Basic Amplifier Structures

Amplifiers using these devices generally have one terminal common and use remaining terminals as input and output.

Since devices are unilateral, designation of input and output terminals is uniquely determined.

Three different ways to designate the common terminal:

- Source or Emitter termed Common Source or Common Emitter
- Gate or Base termed Common Gate or Common Base
- Drain or Collector termed Common Drain or Common Collector
Review from last lecture

**Basic Amplifier Structures**

<table>
<thead>
<tr>
<th>MOS</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td>S</td>
<td>G</td>
</tr>
<tr>
<td>Common Gate or Common Base</td>
<td>G</td>
<td>S</td>
</tr>
<tr>
<td>Common Drain or Common Collector</td>
<td>D</td>
<td>G</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BJT</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td>E</td>
<td>B</td>
</tr>
<tr>
<td>Common Gate or Common Base</td>
<td>B</td>
<td>E</td>
</tr>
<tr>
<td>Common Drain or Common Collector</td>
<td>C</td>
<td>B</td>
</tr>
</tbody>
</table>

Can analyze the BJT structures and then obtain the characteristics of the MOS structure by setting $g_{m}=0$.
Review from last lecture

Characterization of Basic Amplifier Structures

- Observe that the small-signal equivalent of any 3-terminal network is a two-port
- Thus to characterize any of the 3 basic amplifier structures, it suffices to determine the two-port equivalent network

How should the two-port characterization be done?

Why is the two-port characterization useful?
Two-Port Characterization of 3-terminal devices

Review from last lecture

y-parameter characterization of 3-terminal network

\[ i_1 = y_{11}v_1 + y_{12}v_2 \]
\[ i_2 = y_{21}v_1 + y_{22}v_2 \]

- If unilateral, \( y_{12} = 0 \)
- \( y \)-parameters not widely used
Two-Port characterization of unilateral 3-terminal devices

Review from last lecture

By doing a Norton-Thevenin Transformation of Right-Side Obtain

For notational consistency with prior work, rename parameters in this model
Two-Port characterization of unilateral 3-terminal devices

Widely used characterization strategy
Model parameters are \{R_{iX}, A_{V0} and R_{0X}\}

Review from last lecture
Example: Use of two-port unilateral models

Review from last lecture

\[ A_V = \frac{V_{out}}{V_{in}} = \left( \frac{R_{iX1}}{R_{iX1} + R_S} \right) A_{V01} \left( \frac{R_{L1} // R_{iX2}}{R_{L1} // R_{iX2} + R_{0X1}} \right) A_{V02} \left( \frac{R_L}{R_L + R_{0X2}} \right) \]
The three basic amplifier types for both MOS and bipolar processes

- Common Emitter
- Common Source
- Common Base
- Common Gate
- Common Collector
- Common Drain

How can the two-port parameters be obtained for these or any other linear two-port networks?
Two-port model for Common Emitter Configuration

\[ \begin{align*}
R_{iX} &= \frac{1}{g_\pi} \\
A_{V0} &= -\frac{g_m}{g_0} \\
R_{0X} &= \frac{1}{g_0}
\end{align*} \]

In terms of operating point and model parameters:

\[ \begin{align*}
R_{iX} &= \frac{\beta V_t}{I_{CQ}} \\
A_{V0} &= -\beta \\
R_{0X} &= \frac{V_{AF}}{I_{CQ}}
\end{align*} \]

- Input impedance is mid-range
- Voltage Gain is Large and Inverting
- Output impedance is large
- Widely used to build voltage amplifiers
Consider the following CE application:

\[
\begin{align*}
\mathbf{v}_{\text{out}} \left( g_C + g_0 \right) &= g_0 A_{V0} \mathbf{v}_{\text{in}} \\
A_V &= \frac{\mathbf{v}_{\text{out}}}{\mathbf{v}_{\text{in}}} = \frac{g_0 A_{V0}}{g_0 + g_C} = \frac{-g_m}{g_0 + g_C} \\
&\approx -g_m R_C \\
R_{\text{in}} &= R_{iX} = r_{\Pi} \\
R_{\text{out}} &= R_{oX} // R_C \\
&= \frac{1}{g_0 + g_C} \\
&\approx R_C
\end{align*}
\]
Consider the following CE application

