Whether one of the two poles is dominant will depend on the relative values of R_{sig} a[illegible] R_L. If the two poles are close to each other, then the 3-dB frequency f_H can be determin[illegible] either by exact analysis—that is, finding the frequency at which the gain is down by 3 dB— by using the approximate formula in Eq. (10.77),

$$f_H \simeq 1 \bigg/ \sqrt{\frac{1}{f_{P1}^2} + \frac{1}{f_{P2}^2}} \tag{10.164}$$

EXERCISE

10.30 For the CC–CB amplifier of Fig. 10.41(a), let $I = 0.5$ mA, $\beta = 100$, $C_\pi = 6$ pF, $C_\mu = 2$ pF, $R_{sig} = 10$ kΩ, and $R_L = 10$ kΩ. Find the low-frequency overall voltage gain A_M, the frequencies of the poles, and the 3-dB frequency f_H. Find f_H both exactly and using the approximate formula in Eq. (10.164).
Ans. 50 V/V; 6.4 MHz and 8 MHz; f_H by exact evaluation = 4.6 MHz; f_H using Eq. (10.164) = 5 MHz.

Summary

- The coupling and bypass capacitors utilized in discrete-circuit amplifiers cause the amplifier gain to fall off at low frequencies. In the CS amplifier, the capacitors do not interact, and the frequencies of the low-frequency poles can be estimated by considering each of these capacitors separately and determining the resistance seen by the capacitor. The highest-frequency pole is the one that determines the lower 3-dB frequency f_L. In the CE amplifier, the capacitors interact, and thus the poles cannot be easily determined. Rather the method of short-circuit time constants can be used to obtain an estimate of the 3-dB frequency, f_L.

- Both the MOSFET and the BJT have internal capacitive effects that can be modeled by augmenting the device hybrid-π model with capacitances. Usually at least two capacitances are needed: C_{gs} and C_{gd} (C_π and C_μ for the BJT). A figure of merit for the high-frequency operation of the transistor is the frequency f_T at which the short-circuit current gain of the CS (CE) transistor reduces to unity. For the MOSFET, $f_T = g_m/2\pi(C_{gs} + C_{gd})$, and for the BJT, $f_T = g_m/2\pi(C_\pi + C_\mu)$.

- The internal capacitances of the MOSFET and the BJT cause the amplifier gain to fall off at high frequencies. An estimate of the amplifier bandwidth is provided by the frequency f_H at which the gain drops 3 dB below its value at midband, A_M. A figure of merit for the amplifier is the gain–bandwidth product $GB = A_M f_H$. Usually, it is possible to trade off gain for increased bandwidth with GB remaining nearly constant. For amplifiers with a dominant pole with frequency f_H, the gain falls off at a uniform 6-dB/octave (20-dB/decade) rate, reaching 0 dB at $f_t = GB$.

- The high-frequency response of the CS and CE amplifiers is severely limited by the Miller effect: The small capacitance C_{gd} (C_μ) is multiplied by a factor approximately equal to the gain from gate to drain (base to collector) $g_m R_L'$ and thus gives rise to a large capacitance at the amplifier input. The increased C_{in} interacts with the effective signal-source resistance R_{sig}' and causes the amplifier gain to have a 3-dB frequency $f_H = 1/2\pi R_{sig}' C_{in}$.

- The method of open-circuit time constants provides a simple and powerful way to obtain a reasonably good estimate of the upper 3-dB frequency f_H. The capacitors that limit the high-frequency response are considered one at time with $V_{sig} = 0$ and all the other capacitances set to zero (open circuited). The resistance seen by each capacitance is determined, and the overall time constant τ_H is obtained by summing the individual time constants. Then f_H is found as $1/2\pi\tau_H$.

- The CG and CB amplifiers do *not* suffer from the Miller effect. Thus the cascode amplifier, which consists of a cascade of CS and CG stages (CE and CB stages), can be designed to obtain wider bandwidth than that achieved in the CS (CE) amplifier alone. The key, however, is to design the cascode so that the gain obtained in the CS (CE) stage is minimized.

