EE 330
Lecture 33

- High Gain Amplifiers
- Current Sources and Mirrors
- The Cascode Configuration
- The Differential Amplifier
High-gain amplifier

This gain is very large (but realistic)!

And no design parameters affect the gain

But how can we make a current source?
Review from Last Lecture

High-gain amplifier

![Diagram of a high-gain amplifier](image)

\[ A_V \approx -8000 \]

How can we build the dc current source?

What is the small-signal model of an actual current source?
Current Sources/Mirrors

Review from Last Lecture
Review from Last Lecture

Current Sources/Mirrors

Multiple-Output Bipolar Current Sink

\[ I_k = \left[ \frac{A_{E_k}}{A_{E0}} \right] I_0 \]
Review from Last Lecture

Current Sources/Mirrors

Multiple-Output Bipolar Current Source

\[ I_k = \frac{A_{E_k}}{A_{E_0}} I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = \left[ \frac{A_{Enk}}{A_{E0}} \right] I_0 \]

\[ I_{pk} = \left[ \frac{A_{En1}}{A_{E0}} \right] \left[ \frac{A_{Epk}}{A_{Ep0}} \right] I_0 \]
Current Sources/Mirrors

Termed a “current mirror”
Output current linearly dependent on $I_{in}$
Serves as a current amplifier
Widely used circuit

$I_{out} = \begin{bmatrix} A_{E1} \\ A_{E0} \end{bmatrix} I_{in}$
Current Sources/Mirrors

npn current mirror amplifier

\[ i_{\text{out}} = ? \]
Current Sources/Mirrors

nnpn current mirror amplifier

\[ i_{\text{out}} = \left[ \frac{A_{E_1}}{A_{E_0}} \right] i_{\text{in}} \]

Amplifiers both positive and negative currents
Current Sources/Mirrors

npn Current Mirror

n-channel Current Mirror

\[ I_{\text{out}} = ? \]
Current Sources/Mirrors

\[ I_{\text{in}} = \frac{\mu C_{\text{OX}} W_0}{2L_0} (V_{\text{GS0}} - V_{T0})^2 \]

\[ I_{\text{out}} = \frac{\mu C_{\text{OX}} W_1}{2L_1} (V_{\text{GS1}} - V_{T1})^2 \]

If process parameters are matched, it follows that

\[ I_{\text{out}} = \begin{bmatrix} \frac{W_1}{W_0} & \frac{L_0}{L_1} \end{bmatrix} I_{\text{in}} \]

- Current mirror gain can be accurately controlled
- Layout is important to get accurate gain (for both MOS and BJT)
Current Sources/Mirrors Summary

n-channel Current Mirror

\[ I_{out} = \left[ \frac{A_{E1}}{A_{E0}} \right] I_{in} \]

npn Current Mirror

\[ I_{out} = \left[ \frac{W_1}{W_0} \right] \frac{L_0}{L_1} I_{in} \]
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Gate area after fabrication depicted

$$M = \begin{bmatrix} W_2 & L_1 \\ W_1 & L_2 \end{bmatrix}$$

$$M = \begin{bmatrix} \frac{W_2 + 2\Delta W}{W_1 + 2\Delta W} \cdot \frac{L_1 + 2\Delta L}{L_2 + 2\Delta L} \\ \frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} \cdot \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} \neq 2$$
Layout of Current Mirrors

Example with $M = 2$

$$M = \begin{bmatrix} \frac{W_2}{W_1} & \frac{L_1}{L_2} \end{bmatrix}$$

$$M = \begin{bmatrix} \frac{2W_1 + 2\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} \neq 2$$

$$M = \begin{bmatrix} \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} = 2$$

Standard layout

Better Layout
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Better Layout

Even Better Layout

This is termed a common-centroid layout
n-channel current mirror current amplifier

\[ \begin{bmatrix} \frac{W_2}{W_1} \frac{L_1}{L_2} \end{bmatrix} i_{\text{in}} = i_{\text{out}} \]

