EE 330
Lecture 31

Basic amplifier architectures
### Basic Amplifier Structures

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Can analyze the BJT structures and then obtain the characteristics of The MOS structure by setting $g_{m}=0$
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

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

Widely used characterization strategy
Model parameters are \( \{R_{ix}, A_{V0} \text{ and } R_{0X}\} \)
Two-Port characterization of non-unilateral 3-terminal devices

Widely used characterization strategy

Model parameters are \{R_{iX}, A_{V0}, A_{VR} and R_{0X}\}
The three basic amplifier types for both MOS and bipolar processes

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

How can the two-port parameters be obtained for these or any other linear two-port networks?
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

1. \( v_{\text{TEST}} : i_{\text{TEST}} \) Method

2. Write \( v_1 : v_2 \) equations in standard form
   \[
   v_1 = i_1 R_{\text{IN}} + A_{\text{VR}} v_2 \\
   v_2 = i_2 R_{\text{O}} + A_{\text{V0}} v_1
   \]

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches
\( V_{\text{test}} : i_{\text{test}} \) Method for Obtaining Two-Port Amplifier Parameters

**SUMMARY**

\[ A_{V0} = \frac{V_{\text{out}-\text{test}}}{V_{\text{test}}} \]

\[ R_{\text{in}} = \frac{V_{\text{test}}}{i_{\text{test}}} \]

\[ R_0 = \frac{V_{\text{test}}}{i_{\text{test}}} \]

\[ A_{VR} = \frac{V_{\text{out}-\text{test}}}{V_{\text{test}}} \]

If Unilateral, \( A_{VR} = 0 \)
Consider Common Emitter/Common Source Two-port Models

Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_{\pi}=0$
Basic CE/CS Amplifier Structures

The CE and CS amplifiers are themselves two-ports!

Can include or exclude R and $R_1$ in two-port models (of course they are different circuits)

The CE and CS amplifiers are themselves two-ports!
Two-port model for Common Emitter Configuration

It can be readily shown that the common-emitter configuration is unilateral.

Thus it is characterized by the parameters \( \{R_{in}, A_{V0} \text{ and } R_0\} \).
Two-port model for Common Emitter Configuration

\[ \begin{align*}
V_{be} & \quad g_{\pi} \\
\quad & \quad g_m V_{be} \\
B & \quad C \\
E & \quad \text{Common Emitter}
\end{align*} \]

\[ \begin{align*}
R_o & \\
V_1 & \quad i_1 \\
A_{V0} V_1 & \quad i_2 \\
V_2 &
\end{align*} \]

\{R_i, A_{V0} and R_0\}
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

1. $v_{\text{TEST}} : i_{\text{TEST}}$ Method

2. Write $v_1 : v_2$ equations in standard form

   $v_1 = i_1 R_{\text{IN}} + A_{\text{VR}} v_2$

   $v_2 = i_2 R_0 + A_{\text{V0}} v_1$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches
Two-port model for Common Emitter Configuration

By Thevenin : Norton Transformations

\[ R_{\text{in}} = \frac{1}{g_\pi} \]
\[ A_{V0} = -\frac{g_m}{g_0} \]
\[ R_0 = \frac{1}{g_0} \]
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

1. $v_{\text{TEST}} : i_{\text{TEST}}$ method

2. Write $v_1 : v_2$ equations in standard form

\[ v_1 = i_1 R_{\text{IN}} + A_{\text{VR}} v_2 \]
\[ v_2 = i_2 R_{\text{O}} + A_{\text{V0}} v_1 \]

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches
Two-port model for Common Emitter Configuration

Alternately, by \( v_{\text{TEST}} : i_{\text{TEST}} \) Method

To obtain \( R_{\text{in}} \)

\[
\begin{align*}
\{R_{\text{in}}, A_{V0} \text{ and } R_0\}
\end{align*}
\]
Two-port model for Common Emitter Configuration

Alternately, by $v_{\text{TEST}} : i_{\text{TEST}}$ Method

To obtain $A_{V0}$

$$A_{V0} = \frac{v_{\text{out-test}}}{v_{\text{test}}}$$

$$v_{\text{out-test}} = v_{\text{test}} \left( -\frac{g_m}{g_0} \right)$$

$$A_{V0} = -\frac{g_m}{g_0}$$

{${R_{in}, A_{V0}, R_0}$}
Two-port model for Common Emitter Configuration

Alternately, by $\mathbf{v}_{\text{TEST}} : \mathbf{i}_{\text{TEST}}$ Method

To obtain $g_0$

\[ R_0 = \frac{v_{\text{test}}}{i_{\text{test}}} \]

\[ v_{\text{test}} = i_{\text{test}}(g_0) \]

\[ R_0 = \frac{1}{g_0} \]