- The source and emitter followers can have complex poles. Thus, their frequency response is evaluated using the complete transfer function. Followers of both types exhibit wide bandwidths.
- The high-frequency response of the differential amplifier can be obtained by considering the differential and common-mode half-circuits. The CMRR falls off at a relatively low frequency determined by the output impedance of the bias current source.
- The high-frequency response of the current-mirror-loaded differential amplifier is complicated by the fact that there are two signal paths between input and output: a direct path and one through the current mirror.
- Combining two transistors in a way that eliminates or minimizes the Miller effect can result in a much wider bandwidth. Some such configurations are presented in Section 10.8.

PROBLEMS

Computer Simulation Problems

SIM Problems identified by the Multisim/PSpice icon are intended to demonstrate the value of using SPICE simulation to verify hand analysis and design, and to investigate important issues such as gain–bandwidth trade-off. Instructions to assist in setting up PSpice and Multisim simulations for all the indicated problems can be found in the corresponding files on the website. Note that if a particular parameter value is not specified in the problem statement, you are to make a reasonable assumption.

Section 10.1: Low-Frequency Response of Discrete-Circuit Common-Source and Common-Emitter Amplifiers

D 10.1 For the amplifier in Fig. 10.3(a), if $R_{G1} = 2\ \text{M}\Omega$, $R_{G2} = 1\ \text{M}\Omega$, and $R_{sig} = 200\ \text{k}\Omega$, find the value of the coupling capacitor C_{C1} (specified to one significant digit) that places the associated pole at 10 Hz or lower.

D 10.2 For the amplifier in Fig. 10.3(a), if $R_D = 10\ \text{k}\Omega$, $R_L = 10\ \text{k}\Omega$, and r_o is very large, find the value of C_{C2} (specified to one significant digit) that places the associated pole at 10 Hz or lower.

D 10.3 The amplifier in Fig. 10.3(a) is biased to operate at $g_m = 5$ mA/V, and $R_S = 1.8\ \text{k}\Omega$. Find the value of C_S (specified to one significant digit) that places its associated pole at 100 Hz or lower. What are the actual frequencies of the pole and zero realized?

10.4 The amplifier in Fig. 10.3(a) is biased to operate at $g_m = 5$ mA/V, and has the following component values: $R_{sig} = 100\ \text{k}\Omega$, $R_{G1} = 47\ \text{M}\Omega$, $R_{G2} = 10\ \text{M}\Omega$, $C_{C1} = 0.01\ \mu\text{F}$, $R_S = 2\ \text{k}\Omega$, $C_S = 10\ \mu\text{F}$, $R_D = 4.7\ \text{k}\Omega$, $R_L = 10\ \text{k}\Omega$, and $C_{C2} = 1\ \mu\text{F}$. Find $A_M, f_{P1}, f_{P2}, f_Z, f_{P3}$, and f_L.

D 10.5 The amplifier in Fig. P10.5 is biased to operate at $g_m = 2$ mA/V. Neglect r_o.

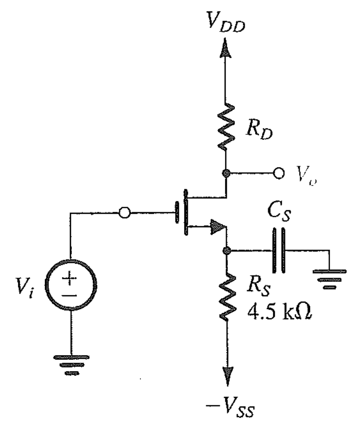

Figure P10.5

(a) Determine the value of R_D that results in a midband gain of −20 V/V.
(b) Determine the value of C_S that results in a pole frequency of 100 Hz.
(c) What is the frequency of the transmission zero introduced by C_S?
(d) Give an approximate value for the 3-dB frequency f_L.

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

(e) Sketch a Bode plot for the gain of this amplifier. What does the plot tell you about the gain at dc? Does this make sense? Why or why not?

