Microelectronics
Circuit Analysis and Design

Donald A. Neamen

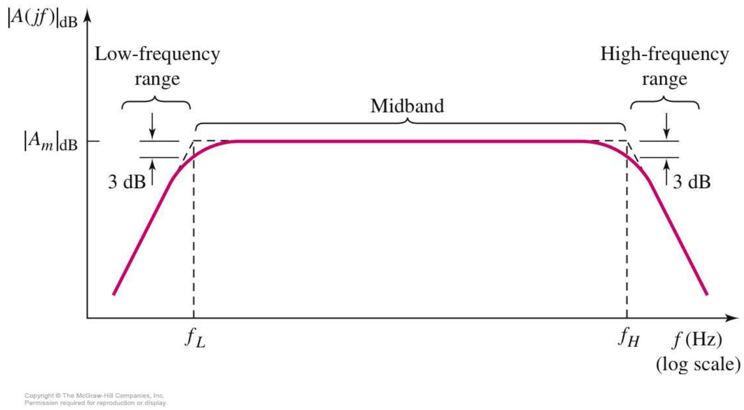
Chapter 7

Frequency Response

In this chapter, we will:

- Discuss the general frequency response characteristics of amplifiers.
- Derive the system transfer functions
  - Develop the Bode diagrams of the magnitude and phase of the transfer functions.
- Analyze the frequency response of transistor circuits with capacitors.
  - Determine the Miller effect and Miller capacitance.
- Determine the high-frequency response of basic transistor circuit configurations.

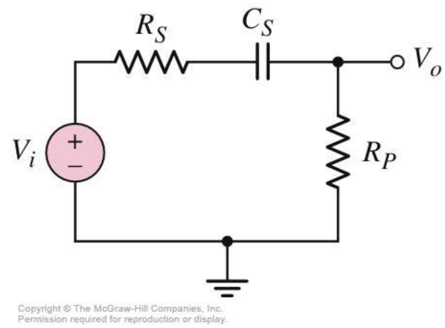
Amplifier Gain Versus Frequency



Transfer Functions of the Complex Frequency

Name of Function	Expression
Voltage Transfer Function	$T(s) = V_o(s)/V_i(s)$
Current Transfer Function	$I_o(s)/I_i(s)$
Transresistance Function	$V_o(s)/I_i(s)$
Transconductance Function	$I_o(s)/V_i(s)$

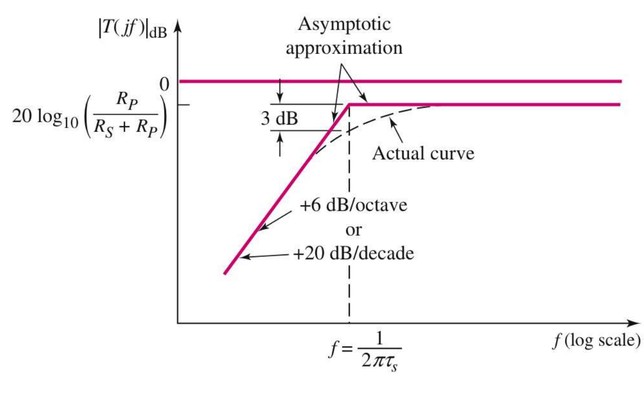
Series Coupling Capacitor Circuit



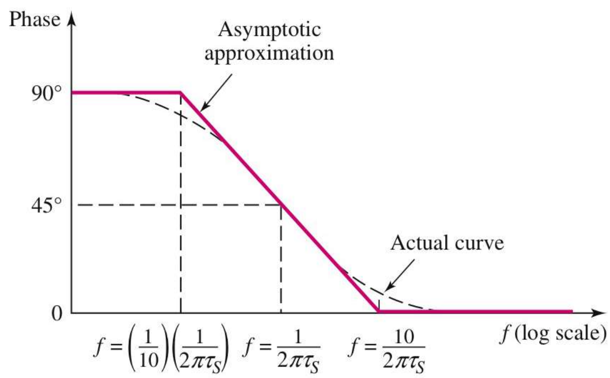
$$T(s) = K_2\left(\frac{s\tau}{1+s\tau}\right)$$

$$\tau = (R_S + R_P)C_S$$

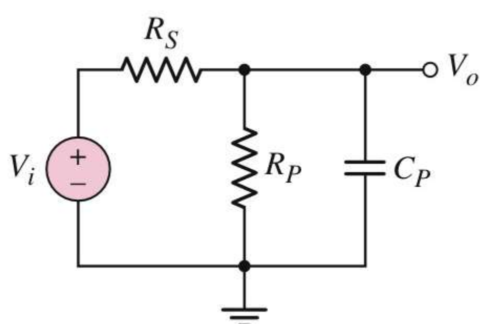
Bode Plot of Voltage Transfer Function Magnitude: Series Coupling Capacitor Circuit