This circuit can also be analyzed directly without using 2-port model for CE configuration.

\[ V_{out} = -g_m V_{in} \left( \frac{1}{g_0 + g_C} \right) \]

\[ A_v = \frac{V_{out}}{V_{in}} = -\left( \frac{g_m}{g_0 + g_C} \right) \approx -g_m R_C \]

\[ R_{in} = r_{\pi} \]

\[ R_{out} = \frac{1}{g_0 + g_C} \approx R_C \]
Common Emitter Configuration

Consider the following CE application

\[
A_v \approx -g_m R_C
\]

\[
R_{out} = \frac{1}{g_0 + g_C} \approx R_C
\]

\[
R_{in} = r_\pi
\]

\[
A_v \approx -\frac{I_{CQ} R_C}{V_t}
\]

\[
R_{out} \approx R_C
\]

\[
R_{in} = \frac{\beta V_t}{I_{CQ}}
\]

- Input impedance is mid-range
- Voltage Gain is Large and Inverting
- Output impedance is mid-range
- Widely used as a voltage amplifier
Two-port model for Common Collector Configuration

It can be readily shown that the common-collector and the common base configurations are not unilateral.

Thus a 4-parameter two-port model is needed to characterize these structures.

Or, equivalently
Two-port model for Common Collector Configuration

\[ \begin{align*}
V_{be} & \quad g_T \quad g_m V_{be} \quad g_O \\
\end{align*} \]

\{R_{ix}, A_{V0}, A_{V0r}, and R_{ox}\}
Two-port model for Common Collector Configuration

Applying KCL at the input and output node, obtain

\[ i_1 = (v_1 - v_2)g_\pi \]
\[ i_2 = (g_m + g_\pi + g_o)v_1 - (g_m + g_\pi)v_2 \]

These can be rewritten as

\[ v_1 = i_1r_\pi + v_2 \]
\[ v_2 = \left( \frac{1}{g_m + g_\pi + g_o} \right) i_2 + \left( \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \right) v_1 \]

It thus follows that

\[ R_{ix} = r_\pi \quad A_{V0r} = 1 \quad R_{0x} = \left( \frac{1}{g_m + g_\pi + g_o} \right) \quad A_{v0} = \left( \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \right) \]
Two-port model for Common Collector Configuration

Two-port Common Collector Model

\[ i_1 \rightarrow B + \Delta V_1 \rightarrow C - \]

\[ i_2 \rightarrow E + \Delta V_2 \rightarrow \]

\[ R_{ix} = r_{\pi} \]

\[ A_{v0r} = 1 \]

\[ R_{0x} = \frac{1}{g_m + g_{\pi} + g_o} \]

\[ A_{v0} = \frac{g_m + g_{\pi}}{g_m + g_{\pi} + g_o} \]
Common Collector Configuration

Consider the following CC application

\[ A_V = \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \left( \frac{g_m + g_\pi + g_o + g_E}{g_m + g_\pi + g_o + g_E} \right) = \frac{g_m + g_\pi}{g_m + g_\pi + g_o + g_E} \approx \frac{g_m}{g_m + g_E} \]

\[ R_{\text{in}} = r_\pi \frac{g_m + g_\pi + g_o + g_E}{g_m + g_\pi + g_o + g_E} \approx r_\pi + \beta R_E \]

\[ R_0 \approx \frac{1}{g_m + g_E + g_\pi} = \frac{1}{g_m + g_E} = \frac{R_E}{1 + g_m R_E} \approx \frac{1}{g_m} \]
Common Collector Configuration