D 10.6 Figure P10.6 shows a CS amplifier biased by a constant-current source I. Let $R_{sig} = 0.5\ \text{M}\Omega$, $R_G = 2\ \text{M}\Omega$, $g_m = 3\ \text{mA/V}$, $R_D = 20\ \text{k}\Omega$, and $R_L = 10\ \text{k}\Omega$. Find A_M. Also, design the coupling and bypass capacitors to locate the three low-frequency poles at 100 Hz, 10 Hz, and 1 Hz. Use a minimum total capacitance, with the capacitors specified only to a single significant digit. What value of f_L results?

D 10.7 Figure P10.7 shows a current-biased CE amplifier operating at 100 μA from ±3-V power supplies. It employs

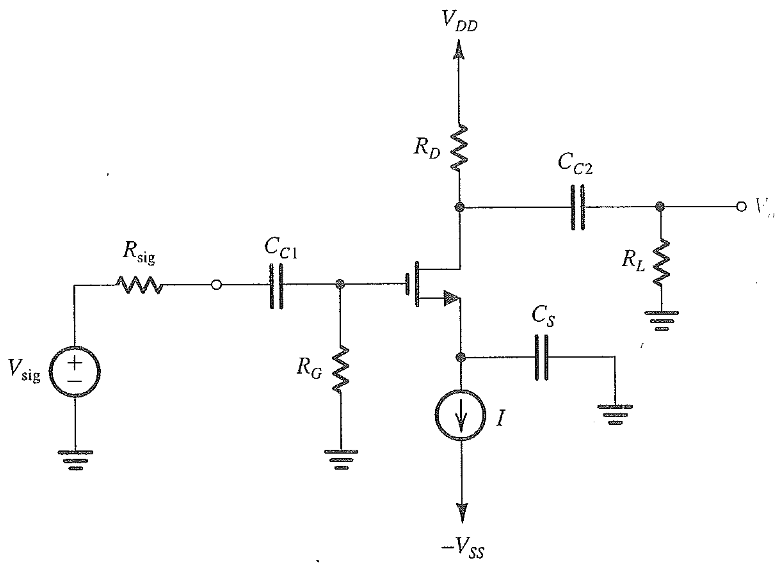

Figure P10.6

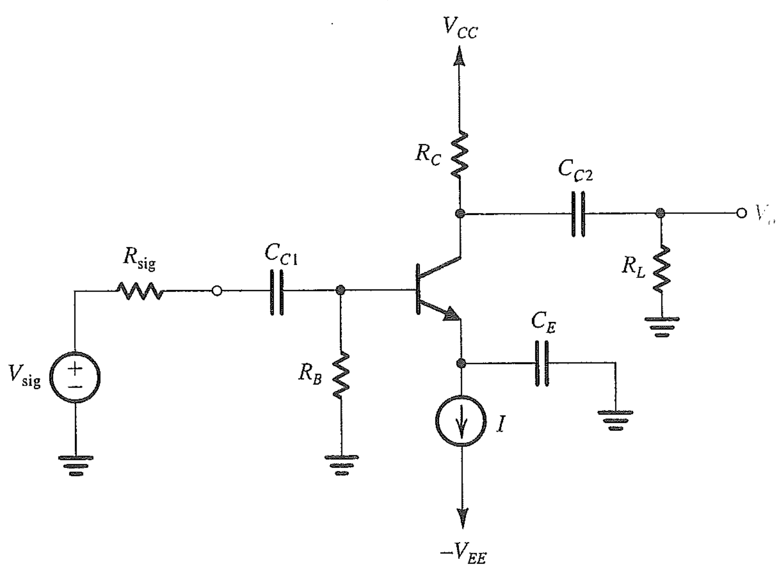

Figure P10.7

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem

of 2 pF. If the device is operated at $I_C = 0.25$ mA, what does its f_T become?