Bode Plot of Voltage Transfer Function Phase: Series Coupling Capacitor Circuit



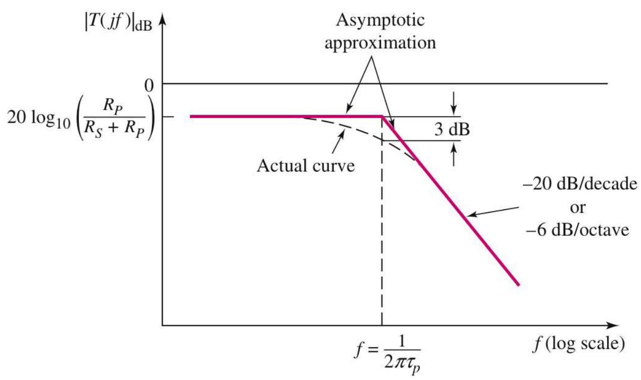
Parallel Load Capacitor Circuit



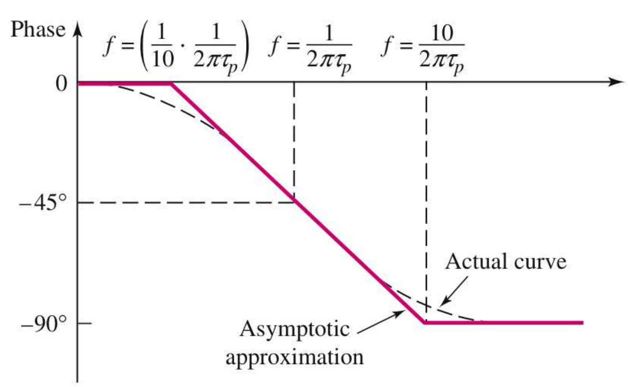
$$T(s) = K_1\left(\frac{1}{1 + s\tau}\right)$$

$$\tau = (R_S \| R_P) C_P$$

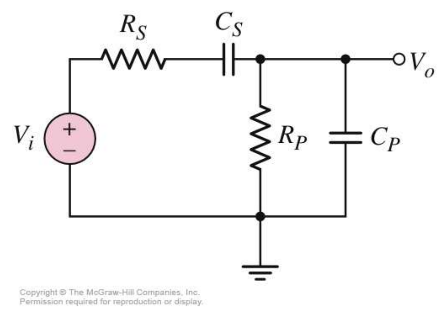
Bode Plot of Voltage Transfer Function Magnitude: Parallel Load Capacitor Circuit



Bode Plot of Voltage Transfer Function Phase: Parallel Load Capacitor Circuit



Circuit with Series Coupling and Parallel Load Capacitor



$$\tau_S = (R_S + R_P)C_S$$

$$\tau_P = (R_S \| R_P)C_P$$

$$f_L = \frac{1}{2\pi\tau_S}$$

$$f_H = \frac{1}{2\pi\tau_P}$$

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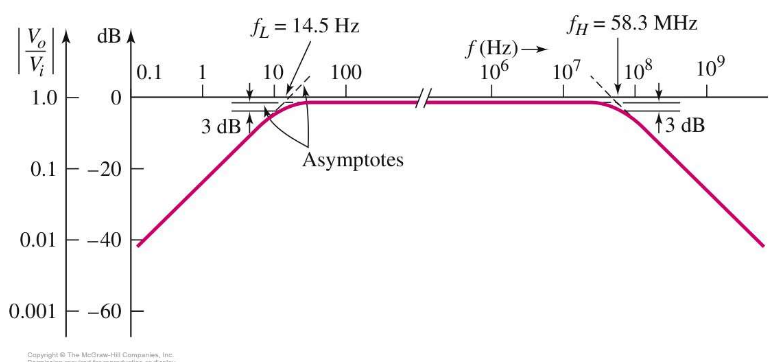
Bode Plot of Magnitude of Voltage Transfer Function:

Series Coupling and Parallel Load Capacitor



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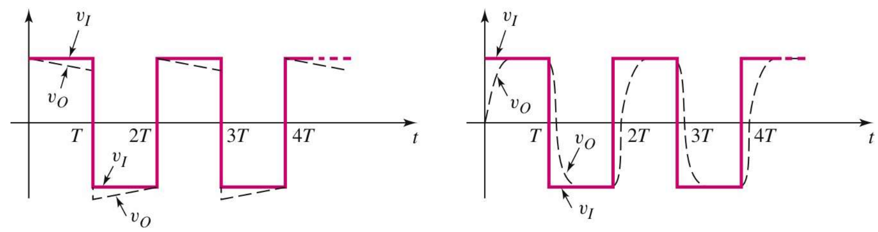
Steady-State Output Response

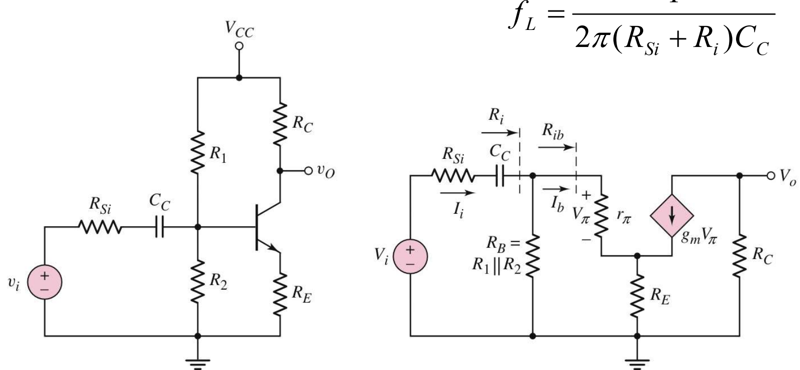


(a) (b)