Consider the following CC application

Alternately, this circuit can also be analyzed directly

\[ v_{out}(g_E + g_0 + g_{\pi}) = v_{in}g_{\pi} + g_mv_1 \]
\[ v_{in} = v_1 + v_{out} \]
\[ i_{in} = g_{\pi}(v_{in} - v_{out}) \]
\[ v_{out}(g_m + g_E + g_0 + g_{\pi}) = v_{in}(g_{\pi} + g_m) \]

\[
A_V = \frac{v_{out}(g_m + g_E + g_0 + g_{\pi})}{v_{in}(g_{\pi} + g_m)} \approx \frac{g_m}{g_m + g_E + g_0 + g_{\pi}} = \frac{I_{CQ}R_E}{I_{CQ}R_E + V_t}
\]

\[
i_{in}(g_m + g_\pi + g_E + g_0) = g_\pi v_{in}(g_E + g_0)
\]

\[
R_{in} = r_{\pi}g_m + g_\pi + g_0 + g_E \approx r_{\pi}g_m + g_E
\]
Common Collector Configuration

Consider the following CC application

\[ A_V = \frac{g_{\pi} + g_m}{g_m + g_E + g_0 + g_{\pi}} \]

\[ R_{in} \approx r_\pi + \beta R_E \]

\[ R_0 \approx \frac{R_E}{1 + g_m R_E} \approx \frac{1}{g_m} \]

\[ A_V \approx \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \]

\[ R_{in} \approx \beta R_E \]

\[ R_0 \approx \frac{V_t}{I_{CQ}} \]

- Output impedance is low
- \( A_{V0} \) is positive and near 1
- Input impedance is very large
- Widely used as a buffer
- Not completely unilateral but output-input transconductance is small
Two-port model for Common Base Configuration

\[ \begin{align*}
\mathcal{V}_{be} & \rightleftharpoons g_T \\
g_m \mathcal{V}_{be} & \rightleftharpoons g_O
\end{align*} \]

\{R_{ix}, A_{V0}, A_{Vo r} and R_{0x}\}
Two-port model for Common Base Configuration

From KCL

\[ i_1 = v_1 g_\pi + (v_1 - v_2) g_0 + g_m v_1 \]
\[ i_2 = (v_2 - v_1) g_0 - g_m v_1 \]

These can be rewritten as

\[ v_1 = \left( \frac{1}{g_m + g_\pi + g_0} \right) i_1 + \left( \frac{g_0}{g_m + g_\pi + g_0} \right) v_2 \]
\[ v_2 = \left( \frac{1}{g_0} \right) i_2 + \left( 1 + \frac{g_m}{g_0} \right) v_1 \]

It thus follows that:

\[ R_{iX} = \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m} \quad A_{\text{VOR}} = \frac{g_0}{g_m + g_\pi + g_0} \quad A_{V0} = 1 + \frac{g_m}{g_0} \approx \frac{g_m}{g_0} \quad R_{oX} = \frac{1}{g_0} \]
Two-port model for Common Base Configuration

\[ R_{ix} = \frac{1}{g_m + g_\pi + g_0} \approx \frac{1}{g_m} \]

\[ A_{VoR} = \frac{g_0}{g_m + g_\pi + g_0} \]

\[ A_{V0} = 1 + \frac{g_m}{g_0} \approx \frac{g_m}{g_0} \]

\[ R_{oX} = \frac{1}{g_0} \]
Consider the following CB application

\[ A_V = A_{V0} \frac{R_C}{R_C + R_{0X}} = \left( \frac{g_m + g_0}{g_0} \right) \left( \frac{g_0}{g_C + g_0} \right) = \frac{g_m + g_0}{g_C + g_0} \approx g_m R_C \]

\[ R_{in} = \frac{v_{in}}{i_1} = i_1 R_{iX} + A_{V0r} v_{out} \rightarrow R_{in} = \frac{R_{iX}}{1 - A_{V0r} A_V} = \frac{R_{iX}}{g_m \left( g_m + g_{\pi} + g_0 \right) + g_{\pi} g_0} \approx \frac{1}{g_m} \]

\[ R_{out} = R_C \parallel R_{0X} \rightarrow R_{out} = \frac{R_C}{1 + g_0 R_C} \]
Consider the following CB application

Alternately, this circuit can also be analyzed directly

By KCL at the output node, obtain

\[(g_C + g_0) V_0 = (g_m + g_0) V_{\text{in}} \]

\[A_V = \frac{g_m + g_0}{g_C + g_0} \approx g_m R_C\]