10.20 An *npn* transistor is operated at $I_C = 1$ mA and $V_{CB} = 2$ V. It has $\beta_0 = 100$, $V_A = 50$ V, $\tau_F = 30$ ps, $C_{je0} = 20$ fF, $C_{\mu 0} = 30$ fF, $V_{0c} = 0.75$ V, $m_{CBJ} = 0.5$, and $r_x = 100\ \Omega$. Sketch the complete hybrid-π model, and specify the values of all its components. Also, find f_T.

10.21 Measurement of h_{fe} of an *npn* transistor at 50 MHz shows that $|h_{fe}| = 10$ at $I_C = 0.2$ mA and 12 at $I_C = 1.0$ mA. Furthermore, C_μ was measured and found to be 0.1 pF. Find f_T at each of the two collector currents used. What must τ_F and C_{je} be?

10.22 A particular small-geometry BJT has f_T of 10 GHz and $C_\mu = 0.1$ pF when operated at $I_C = 1.0$ mA. What is C_π in this situation? Also, find g_m. For $\beta = 120$, find r_π and f_β.

10.23 For a BJT whose unity-gain bandwidth is 2 GHz and $\beta_0 = 200$, at what frequency does the magnitude of h_{fe} become 40? What is f_β?

*10.24 For a sufficiently high frequency, measurement of the complex input impedance of a BJT having (ac) grounded emitter and collector yields a real part approximating r_x. For what frequency, defined in terms of ω_β, is such an estimate of r_x good to within 10% under the condition that $r_x \le r_\pi/10$?

*10.25 Complete the table entries on the previous page for transistors (a) through (g), under the conditions indicated. Neglect r_x.

Section 10.3: High-Frequency Response of the CS and CE Amplifiers

10.26 In a particular common-source amplifier for which the midband voltage gain between gate and drain (i.e., $-g_m R_L'$) is -39 V/V, the NMOS transistor has $C_{gs} = 1.0$ pF and $C_{gd} = 0.1$ pF. What input capacitance would you expect? For what range of signal-source resistances can you expect the 3-dB frequency to exceed 1 MHz? Neglect the effect of R_G.

D 10.27 In the circuit of Fig. P10.27, the voltage amplifier is ideal (i.e., it has an infinite input resistance and a zero output resistance).

(a) Use the Miller approach to find an expression for the input capacitance C_{in} in terms of A and C.

(b) Use the expression for C_{in} to obtain the transfer function $V_o(s)/V_{sig}(s)$.

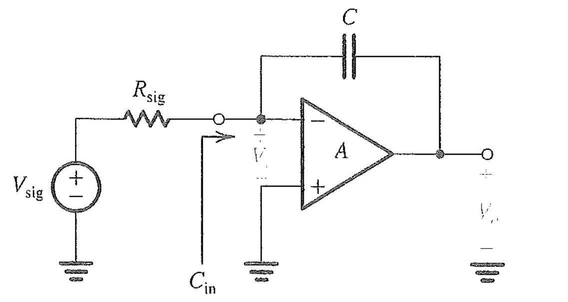

Figure P10.27

(c) If $R_{sig} = 1$ kΩ, and the gain V_o/V_{sig} is to have a dc value of 40 dB and a 3-dB frequency of 100 kHz, find the values required for A and C.

(d) Sketch a Bode plot for the gain and use it to determine the frequency at which its magnitude reduces to unity.

10.28 An ideal voltage amplifier having a voltage gain of -1000 V/V has a 0.2-pF capacitance connected between its output and input terminals. What is the input capacitance of the amplifier? If the amplifier is fed from a voltage source V_{sig} having a resistance $R_{sig} = 1$ kΩ, find the transfer function V_o/V_{sig} as a function of the complex-frequency variable s and hence the 3-dB frequency f_H and the unity-gain frequency f_t.

D 10.29 A design is required for a CS amplifier for which the MOSFET is operated at $g_m = 5$ mA/V and has $C_{gs} = 5$ pF and $C_{gd} = 1$ pF. The amplifier is fed with a signal source having $R_{sig} = 1$ kΩ, and R_G is very large. What is the largest value of R_L' for which the upper 3-dB frequency is at least 6 MHz? What is the corresponding value of midband gain and gain–bandwidth product? If the specification on the upper 3-dB frequency can be relaxed by a factor of 3, that is, to 2 MHz, what can A_M and GB become?