Coupling Capacitor Load Capacitor

Common Emitter with Coupling Capacitor

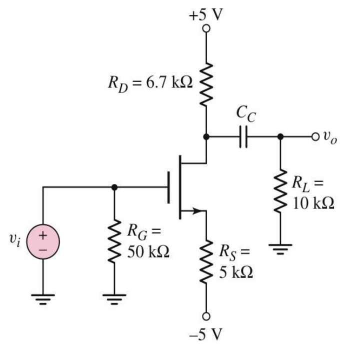
$$f_L = \frac{1}{2\pi(R_{Si} + R_i)C_C}$$



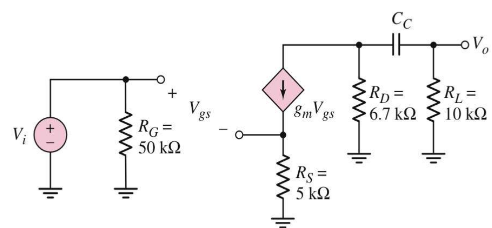
(a) (b)

Common Source with Output Coupling Capacitor

$$f_L = \frac{1}{2\pi(R_D + R_C)C_C}$$



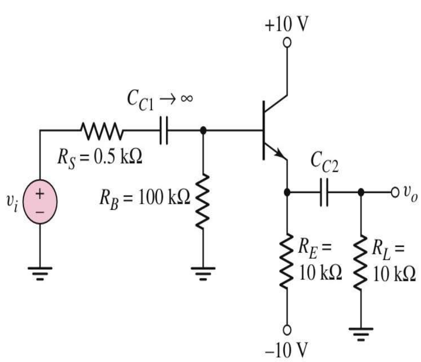
(a)



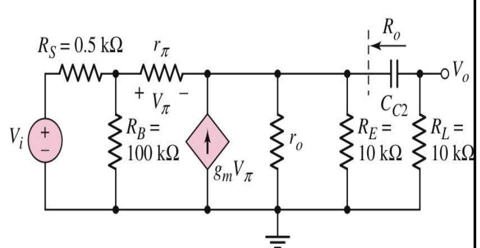
(b)

Emitter Follower with Output Coupling Capacitor

$$f_L = \frac{1}{2\pi(R_o + R_L)C_{C2}}$$



(a)



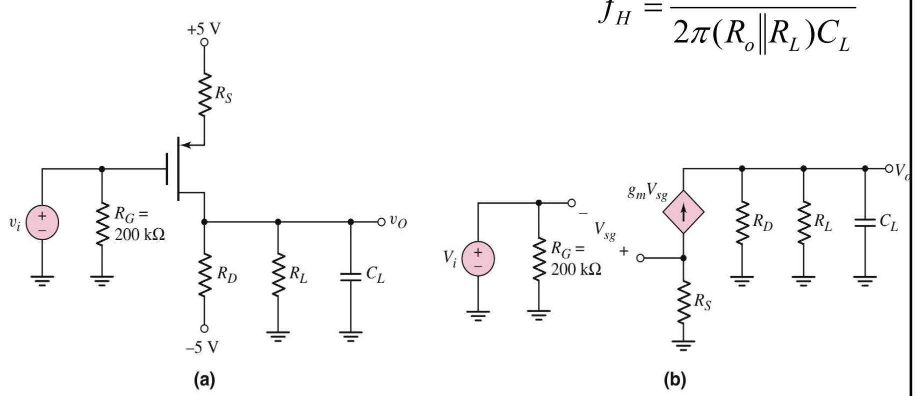
(b)

Problem-Solving Technique: Bode Plot of Gain Magnitude

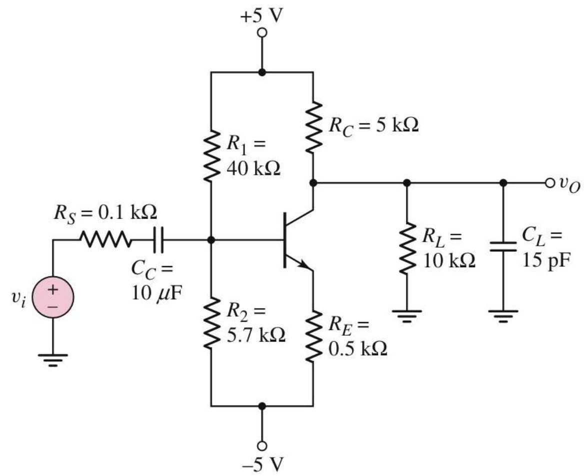
1. Determine whether capacitor is producing a low-pass or high-pass circuit.
   a. Sketch general shape of Bode plot
2. Corner frequency is $f = 1/(2\pi\tau)$ where $\tau = R_{eq}C$
   a. R_{eq} is resistance seen by capacitor
3. Maximum gain magnitude is midband gain.
   a. Coupling and bypass capacitors act as shorts
   b. Load capacitors act as opens

Common Source with Load Capacitor

$$f_H = \frac{1}{2\pi(R_o \| R_L)C_L}$$



Coupling and Parallel Load Capacitors



(a)

