Lecture 20

OUTLINE
- Review of MOSFET Amplifiers
- MOSFET Cascode Stage
- MOSFET Current Mirror
- Reading: Chapter 9

Review: MOSFET Amplifier Design
- A MOSFET amplifier circuit should be designed to
  1. ensure that the MOSFET operates in the saturation region,
  2. allow the desired level of DC current to flow, and
  3. couple to a small-signal input source and to an output “load”.
- Proper “DC biasing” is required!
  (DC analysis using large-signal MOSFET model)
- Key amplifier parameters:
  (AC analysis using small-signal MOSFET model)
  - Voltage gain $A_v = \frac{v_{out}}{v_{in}}$
  - Input resistance $R_{in} = \frac{v_{in}}{i_{in}}$
  - Output resistance $R_{out} = \frac{i_{out}}{v_{out}}$

MOSFET Models
- The large-signal model is used to determine the DC operating point $(V_{GB}, V_{DS}, I_D)$ of the MOSFET.

- The small-signal model is used to determine how the output responds to an input signal.

Common Source Stage

$$\begin{align*}
\lambda &= 0 \\
A_s &= \frac{R_e}{R_s} \frac{R_s}{R_s + R_e} - R_{DS} \frac{1}{g_m} + R_s \\
R_{in} &= R_s \frac{R_{DS} + R_s}{R_s} \\
R_{out} &= R_D \\
R_{out} &= R_D \left( R_{DS} + g_m R_s \right)
\end{align*}$$

Common Gate Stage

$$\begin{align*}
\lambda &= 0 \\
A_s &= \frac{1}{g_m} \frac{R_s}{R_s + \frac{1}{g_m} + R_s} \\
R_{in} &= \frac{1}{g_m} R_s \\
R_{out} &= R_D \\
R_{out} &= R_D \left( g_m R_s + R_s \right)
\end{align*}$$

Comparison of Amplifier Topologies

<table>
<thead>
<tr>
<th>Source</th>
<th>Common Source</th>
<th>Common Gate</th>
<th>Source Follower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large $A_s &lt; 0$</td>
<td>- degraded by $R_s$</td>
<td>- decreased by $R_s$</td>
<td>$0 &lt; A_s \leq 1$</td>
</tr>
<tr>
<td>Large $R_m$</td>
<td>- determined by biasing circuitry</td>
<td>$R_s$</td>
<td>$R_s$</td>
</tr>
<tr>
<td>$R_{out} = R_s$</td>
<td>$R_{out} = R_s$</td>
<td>$r_o$ decreases $A_s$ &amp; $R_{out}$</td>
<td></td>
</tr>
</tbody>
</table>

...
**Source Follower**

\[ \lambda = 0 \]
\[ A_i = \frac{R_D}{1 + R_S} \]
\[ R_{m} = R_{G} \]
\[ R_{V} = \frac{1}{S_m} || R_S \]

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**CS Stage Example 1**

- \( M_1 \) is the amplifying device; \( M_2 \) and \( M_3 \) serve as the load.

Equivalent circuit for small-signal analysis, showing resistances connected to the drain.

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**CS Stage Example 2**

- \( M_1 \) is the amplifying device; \( M_2 \) serves as a source (degeneration) resistance; \( M_3 \) serves as the load.

Equivalent circuit for small-signal analysis.

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**CS Stage vs. CG Stage**

- With the input signal applied at different locations, these circuits behave differently, although they are identical in other aspects.

**Composite Stage Example 1**

- By replacing \( M_1 \) and the current source with a Thévenin equivalent circuit, and recognizing the right side as a CG stage, the voltage gain can be easily obtained.

**Composite Stage Example 2**

- This example shows that by probing different nodes in a circuit, different output signals can be obtained.

- \( V_{out1} \) is a result of \( M_1 \) acting as a source follower, whereas \( V_{out2} \) is a result of \( M_1 \) acting as a CS stage with degeneration.
NMOS Cascode Stage

\[ R_{out} = (1 + g_m r_{o2}) r_{o1} + r_{o1} \]
\[ R_{out} \approx g_m r_{o2} r_{o1} \]

- Unlike a BJT cascode, the output impedance is not limited by \( \beta \).

PMOS Cascode Stage

\[ R_{out} = (1 + g_m r_{o2}) r_{o1} + r_{o1} \]
\[ R_{out} \approx g_m r_{o2} r_{o1} \]

Short-Circuit Transconductance

- The short-circuit transconductance is a measure of the strength of a circuit in converting an input voltage signal into an output current signal:

\[ G_m \equiv \left. \frac{i_{out}}{v_{in}} \right|_{v_{in}=0} \]

- The voltage gain of a linear circuit is

\[ A_v = -G_m R_{out} \]

(MOS output impedance is the output resistance of the circuit)

Transconductance Example

\[ G_m = g_m r_{11} \]

MOS Cascode Amplifier

\[ A_v = -G_m R_{out} \]
\[ A_v = -g_m [1 + g_m r_{o2}] r_{o1} + r_{o2} \]
\[ A_v = -g_m r_{o1} r_{o2} \]

PMOS Cascode Current Source as Load

- A large load impedance can be achieved by using a PMOS cascode current source.
MOS Current Mirror

- The motivation behind a current mirror is to duplicate a (scaled version of the) “golden current” to other locations.

MOS Current Mirror – NOT!

- This is not a current mirror because the relationship between \( V_X \) and \( I_{REF} \) is not clearly defined.

Example: Current Scaling

- MOS current mirrors can be used to scale \( I_{REF} \) up or down

\[ I_{REF} = 0.2 \text{mA}; \quad I_2 = 0.5 \text{mA} \]

\[ \lambda = 0 \]

\[ I_{REF} \quad 0.3 \text{mA} \]

\[ 3 \left( \frac{W}{L} \right) \]

Impact of Channel-Length Modulation

- The only way to clearly define \( V_X \) with \( I_{REF} \) is to use a diode-connected MOS since it provides square-law \( I-V \) relationship.

CMOS Current Mirror