10.30 Reconsider Example 10.3 for the situation in which the transistor is replaced by one whose width W is half that of the original transistor while the bias current remains unchanged. Find modified values for all the device parameters along with A_M, f_H, and the gain–bandwidth product, GB. Contrast this with the original design by calculating the ratios of new value to old for W, V_{OV}, g_m, C_{gs}, C_{gd}, C_{in}, A_M, f_H, and GB.

D *10.31 In a CS amplifier, such as that in Fig. 10.3(a), the resistance of the source $R_{sig} = 100$ kΩ, amplifier input resistance (which is due to the biasing network) $R_{in} = 100\ \text{k}\Omega$, $C_{gs} = 1\ \text{pF}$, $C_{gd} = 0.2\ \text{pF}$, $g_m = 3\ \text{mA/V}$, $r_o = 50\ \text{k}\Omega$, $R_D = 8\ \text{k}\Omega$, and $R_L = 10\ \text{k}\Omega$. Determine the expected 3-dB cutoff frequency f_H and the midband gain. In evaluating ways to double f_H, a designer considers the alternatives of changing either R_L or R_{in}. To raise f_H as described, what separate change in each would be required? What midband voltage gain results in each case?

10.32 A discrete MOSFET common-source amplifier has $R_G = 2\ \text{M}\Omega$, $g_m = 5\ \text{mA/V}$, $r_o = 100\ \text{k}\Omega$, $R_D = 20\ \text{k}\Omega$, $C_{gs} = 3\ \text{pF}$, and $C_{gd} = 0.5\ \text{pF}$. The amplifier is fed from a voltage source with an internal resistance of 500 kΩ and is connected to a 20-kΩ load. Find:

(a) the overall midband gain A_M
(b) the upper 3-dB frequency f_H
(c) the frequency of the transmission zero, f_Z.

10.33 For the discrete-circuit CS amplifier in Fig. 10.3(a) let $R_{sig} = 100\ \text{k}\Omega$, $R_{G1} = 47\ \text{M}\Omega$, $R_{G2} = 10\ \text{M}\Omega$, $R_S = 2\ \text{k}\Omega$, $R_D = 4.7\ \text{k}\Omega$, $R_L = 10\ \text{k}\Omega$, $g_m = 3\ \text{mA/V}$, $r_o = 100\ \text{k}\Omega$, $C_{gs} = 1\ \text{pF}$, and $C_{gd} = 0.2\ \text{pF}$. Find A_M and f_H.

10.34 Consider the integrated-circuit CS amplifier in Fig. P10.34 for the case $I_{BIAS} = 100\ \mu\text{A}$, Q_2 and Q_3 are matched, and $R_{sig} = 200\ \text{k}\Omega$. For Q_1: $\mu_n C_{ox} = 90\ \mu\text{A/V}^2$, $V_A = 12.8\ \text{V}$, $W/L = 100\ \mu\text{m}/1.6\ \mu\text{m}$, $C_{gs} = 0.2\ \text{pF}$, and $C_{gd} = 0.015\ \text{pF}$. For Q_2: $|V_A| = 19.2\ \text{V}$. Neglecting the effect of the capacitance inevitably present at the output node, find the low-frequency gain, the 3-dB frequency f_H, and the frequency of the zero f_Z.