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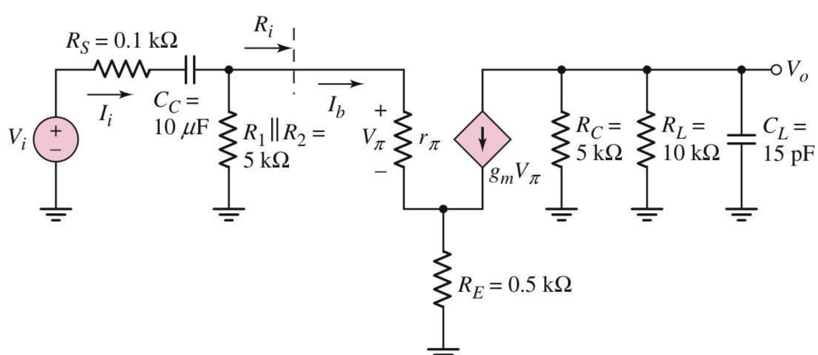
Small-Signal Equivalent Circuit: Coupling and Parallel Load Capacitor



(b)

$$f_L = \frac{1}{2\pi[R_S + (R_1 \| R_2 \| R_i)]C_C}$$

$$f_H = \frac{1}{2\pi(R_C \| R_L)C_P}$$

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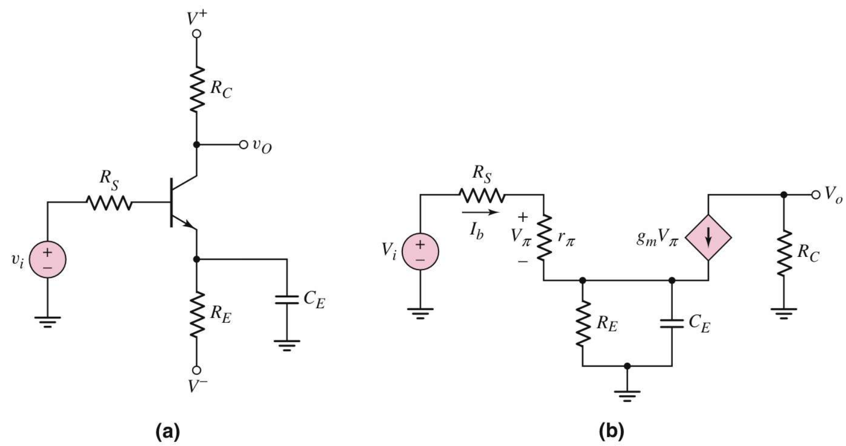
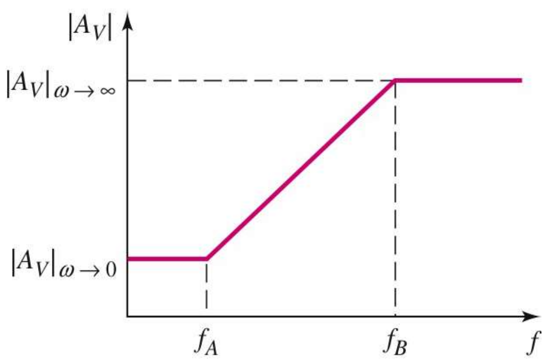
Emitter Bypass Capacitor



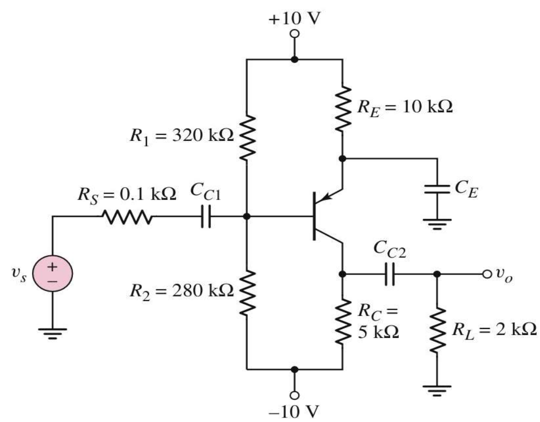
Bode Plot of Voltage Gain Magnitude: Emitter Bypass Capacitor



$$\left|A_v\right|_{\omega\to 0} = \frac{g_m r_\pi R_C}{R_S + r_\pi + (1 = \beta) R_E}$$

$$\left|A_v\right|_{\omega\to \infty} = \frac{g_m r_\pi R_C}{R_S + r_\pi}$$

Two Coupling Capacitors and a Emitter Bypass Capacitor



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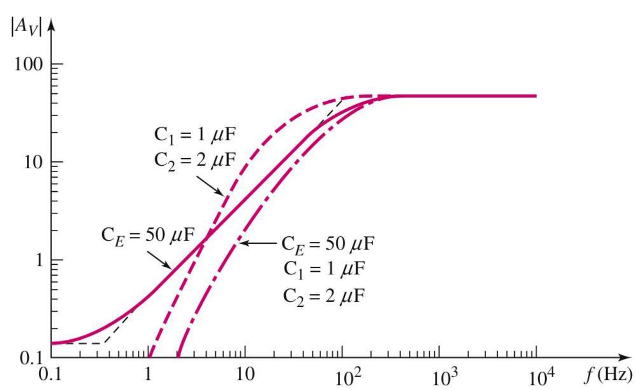
PSpice Results for Two Coupling Capacitors and a Emitter Bypass Capacitor