Amplifies both positive and negative currents
Current Sources/Mirrors

\[ I_k = \begin{bmatrix} \frac{W_k}{W_0} & \frac{L_k}{L_0} \end{bmatrix} I_0 \]

multiple output n-channel current sink array

multiple output p-channel current source array
Current Sources/Mirrors

multiple sourcing and sinking current outputs

\[ I_{pj} = \left[ \frac{W_{pj}}{L_{pj}} \cdot \frac{L_{p0}}{W_{p0}} \right] M I_0 \]

\[ M = \left[ \frac{W_{n0}}{L_{n0j}} \cdot \frac{L_0}{W_0} \right] \]

\[ I_{nj} = \left[ \frac{W_{nj}}{L_{nj}} \cdot \frac{L_0}{W_0} \right] I_0 \]

m and k may be different
Often \( M = 1 \)
High-gain amplifier

\[ A_V \approx -8000 \]

How can we build the current source?

What is the small-signal model of an actual current source?
Basic Current Sources and Sinks

Bipolar Mirror-Based Current Sink

Biasing circuit uses same $V_{CC}$ as amplifier and no other independent sources
High-gain amplifier

- Bias circuitry requires only a single independent dc voltage source!
- **Incremental** overhead is only one transistor, $Q_B$
Basic Current Sources and Sinks

Basic Bipolar Current Sinks

- Very practical methods for biasing the BJTs (or MOSFETs) can be used
- Current Mirrors often used for generating sourcing and sinking currents
- Can think of biasing transistors with $V_{XX}$ and $V_{YY}$ in these current sources
High-gain amplifier

\[ A_V \approx -8000 \]

How can we build the current source?

What is the small-signal model of an actual current source?
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other BJT Sinks and Sources introduced so far are the same
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Small-signal model of all other MOS Sinks and Sources introduced thus far are the same
High-gain amplifier

\[ A_V = \frac{-g_m}{g_0} \]

\[ A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \approx \frac{-g_{m1}}{2g_{01}} \]
High-gain amplifier

\[ g_m = \frac{V_{AF}}{V_t} \approx 8000 \]

\[ A_V = \frac{-g_m}{g_0} \]

- Nonideal current source decreased the gain by a factor of 2
- But the voltage gain is still quite large (-4000)

Can the gain be made even larger?
High-gain amplifier
Can the gain be made even larger?

The Cascode Configuration

Discuss
The Cascode Amplifier (consider npn BJT version)

- Actually a cascade of a CE stage followed by a CB stage but usually viewed as a “single-stage” structure
- Cascode structure is widely used
Basic Amplifier Structures

1. Common Emitter/Common Source
2. Common Collector/Common Drain
3. Common Base/Common Gate
4. Common Emitter with $R_E$/ Common Source with $R_S$

5. Cascode (actually CE:CB or CS:CD cascade)
6. Darlington (special CE:CE or CS:CS cascade)

The first 4 are most popular
Cascode Configuration

Two-port model of cascode amplifier

\[
\begin{align*}
(V_X + V_2)g_{02} + V_2g_{m2} &= I_X \\
V_1g_{m1} - V_2(g_{01} + g_{\pi 2}) &= I_X
\end{align*}
\]

Observing \(V_1 = V_{IN}\) and eliminating \(V_2\) between these two equations, we obtain

\[
V_X = -\left\{ \frac{g_{m1}(g_{02} + g_{m2})}{g_{02}(g_{\pi 2} + g_{01})} \right\} V_{IN} + \left\{ \frac{g_{01} + g_{02} + g_{\pi 2} + g_{m2}}{g_{02}(g_{01} + g_{\pi 2})} \right\} I_X
\]

and

\[
V_{IN} = \frac{1}{g_{\pi 1}} I_1
\]
Cascode Configuration

Two-port model of cascode amplifier

\[ V_X = \left[ \frac{g_{m1}(g_{02}+g_{m2})}{g_{02}(g_{\pi2}+g_{01})} \right] V_1 + \left[ \frac{g_{01} + g_{02} + g_{\pi2} + g_{m2}}{g_{02}(g_{01}+g_{\pi2})} \right] I_X \]

\[ V_{IN} = \frac{1}{g_{\pi1}} I_1 \]