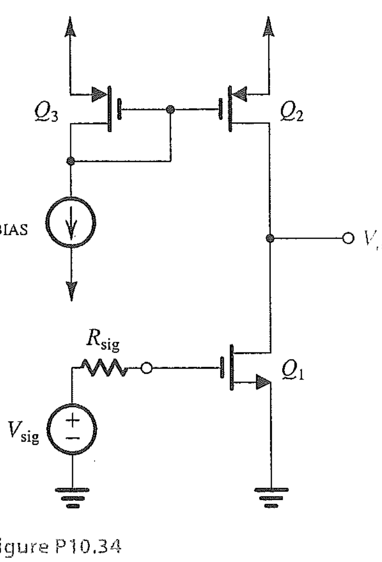

Figure P10.34

10.35 A common-emitter amplifier is measured at midband and found to have a gain of −50 V/V between base and collector. If $C_\pi = 10\ \text{pF}$, $C_\mu = 1\ \text{pF}$, and the effective source resistance $R'_{sig} = 5\ \text{k}\Omega$ [refer to Fig. 10.19(b)], find C_{in} and the 3-dB frequency f_H.

10.36 For a CE amplifier represented by the equivalent circuit in Fig. 10.19(a), let $R_{sig} = 10\ \text{k}\Omega$, $R_B = 100\ \text{k}\Omega$, $r_x = 100\ \Omega$, $C_\pi = 10\ \text{pF}$, $C_\mu = 1\ \text{pF}$, $g_m = 40\ \text{mA/V}$, $r_o = 100\ \text{k}\Omega$, $R_C = 10\ \text{k}\Omega$, $R_L = 10\text{k}\Omega$, and $\beta = 100$. Find the midband gain and the 3-dB frequency f_H.

10.37 A designer wishes to investigate the effect of changing the bias current I_E on the midband gain and high-frequency response of the CE amplifier considered in Example 10.4. Let I_E be doubled to 2 mA, and assume that β_0 and f_T remain unchanged at 100 and 800 MHz, respectively. To keep the node voltages nearly unchanged, the designer reduces R_B and R_C by a factor of 2, to 50 kΩ and 4 kΩ, respectively. Assume $r_x = 50\ \Omega$, and recall that $V_A = 100\ \text{V}$ and that C_μ remains constant at 1 pF. As before, the amplifier is fed with a source having $R_{sig} = 5\ \text{k}\Omega$ and feeds a load $R_L = 5\ \text{k}\Omega$. Find the new values of A_M, f_H, and the gain–bandwidth product, $|A_M| f_H$. Comment on the results. Note that the price paid for whatever improvement in performance is achieved is an increase in power. By what factor does the power dissipation increase?

*10.38 The purpose of this problem is to investigate the high-frequency response of the CE amplifier when it is fed with a relatively large source resistance R_{sig}. Refer to the amplifier in Fig. 10.9(a) and to its high-frequency, equivalent-circuit model and the analysis shown in Fig. 10.19. Let $R_B \gg R_{sig}$, $r_x \ll R_{sig}$, $R_{sig} \gg r_\pi$, $g_m R'_L \gg 1$, and $g_m R'_L C_\mu \gg C_\pi$. Under these conditions, show that:

(a) the midband gain $A_M \simeq -\beta R'_L / R_{sig}$
(b) the upper 3-dB frequency $f_H \simeq 1/2\pi C_\mu \beta R'_L$
(c) the gain–bandwidth product $|A_M| f_H \simeq 1/2\pi C_\mu R_{sig}$

Evaluate this approximate value of the gain–bandwidth product for the case $R_{sig} = 25\ \text{k}\Omega$ and $C_\mu = 1\ \text{pF}$. Now, if the transistor is biased at $I_C = 1\ \text{mA}$ and has $\beta = 100$, find the midband gain and f_H for the two cases $R'_L = 25\ \text{k}\Omega$ and $R'_L = 2.5\ \text{k}\Omega$. On the same coordinates, sketch Bode plots for the gain magnitude versus frequency for the two cases. What f_H is obtained when the gain is unity? What value of R'_L corresponds?

10.39 For a version of the CE amplifier circuit in Fig. 10.9(a), $R_{sig} = 10\ \text{k}\Omega$, $R_{B1} = 68\ \text{k}\Omega$, $R_{B2} = 27\ \text{k}\Omega$,

SIM = Multisim/PSpice; * = difficult problem; ** = more difficult; *** = very challenging; D = design problem