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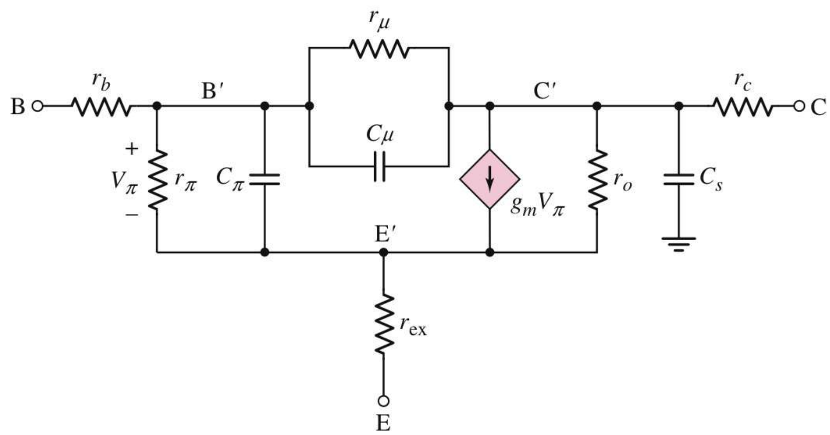
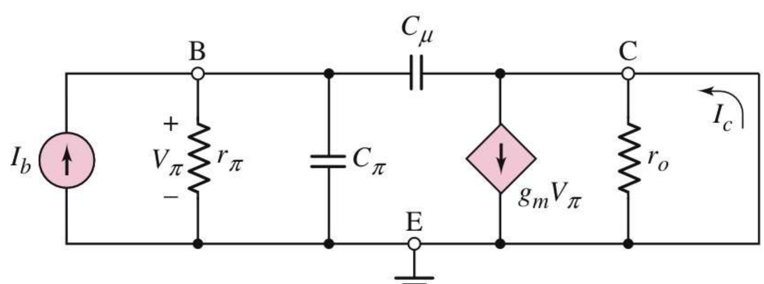
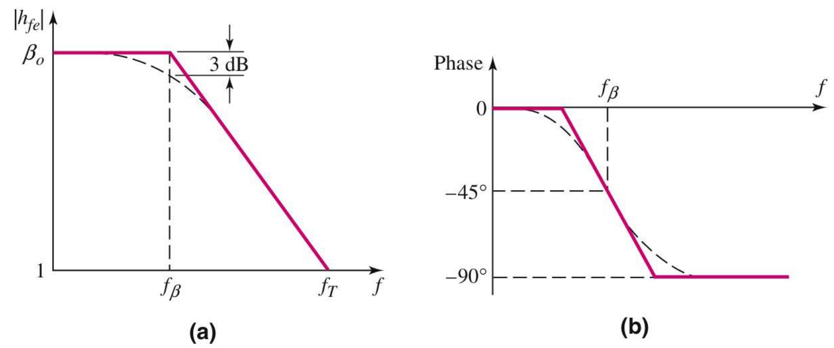
Expanded Hybrid π Equivalent Circuit



Short-Circuit Current Gain: Analysis of Frequency Response of BJT

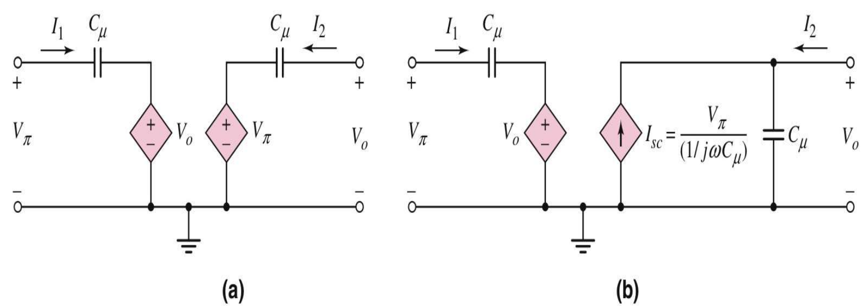


Bode Plot: Short-Circuit Current Gain



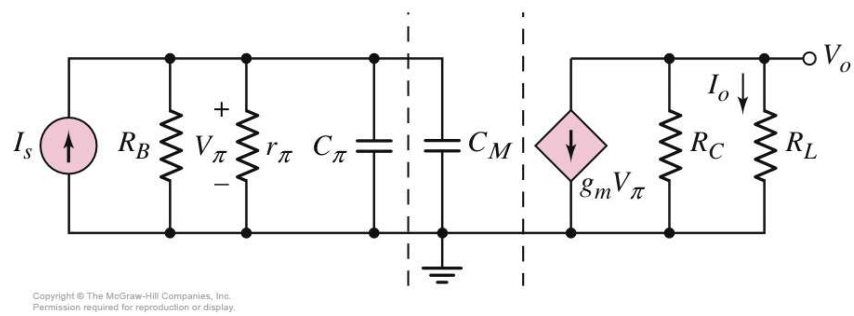
$$f_\beta = \frac{1}{2\pi\, r_\pi (C_\pi + C_\mu)} \qquad f_T = \beta_o f_\beta$$

