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

<table>
<thead>
<tr>
<th>Name of Function</th>
<th>Expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage Transfer Function</td>
<td>$T(s) = \frac{V_o(s)}{V_i(s)}$</td>
</tr>
<tr>
<td>Current Transfer Function</td>
<td>$I_o(s)/I_i(s)$</td>
</tr>
<tr>
<td>Transresistance Function</td>
<td>$V_o(s)/I_i(s)$</td>
</tr>
<tr>
<td>Transconductance Function</td>
<td>$I_o(s)/V_i(s)$</td>
</tr>
</tbody>
</table>
Series Coupling Capacitor Circuit

\[ T(s) = K_s \left( \frac{s\tau}{1 + s\tau} \right) \]
\[ \tau = (R_S + R_P)C_S \]

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

\[ 20 \log_{10} \left( \frac{R_p}{R_p + R_f} \right) \]

Asymptotic approximation

-20 dB/decade or -6 dB/octave

Actual curve

\[ f = \frac{1}{2\pi f_p} \]

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

\[ f = \left( \frac{1}{10} \cdot \frac{1}{2\pi f_p} \right) \quad f = \frac{1}{2\pi f_p} \quad f = \frac{10}{2\pi f_p} \]

Asymptotic approximation

Actual curve
Circuit with Series Coupling and Parallel Load Capacitor

\[ \tau_s = (R_s + R_p)C_s \]
\[ \tau_p = (R_s \parallel R_p)C_p \]
\[ f_L = \frac{1}{2\pi \tau_s} \]
\[ f_H = \frac{1}{2\pi \tau_p} \]

Bode Plot of Magnitude of Voltage Transfer Function:
Series Coupling and Parallel Load Capacitor
Steady-State Output Response

Coupling Capacitor

Load Capacitor

Common Emitter with Coupling Capacitor

\[ f_L = \frac{1}{2\pi(R_{Si} + R_i)C_C} \]
Common Source with Output Coupling Capacitor

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

Emitter Follower with Output Coupling Capacitor

\[ f_L = \frac{1}{2\pi(R_E + R_L)C_{C2}} \]
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 \( f = \frac{1}{2\pi \tau} \) where \( \tau = R_{\text{eq}} C \)  
   a. \( R_{\text{eq}} \) 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

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

(a)  
(b)
Coupling and Parallel Load Capacitors

![Circuit Diagram](a)

Small-Signal Equivalent Circuit: Coupling and Parallel Load Capacitor

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

\[ f_H = \frac{1}{2\pi(R_C || R_L)C_p} \]
Emitter Bypass Capacitor

Bode Plot of Voltage Gain Magnitude: Emitter Bypass Capacitor

\[ |A_V| \]

\[ |A_V|_{\omega \to \infty} \]

\[ |A_V|_{\omega \to 0} \]

\[ f_A \]

\[ f_B \]

\[ |A_V|_{\omega \to 0} = \frac{g_m r_\pi R_C}{R_S + r_a + (1 - \beta) R_E} \]

\[ |A_V|_{\omega \to \infty} = \frac{g_m r_\pi R_C}{R_S + r_a} \]
Two Coupling Capacitors and a Emitter Bypass Capacitor

PSpice Results for Two Coupling Capacitors and a Emitter Bypass Capacitor
Expanded Hybrid \( \pi \) Equivalent Circuit

Short-Circuit Current Gain: Analysis of Frequency Response of BJT
**Bode Plot:**
Short-Circuit Current Gain

\[
\beta_o \left| \frac{V_{in}}{I_{out}} \right| \quad 3 \text{ dB}
\]

\[f_p = \frac{1}{2\pi r_x (C_x + C_{\mu})}\]

\[f_T = \beta_o f_p\]

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**2-Port Equivalent Circuit of C_\mu: BJT**

(a) Thevenin Equivalent

(b) Norton Equivalent
Small-Signal Equivalent Circuit with Miller Capacitance: BJT

\[ C_M = C_u [1 + g_m (R_C || R_L)] \]

Inherent Resistances and Capacitances in n-Channel MOSFET

\[ C_{gs} \approx C_{gd} \approx \frac{1}{2} W L C_{ox} \]
**Equivalent Circuit for n-Channel Common Source MOSFET**

- $C_{gd}$
- $r_d$
- $V'_gs$
- $C_{gs}$
- $r_o$
- $C_{ds}$
- $r_s$
- $s_mV'_gs$

**Unity-Gain Bandwidth**

\[ f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})} \]
Small-Signal Equivalent Circuit with Miller Capacitance: MOSFET

\[ C_M = C_{gd} \left[ 1 + g_m R_L \right] \]

Common-Emitter Amplifier
High-Frequency Equivalent Circuit: Common Emitter

\[ f_H = \frac{1}{2\pi r_c |R_B||R_S|(C_C + C_m)} \]

PSpice Results for Common Emitter

\[ |A_V| \]

\[ C_L = 150 \text{ pF} \]

\[ C_C \text{ and } C_H \text{ only} \]

\[ C_C \text{ only} \]

\[ C_L = 5 \text{ pF} \]
Common-Base Amplifier

High-Frequency Equivalent Circuit: Common Base

\[ f_{Hi} = \frac{1}{2\pi \left( \frac{r_x}{1 + \beta} R_B \parallel R_f \right) C_\pi} \]

\[ f_{H\mu} = \frac{1}{2\pi (R_C \parallel R_L) C_\mu} \]
PSpice Results for Common Emitter

Cascode Circuit
High-Frequency Equivalent Circuit: Cascode

\[ f_{He} = \frac{1}{2\pi[R_s || R_{B1}] C_{\pi1} (C_{\pi1} + C_{M1})} \]

\[ f_{H\mu} = \frac{1}{2\pi(R_c || R_L) C_{\mu2}} \]

PSpice Results for Cascode

- \( C_L = 150 \text{ pF} \)
- \( C_\pi \) only
- \( C_\mu \) only
- \( C_L = 5 \text{ pF} \)

\( |A_V| \) vs. \( f (\text{Hz}) \)
Emitter-Follower Circuit

![Emitter-Follower Circuit Diagram]

High-Frequency Equivalent Circuit: Emitter Follower

\[ f_H \approx \frac{1}{2\pi R_R \left( R_R || (1 + g_m R_z) r_o \right) \left( C_\mu + \frac{C_s}{1 + g_m R_L} \right)} \]