It thus follows for the npn bipolar structure that:

\[ A_{VCC} = -\left[ \frac{g_{m1}(g_{02}+g_{m2})}{g_{02}(g_{\pi2}+g_{01})} \right] \approx -\left[ \frac{g_{m1} g_{m2}}{g_{02} g_{\pi2}} \right] \]

\[ g_{0CC} = \left[ \frac{g_{02} (g_{01}+g_{\pi2})}{g_{01} + g_{02} + g_{\pi2} + g_{m2}} \right] \approx \left[ \frac{g_{02} g_{\pi2}}{g_{m2}} \right] \]

\[ g_{\piCC} = g_{\pi1} \]
Cascode Configuration

- Voltage gain is a factor of $\beta$ larger than that of the CE amplifier with current source load.
- Output impedance is a factor of $\beta$ larger than that of the CE amplifier.

$$A_{VCC} \approx -\left[ \frac{g_{m1}g_{m2}}{g_{02}g_{\pi2}} \right]$$

$$g_{0CC} \approx \left[ \frac{g_{02}g_{\pi2}}{g_{m2}} \right]$$

$$g_{\pi CC} = g_{\pi1}$$

$$A_{VCC} \approx -\left[ \frac{g_{m1}}{g_{02}} \right] \approx -\left[ \frac{g_{m1}}{g_{01}} \right] \beta$$

$$g_{0CC} \approx \frac{g_{01}}{\beta}$$
What happens to the gain if a transistor-level current source is used for $I_B$?

This gain is very large and only requires two transistors!
Cascode Configuration

\[ V_{CC} \to Q_1 \to I_B \to \nu_{OUT} \]

\[ V_{XX} \to Q_2 \to V_{SS} \]

\[ V_{IN} \to \]

\[ V_C \]

\[ V_{YY} \]

\[ Q_3 \]
Cascode Configuration
High-gain amplifier comparisons

It thus follows that

\[ A_V = A_{VCC} \left( \frac{g_{0CC}}{g_{03} + g_{0CC}} \right) \]

But \[ g_{0CC} \approx g_{03}/\beta \]

\[ A_V \approx A_{VCC} \left( \frac{g_{0CC}}{g_{03}} \right) \approx \frac{A_{VCC}}{\beta} \]

This is a dramatic reduction in gain compared to what the ideal current source biasing provided.
Cascode Configuration

\[ A_V = A_{VCC} \left( \frac{g_{0CC}}{g_{03}} \right) \approx \frac{A_{VCC}}{\beta} \]

But recall

\[ A_{VCC} \approx -\left( \frac{g_{m1}}{g_{01}} \right) \beta \]

Thus

\[ A_V \approx -\left( \frac{g_{m1}}{g_{01}} \right) \]

- This is still a factor of 2 better than that of the CE amplifier with transistor current source
  \[ A_{VCE} = -\left( \frac{g_{m1}}{2g_{01}} \right) \]
- It only requires one additional transistor
- But its not nearly as good as the gain the cascode circuit seemed to provide
Cascode Configuration Comparisons

\[ A_V = \frac{-g_m}{g_0} \]

\[ A_V \approx \frac{-g_{m1}}{g_{01} + g_{02}} = \frac{-g_{m1}}{2g_{01}} \]

Gain limited by output impedance of current source !!
Can we design a better current source?
In particular, one with a higher output impedance?
Better current sources

Need a higher output impedance than $g_o$.

The output impedance of the cascode circuit itself was very large!

$$g_{0CC} \approx \frac{g_{01}}{\beta}$$

Can a current source be built with the cascode circuit?
Cascode current sources

\[ V_{XX}, V_{YY}, V_{SS} \]

\[ I_x, V_{CC}, V_{DD} \]

\[ Q_1, Q_2, M_1, M_2 \]
Cascode Configuration

\[ A_V = -\left[ \frac{g_{m1}}{g_{01}} \right] \frac{\beta}{2} \]

This gain is very large and is a factor of 2 below that obtained with an ideal current source biasing.