2-Port Equivalent Circuit of Cμ: BJT



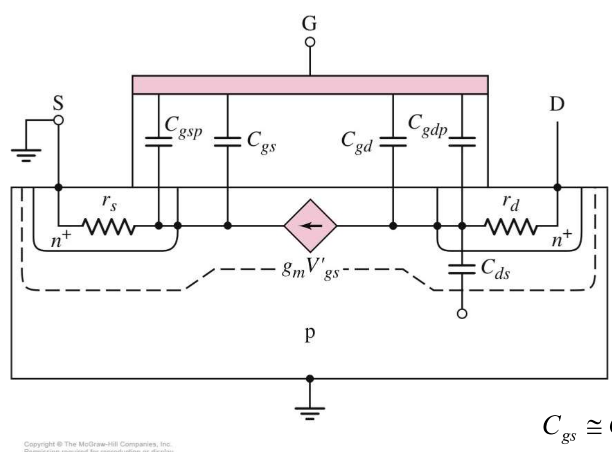
Thevenin Equivalent   Norton Equivalent

Small-Signal Equivalent Circuit with Miller Capacitance: BJT



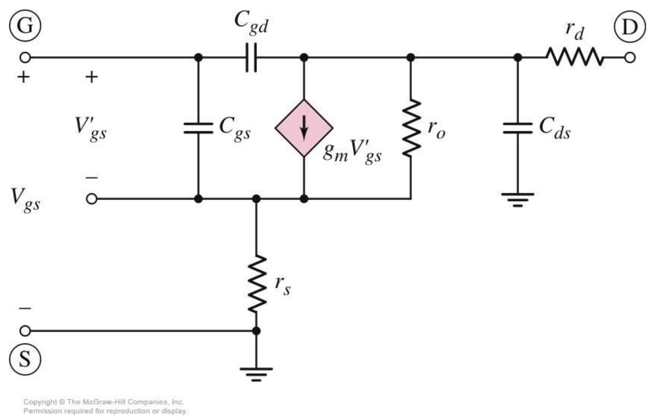
$$C_M = C_\mu[1 + g_m(R_C \| R_L)]$$

Inherent Resistances and Capacitances in n-Channel MOSFET

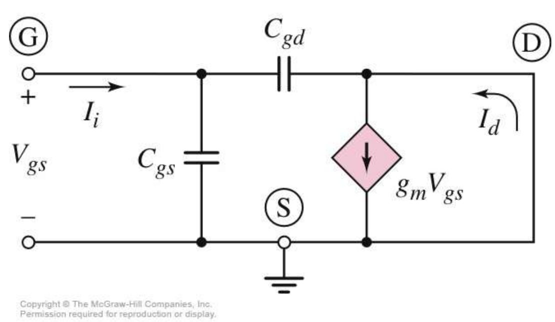


$$C_{gs} \cong C_{gd} \cong \frac{1}{2} WLC_{ox}$$

Equivalent Circuit for n-Channel Common Source MOSFET

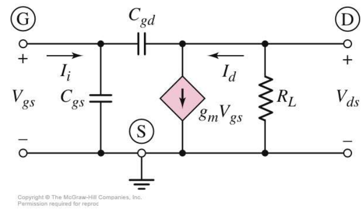


Unity-Gain Bandwidth

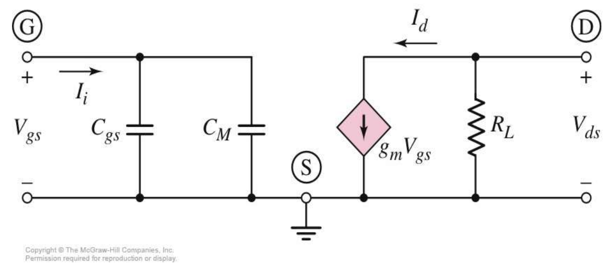


$$f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}$$

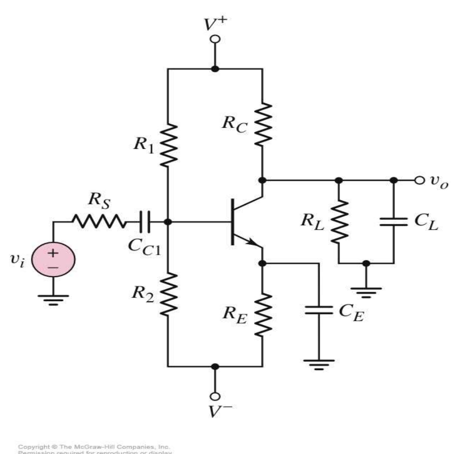
Small-Signal Equivalent Circuit with Miller Capacitance: MOSFET



