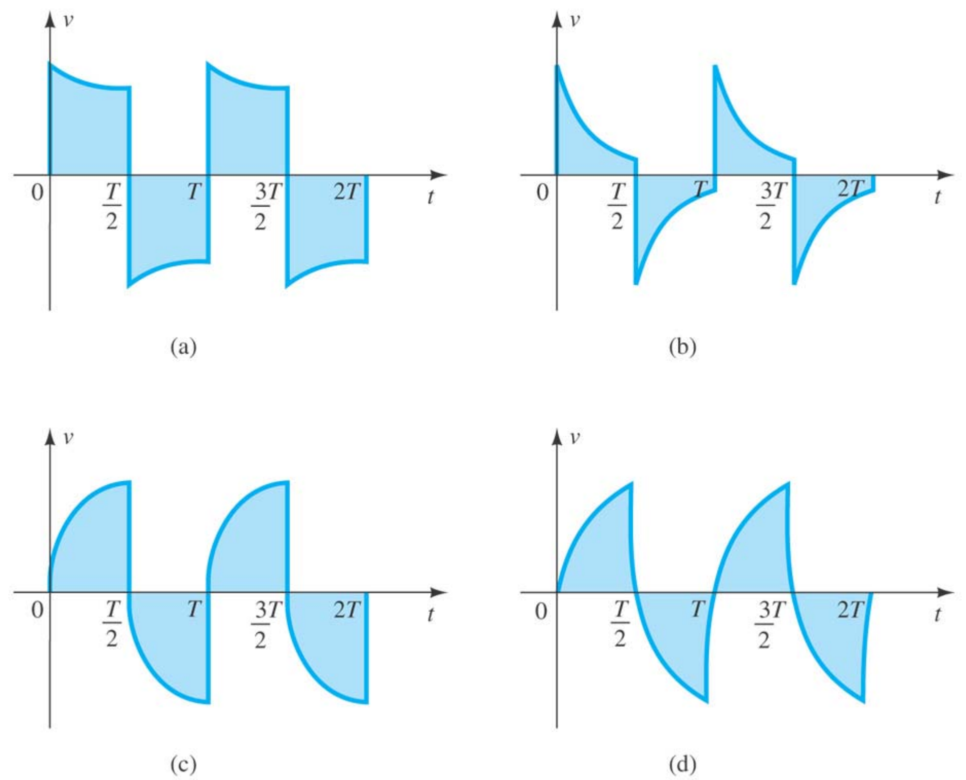
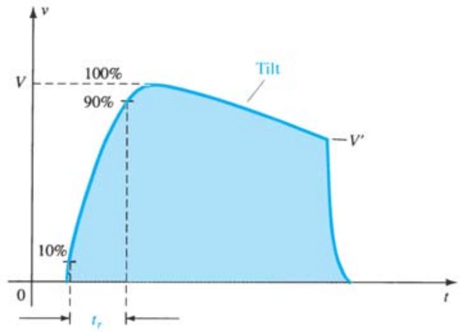


Fig. 11.60 (a) Poor low-frequency response; (b) very poor low-frequency response; (c) poor high-frequency response; (d) very poor high-frequency response.

- The actual high cutoff frequency (or BW) can be determined from the output waveform by carefully measuring the rise time defined between 10% and 90% of the peak value, as shown in the Fig. below.



- Substituting into the following equation will provide the upper cutoff frequency, and since BW = f_{Hi}- f_{Lo} ≅ f_{Hi}, the equation also provides an indication of the BW of the amplifier.

$$\text{BW} \cong f_{Hi} = \frac{0.35}{t_r}$$

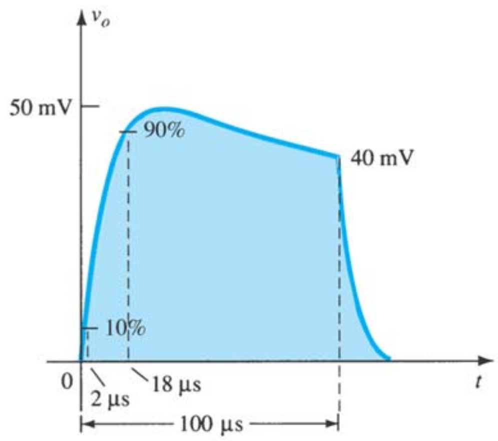
- The low cutoff frequency can be determined from the output response by carefully measuring the tilt and substituting into one of the following equations:

$$\%\text{tilt} = P\% = \frac{V - V'}{V} \times 100\%$$

$$= P = \frac{V - V'}{V} \quad \text{(decimal form)}$$

- The low cutoff frequency is then determined from

$$f_{Lo} = \frac{P}{\pi} f_s$$



Ex. The application of a 1-mV, 5-kHz square wave to an amplifier resulted in the output waveform of the given Fig.

(a) Write the Fourier series expansion for the square wave through the ninth harmonic.
(b) Determine the bandwidth of the amplifier.

Solution:

(a) $$v_i = \frac{4\text{ mV}}{\pi}\left(\sin 2\pi(5\times10^3)t + \frac{1}{3}\sin 2\pi(15\times10^3)t + \frac{1}{5}\sin 2\pi(25\times10^3)t + \frac{1}{7}\sin 2\pi(35\times10^3)t + \frac{1}{9}\sin 2\pi(45\times10^3)t\right.$$

(b) $t_r = 18\ \mu s - 2\ \mu s = 16\ \mu s$

$$\text{BW} = \frac{0.35}{t_r} = \frac{0.35}{16\ \mu s} = \mathbf{21{,}875\ Hz} \cong 4.4 f_s$$

(c) $$P = \frac{V - V'}{V} = \frac{50\text{ mV} - 40\text{ mV}}{50\text{ mV}} = 0.2$$

$$f_{L_o} = \frac{P}{\pi} f_s = \left(\frac{0.2}{\pi}\right)(5\text{ kHz}) = \mathbf{318.31\ Hz}$$