\{ $R_{\text{in}}$, $A_{V0}$ and $R_0$ \}
Two-port model for Common Emitter Configuration

\[ R_{in} = \frac{1}{g_{\pi}} \quad A_{V0} = -\frac{g_m}{g_0} \quad R_0 = \frac{1}{g_0} \]

In terms of operating point and model parameters:

\[ R_i = \frac{\beta V_t}{I_{CQ}} \quad A_{V0} = -\frac{V_{AF}}{V_t} \quad R_0 = \frac{V_{AF}}{I_{CQ}} \]

- Input impedance is mid-range
- Voltage Gain is Large and Inverting
- Output impedance is large
- Widely used to build voltage amplifiers
Common Emitter Configuration

Consider the following CE application

\[ V_{out} \left( g_C + g_0 \right) = g_0 A_{V0} V_{in} \]

\[ A_{VC} = \frac{V_{out}}{V_{in}} = \frac{g_0 A_{V0}}{g_0 + g_C} = \frac{-g_m}{g_0 + g_C} \approx -g_m R_C \]

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

\[ R_{outC} = R_o // R_C = \frac{1}{g_0 + g_C} g_o \ll g_c \approx R_C \]
Consider the following CE application

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

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

\[ \mathbf{A}_V = \frac{\mathbf{V}_{out}}{\mathbf{V}_{in}} = -\left( \frac{g_m}{g_0 + g_C} \right) \approx -g_m R_C \]

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

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

Consider the following CE application

(this is also a two-port model for this CE application)

- Input impedance is mid-range
- Voltage Gain is large and Inverting
- Output impedance is mid-range
- Widely used as a voltage amplifier

Small signal parameter domain

\[
A_v \approx -g_m R_C
\]

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

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

Operating point and model parameter domain

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

\[
R_{out} \approx R_C
\]

\[
R_{in} = \frac{\beta V_t}{I_{CQ}}
\]
In terms of operating point and model parameters:

\[
R_{\text{in}} = \frac{1}{g_{\pi}} \quad A_{V0} = -\frac{g_m}{g_0} \quad R_0 = \frac{1}{g_0} \quad R_{\text{in}} = \infty \quad A_{V0} = -\frac{g_m}{g_0} \quad R_0 = \frac{1}{g_0}
\]

\[
R_{\text{in}} = \frac{\beta V_t}{I_{CQ}} \quad A_{V0} = -\frac{V_{AF}}{V_t} \quad R_0 = \frac{V_{AF}}{I_{CQ}} \quad R_{\text{in}} = \infty \quad R_0 = \frac{1}{\lambda I_{DQ}} = \frac{V_{AF}}{I_{DQ}}
\]

\[
A_{V0} = -\frac{2}{\lambda V_{EBQ}} = -2 \frac{V_{AF}}{V_{EBQ}}
\]

- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is large
- Widely used to build voltage amplifiers
Common Source/Common Emitter Configuration

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

\[ A_v \approx -g_m R_C \]

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

In terms of operating point and model parameters:

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

\[ R_{\text{out}} \approx R_C \]

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

- Input impedance is mid-range (infinite for MOS)
- Voltage Gain is Large and Inverting
- Output impedance is mid-range
- Widely used as a voltage amplifier
Consider Common Collector/Common Drain Two-port Models

Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_{m}=0$. 

---

Common Emitter

Common Base

Common Collector

Common Source

Common Gate

Common Drain
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

\[ \begin{align*}
    V_{be} & \quad g_{\pi} \\
    g_m V_{be} & \quad g_o
\end{align*} \]

\[ \begin{align*}
    i_1 & \quad R_{iX} \\
    A_{v0r} V_2 & \quad A_{v0} V_1
\end{align*} \]

\[ \begin{align*}
    \{R_{iX}, A_{v0}, A_{v0r} \text{ and } R_{oX}\} \]
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

1. $v_{\text{TEST}} : i_{\text{TEST}}$ Method

2. Write $v_1 : v_2$ equations in standard form

   $v_1 = i_1 R_{\text{IN}} + A_{\text{VR}} v_2$

   $v_2 = i_2 R_{O} + A_{\text{V0}} v_1$

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches
Two-port model for Common Collector Configuration