By KCL at the emitter node, obtain

\[i_1 = (g_m + g_{\pi} + g_0) V_{\text{in}} - g_0 V_{\text{out}} \]

\[R_{\text{in}} = \frac{g_0 + g_C}{g_C (g_m + g_{\pi} + g_0) + g_{\pi} g_0} \approx \frac{1}{g_m}\]

\[R_{\text{out}} = R_C // r_0 \]

\[R_{\text{out}} = \frac{R_C}{1 + g_0 R_C}\]
Two-port model for Common Base Configuration

\[ A_V \approx g_m R_C \]
\[ R_{in} \approx \frac{1}{g_m} \]
\[ R_{out} \approx R_C \]

\[ A_V = \frac{I_{CQ} R_C}{V_t} \]
\[ R_{in} = \frac{V_t}{I_{CQ}} \]
\[ R_{out} \approx R_C \]

- Output impedance is mid-range
- \( A_{V0} \) is large and positive (equal in mag to that to CE)
- Input impedance is very low
- Not completely unilateral but output-input transconductance is small
Common Emitter with Emitter Resistor Configuration

By KCL at two non-grounded nodes

\[
\begin{align*}
\nu_{out} (g_C + g_0) + (\nu_{in} - \nu_E) g_m &= g_0 \nu_E \\
\nu_E (g_E + g_0 + g_\pi) - (\nu_{in} - \nu_E) g_m &= g_0 \nu_{out} + g_\pi \nu_{in}
\end{align*}
\]

\[
A_V = \frac{\nu_{out}}{\nu_{in}} = \frac{-g_m g_E + g_0 g_\pi}{g_C g_m + g_C (g_0 + g_\pi + g_E) + g_0 (g_\pi + g_E)} \approx \frac{-R_C}{R_E}
\]
Common Emitter with Emitter Resistor Configuration

\[ A_V \approx -\frac{R_C}{R_E} \]

It can also be shown that

\[ R_{in} \approx r_{\pi} + \beta R_E \]

\[ R_{out} \approx R_C \]
Common Emitter with Emitter Resistor Configuration

\[ A_v \approx -\frac{R_C}{R_E} \]

\[ R_{in} \approx r_{\text{in}} + \beta R_E \]

\[ R_{out} \approx R_C \]

- Analysis would simplify if \( g_0 \) were set to 0 in model
- Gain can be accurately controlled with resistor ratios
- Useful for reasonably accurate low gains
- Input impedance is high
## Basic Amplifier Gain Table

<table>
<thead>
<tr>
<th>Configuration</th>
<th>MOS</th>
<th>BJT</th>
<th>MOS</th>
<th>BJT</th>
<th>MOS</th>
<th>BJT</th>
<th>MOS</th>
<th>BJT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$A_V$</strong></td>
<td>$-g_m R_C$</td>
<td>$\frac{g_m}{g_m + g_E}$</td>
<td>$\frac{g_m R_C}{V_EB}$</td>
<td>$\frac{2I_{DQ} R_C}{V_EB}$</td>
<td>$\frac{I_{CQ} R_C}{V_EB}$</td>
<td>$\frac{2I_{DQ} R_C}{V_EB}$</td>
<td>$\frac{I_{CQ} R_C}{V_EB}$</td>
<td>$\frac{2I_{DQ} R_C}{V_EB}$</td>
</tr>
<tr>
<td><strong>$R_{in}$</strong></td>
<td>$r_{Tt}$</td>
<td>$r_{Tt} + \beta R_E$</td>
<td>$\frac{\beta V_t}{I_{CQ}}$</td>
<td>$\frac{\beta}{I_{CQ}} \left( V_t + R_E \right)$</td>
<td>$\frac{2I_{DQ}}{V_EB}$</td>
<td>$\frac{I_{CQ}}{V_t}$</td>
<td>$\frac{2I_{DQ}}{V_EB}$</td>
<td>$\frac{I_{CQ}}{V_t}$</td>
</tr>
<tr>
<td><strong>$R_{out}$</strong></td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
<td>$R_C$</td>
<td>$g_m^{-1}$</td>
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