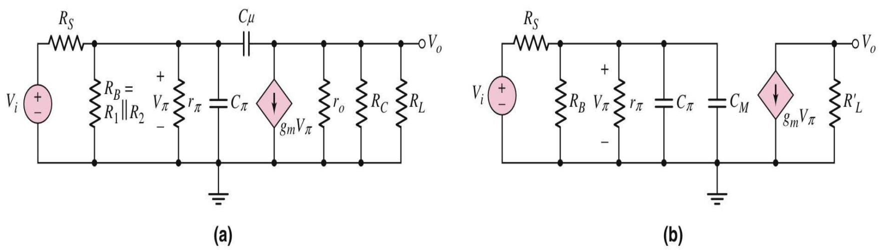
$$C_M = C_{gd}[1 + g_m R_L]$$



Common-Emitter Amplifier

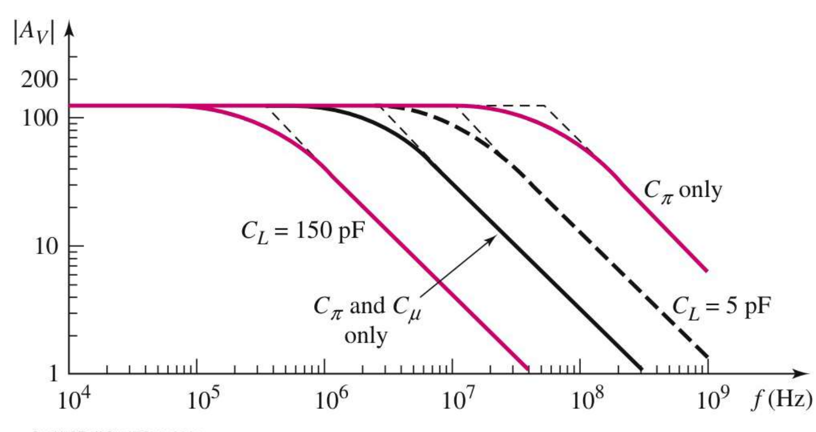


High-Frequency Equivalent Circuit: Common Emitter

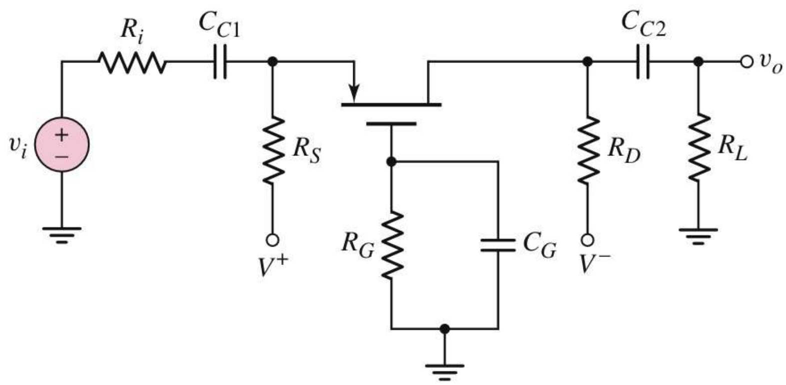


$$f_H = \frac{1}{2\pi[r_\pi \| R_B \| R_S](C_\pi + C_\mu)}$$

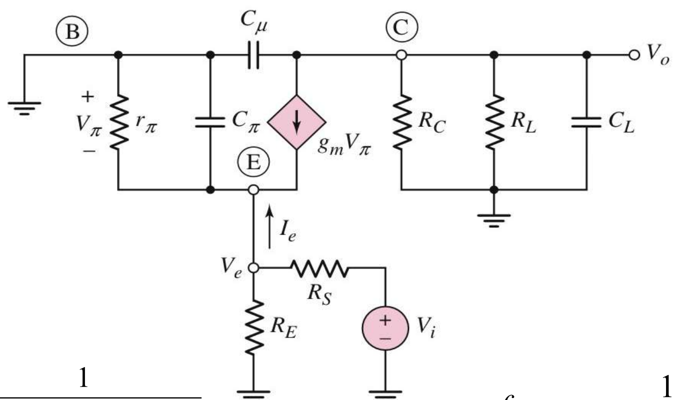
PSpice Results for Common Emitter



Common-Base Amplifier



High-Frequency Equivalent Circuit: Common Base

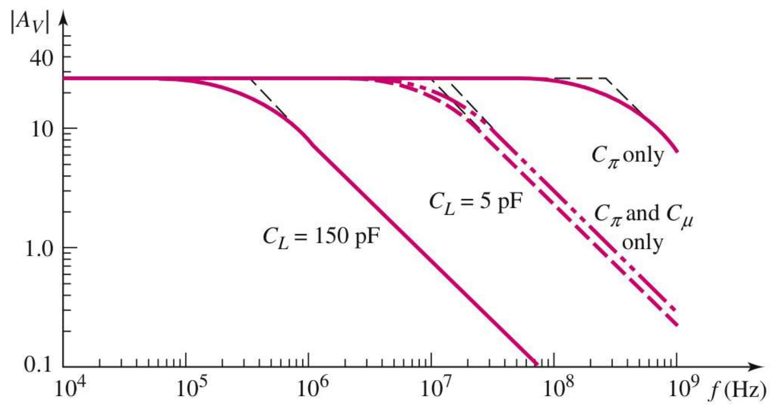


$$f_{H\pi} = \frac{1}{2\pi[\frac{r_\pi}{1+\beta} \| R_B \| R_S]C_\pi}$$

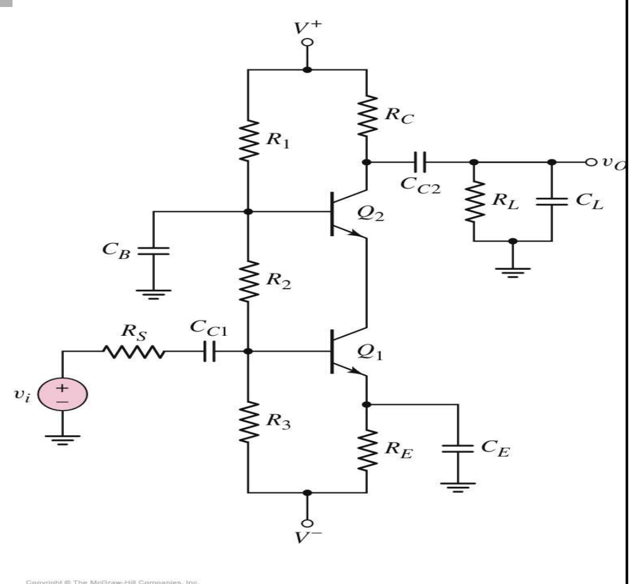
(a)