Applying KCL at the input and output node, obtain

\[
\begin{align*}
    i_1 &= (V_1 - V_2)g_{\pi} \\
    i_2 &= (g_m + g_{\pi} + g_o)V_2 - (g_m + g_{\pi})V_1
\end{align*}
\]

These can be rewritten as

\[
\begin{align*}
    V_1 &= i_1r_{\pi} + V_2 \\
    V_2 &= \left(\frac{1}{g_m + g_{\pi} + g_o}\right)i_2 + \left(\frac{g_m + g_{\pi}}{g_m + g_{\pi} + g_o}\right)V_1
\end{align*}
\]

It thus follows that

\[
\begin{align*}
    R_{iX} &= r_{\pi} & A_{v0} &= 1 \\
    R_{0X} &= \left(\frac{1}{g_m + g_{\pi} + g_o}\right) & A_{v0} &= \left(\frac{g_m + g_{\pi}}{g_m + g_{\pi} + g_o}\right)
\end{align*}
\]
Two-port model for Common Collector Configuration

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

\[ A_{vor} = 1 \]

\[ \frac{1}{g_m + g_\pi + g_o} \approx \frac{1}{g_m} \]

\[ A_{v0} = \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \approx 1 \]
Common Collector Configuration

Consider the following CC application

Determine $R_{in}$, $R_0$, and $A_V$

(this is not asking for a two-port model for the CC application – $R_{in}$ and $A_V$ defined for no additional load on output, $R_0$ defined for short-circuit input)

\[
A_V = A_{V0} \frac{g_{ox}}{g_{ox} + g_E} = \frac{g_m + g_\pi}{g_m + g_\pi + g_o} \left( \frac{g_m + g_\pi + g_o}{g_m + g_\pi + g_o + g_E} \right) = \frac{g_m + g_\pi}{g_m + g_\pi + g_o + g_E} \approx \frac{g_m}{g_m + g_E} \quad \text{if } g_m >> g_\pi
\]

\[
\mathbf{V}_{in} = i_1 R_{ix} + A_{V0} A_{V0} \frac{g_{ox}}{g_{ox} + g_E} \mathbf{V}_{in} \quad \Rightarrow \quad R_{in} = \frac{r_\pi}{1 - \frac{g_m + g_\pi}{g_m + g_\pi + g_o + g_E}} = r_\pi \frac{g_m + g_\pi + g_o + g_E}{g_o + g_E} \approx r_\pi + \beta R_E
\]

\[
R_0 \approx \frac{1}{g_m + g_E + g_0 + g_\pi} = \frac{1}{g_m + g_E} = \frac{R_E}{1 + g_m R_E} \approx \frac{1}{g_m}
\]
Common Collector Configuration

Consider the following CC application

\[ V_{\text{in}} \] \[ \rightarrow \] \[ V_{\text{in}} \] \[ \downarrow \] \[ V_{\text{out}} \] \[ \uparrow \] \[ V_{\text{IN}} \] \[ \text{Common Collector} \] \[ \text{RE} \] \[ V_{\text{OUT}} \]

(this is not asking for a two-port model for the CC application, \(- R_{\text{in}} \) and \( A_v \) defined for no additional load on output, \( R_o \) defined for short-circuit input -)

Alternately, this circuit can also be analyzed directly (analysis shown for \( A_v \) and \( R_{\text{in}} \) only)

\[ V_{\text{out}} \left(g_E + g_0 + g_\pi\right) = V_{\text{in}} g_\pi + g_m V_1 \]
\[ V_{\text{in}} = V_1 + V_{\text{out}} \]
\[ i_{\text{in}} = g_\pi \left(V_{\text{in}} - V_{\text{out}}\right) \]
\[ V_{\text{out}} \left(g_m + g_E + g_0 + g_\pi\right) = V_{\text{in}} \left(g_\pi + g_m\right) \]
\[ A_v = \frac{g_\pi + g_m}{g_m + g_E + g_0 + g_\pi} \approx \frac{g_m}{g_m + g_E} = \frac{I_{\text{CQ}} R_E}{I_{\text{CQ}} R_E + V_t} \]
\[ i_{\text{in}} \left(g_m + g_\pi + g_E + g_0\right) = g_\pi V_{\text{in}} \left(g_E + g_0\right) \]
\[ g_\pi >> g_o \]
\[ R_{\text{in}} = r_{\pi} \frac{g_m + g_\pi + g_o + g_E}{g_o + g_E} \approx r_{\pi} + \beta R_E \]
Common Collector Configuration