Although the factor of 2 is not desired, the performance of this circuit is still very good.

This factor of 2 gain reduction is the same as was observed for the CE amplifier when a transistor-level current source was used.
Can we use more cascoding to further increase the gain?
The Cascode Amplifier (consider n-ch MOS version)

\[ A_{\text{VCC}} \approx -\frac{g_{m1}g_{m2}}{g_{01}g_{02}} \]

\[ g_{0\text{CC}} \approx \frac{g_{01}g_{02}}{g_{m2}} \]

Same issues for biasing with current source as for BJT case

With cascode current source, gain only drops by a factor of 2
The Cascode Amplifier (consider n-ch MOS version)

\[ A_{\text{VCC}} \approx - \left[ \frac{g_{m1}g_{m2}}{g_{01}g_{02}} \right] \]

\[ A_{\text{VCC}} \approx - \left[ \frac{g_{m1}}{g_{01}} \right] \]

\[ A_{\text{VCC}} \approx - \frac{1}{2} \left[ \frac{g_{m1}g_{m2}}{g_{01}g_{02}} \right] \]
Current Source Summary (BJT)

**Basic**

- $V_{YY}$ to $Q_1$
- $V_{SS}$
- $V_{CC}$

**Cascode**

- $V_{XX}$ to $Q_2$
- $V_{YY}$
- $V_{SS}$

\[ g_0 \approx g_{01} \]
\[ g_{0CC} \approx \frac{g_{01}}{\beta} \]
Current Source Summary (MOS)

Basic

\[ V_{YY} \rightarrow M_1 \]
\[ V_{SS} \]
\[ \rightarrow I_X \]

\[ V_{YY} \rightarrow M_1 \]
\[ V_{DD} \]
\[ \rightarrow I_X \]

\[ g_0 \approx g_{01} \]

Cascode

\[ V_{XX} \rightarrow M_2 \]
\[ V_{YY} \rightarrow M_1 \]
\[ V_{SS} \]
\[ \rightarrow I_X \]

\[ V_{YY} \rightarrow M_1 \]
\[ V_{DD} \]
\[ \rightarrow I_X \]

\[ g_0 \approx g_{01} \frac{g_{02}}{g_{m2}} \]
High Gain Amplifier Comparisons (n-ch MOS)

\[ A_V \approx -\left[ \frac{g_{m1}}{g_{01}} \right] \]

\[ A_V \approx -\frac{1}{2} \left[ \frac{g_{m1}}{g_{01}} \right] \]

\[ A_{VCC} = -\left[ \frac{g_{m1}g_{m2}}{g_{01}g_{02}} \right] \]

\[ A_{VCC} \approx -\left[ \frac{g_{m1}}{g_{01}} \right] \]

\[ A_{VCC} \approx -\frac{1}{2} \left[ \frac{g_{m1}g_{m2}}{g_{01}g_{02}} \right] \]
High Gain Amplifier Comparisons (BJT)

\[ A_V = \frac{-g_m}{g_0} \]

\[ A_V \approx -\frac{1}{2} \frac{g_{m1}}{g_{01}} \]

\[ A_V = -\left[ \frac{g_{m1}}{g_{01}} \right] \beta \]

- Single-ended high-gain amplifiers inherently difficult to bias (because of the high gain)
- Biasing becomes practical when used in differential applications
- These structures are widely used but usually with differential inputs
The Cascode Amplifier

• Operational amplifiers often built with basic cascode configuration

• CMFB used to address the biasing problem

• Usually configured as a differential structure when building op amps

• Have high output impedance (but can be buffered)

• Terms “telescopic cascode”, “folded-cascode”, and “regulated cascode” often refer to op amps based upon the cascode configuration
End of Lecture 33