$$f_{H\mu} = \frac{1}{2\pi(R_C \| R_L)C_\mu}$$

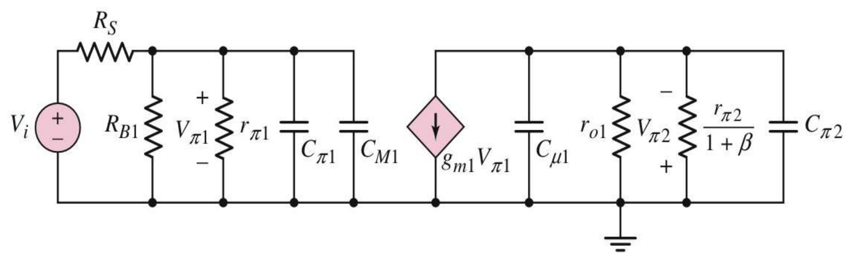
PSpice Results for Common Emitter



Cascode Circuit



High-Frequency Equivalent Circuit: Cascode

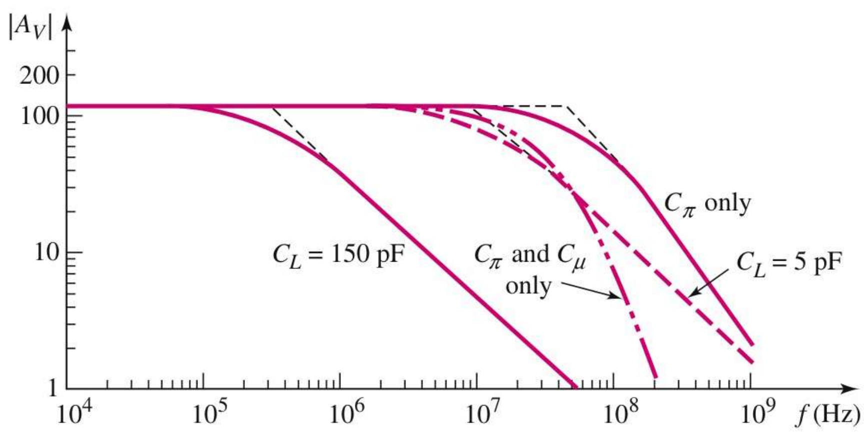


(c)

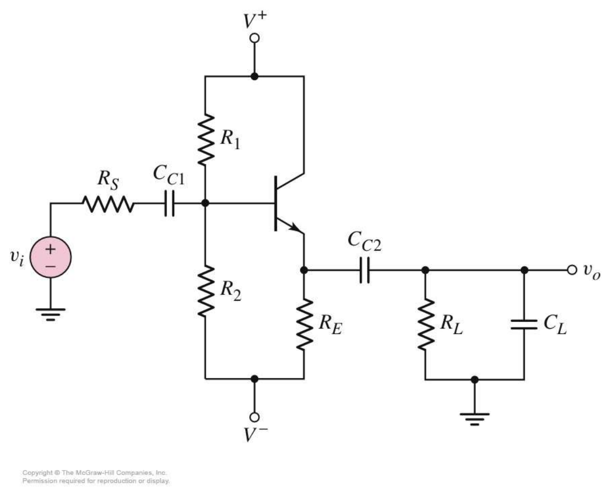
$$f_{H\pi} = \frac{1}{2\pi[R_S \| R_{B1} \| r_{\pi 1}](C_{\pi 1} + C_{M1})}$$

$$f_{H\mu} = \frac{1}{2\pi(R_C \| R_L)C_{\mu 2}}$$

PSpice Results for Cascode



Emitter-Follower Circuit



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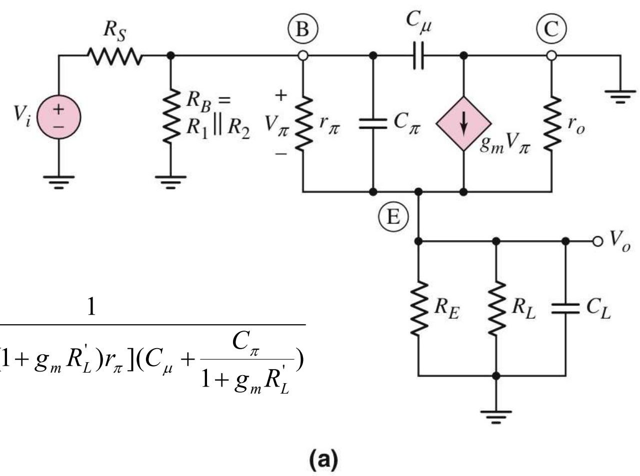
High-Frequency Equivalent Circuit: Emitter Follower



$$f_H \cong \frac{1}{2\pi[R_S \| R_B \| (1+g_m R_L^{'})r_\pi](C_\mu + \frac{C_\pi}{1+g_m R_L^{'}})}$$

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PSpice Results for Emitter Follower