For this CC application

(this is not a two-port model for this CC application)

Small signal parameter domain

\[
A_V = \frac{g_\pi + g_m}{g_m + g_E + g_0 + g_\pi} \approx 1
\]

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

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

Operating point and model parameter domain

\[
A_V \approx \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \approx 1
\]

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

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

- 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
Common Collector/Common Source Configurations

For these CC/CS applications

(not two-port models for these applications)

In terms of operating point and model parameters:

- 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

\[
A_V = \frac{g_n + g_m}{g_m + g_E + g_0 + g_x} \quad \text{if } g_n \gg g_x \Rightarrow 1
\]

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

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

\[
A_V \approx \frac{I_{CQ} R_E}{I_{CQ} R_E + V_t} \quad \text{if } I_{CQ} R_E \gg V_t \Rightarrow 1
\]

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

\[
R_0 \approx \frac{V_{EBQ}}{V_{EBQ} + 2I_{DQ} R_S} \approx \frac{V_{EBQ}}{2I_{DQ}}
\]

\[
R_{in} = \infty
\]
Consider Common Base/Common Gate Two-port Models

Will focus on Bipolar Circuit since MOS counterpart is a special case obtained by setting $g_{\pi}=0$
Two-port model for Common Base Configuration

\[ \begin{align*}
\text{Common Base} & \quad \text{Common Base} \\
\text{\{} & \quad \text{\{} \\
\{R_{iX}, A_{V0}, A_{V0r} \text{ and } R_{0X}\} & \quad \{R_{iX}, A_{V0}, A_{V0r} \text{ and } R_{0X}\}
\end{align*}\]
Two-Port Models of Basic Amplifiers widely used for Analysis and Design of Amplifier Circuits

Methods of Obtaining Amplifier Two-Port Network

1. $v_{TEST}$ : $i_{TEST}$ Method

2. Write $v_1 : v_2$ equations in standard form

\[ v_1 = i_1 R_{IN} + A_{VR} v_2 \]
\[ v_2 = i_2 R_O + A_{V0} v_1 \]

3. Thevenin-Norton Transformations

4. Ad Hoc Approaches
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:

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

Two-port Common Base Model

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

\[ A_{V0r} = \frac{g_0}{g_m + g_\pi + g_0} \approx \frac{g_0}{g_m} \]

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

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

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

\[ R_{in} = \frac{\nu_{in}}{i_1} = i_1 R_{iX} + A_{V0r} \nu_{out} \]

\[ R_{out} = R_C / / R_{0X} \]

\[ R_{in} = \frac{R_{iX}}{1 - A_{V0r} A_V} = \frac{g_0 + g_C}{g_C (g_m + g_\pi + g_0) + g_\pi g_0} \approx \frac{1}{g_m} \]
Common Base Configuration

Consider the following CB application

(this is not asking for a two-port model for this CB application – $R_{in}$ and $A_V$ defined for no load on output, $R_o$ defined for short-circuit input)

Alternately, this circuit can also be analyzed directly

By KCL at the output node, obtain

$$ (g_C + g_0) V_0 = (g_m + g_0) V_{in} $$

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

By KCL at the emitter node, obtain

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

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

$$ R_{out} = R_C // r_0 $$

$$ R_{out} = \frac{R_C}{1 + g_0 R_C} $$
Common Base Application

(this is not a two-port model for this CB application)

\[ A_V \approx g_m R_C \]
\[ R_{in} \approx \frac{1}{g_m} \]
\[ R_c \ll r_0 \]
\[ R_{out} \approx R_C \]

\[ A_V \approx \frac{I_{CQ} R_C}{V_t} \]
\[ R_{in} \approx \frac{V_t}{I_{CQ}} \]
\[ R_c \ll r_0 \]
\[ R_{out} \approx R_C \]

- 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 Base/Common Gate Application

(These are not a two-port models)

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

In terms of operating point and model parameters:

\[ A_V \approx \frac{I_{CQ} R_C}{V_t} \]
\[ R_{in} \approx \frac{V_t}{I_{CQ}} \]
\[ R_{out} \approx \frac{I_{o0} R_C}{V_A^f} \]

- 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
End of Lecture 31