EE 330
Lecture 33

• High Gain Amplifiers
• Current Sources and Mirrors
• The Cascode Configuration
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

$A_V \approx -8000$

How can we build the dc current source?

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

- Multiple Outputs Possible
- Can be built for sourcing or sinking currents
- Also useful as a current amplifier
- MOS counterparts work very well and are not plagued by base current
Current Sources/Mirrors

Biasing Circuit

Key Block

Current Sink

Review from Last Lecture
Current Sources/Mirrors

Multiple-Output Bipolar Current Sink

$$I_k = \left[ \begin{array}{c} \frac{A_{E_k}}{A_{E_0}} \end{array} \right] I_0$$
Current Sources/Mirrors

Multiple-Output Bipolar Current Source

\[ I_k = \begin{bmatrix} A_{E_k} \\ A_{E_0} \end{bmatrix} I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = ? \quad I_{pk} = ? \]
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

$\begin{align*}
I_{out} &= \frac{A_{E1}}{A_{E0}} I_{in} \\
\text{But } I_{in} \text{ and } I_{out} \text{ must be positive!}
\end{align*}$
Current Sources/Mirrors

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

 npn current mirror amplifier

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

Amplifiers both positive and negative currents (provided \( i_{\text{in}} > -I_{BS} \))
Current Sources/Mirrors

npn Current Mirror

n-channel Current Mirror

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

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

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

If process parameters are matched, it follows that

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

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

npn Current Mirror

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

n-channel Current Mirror

\[ I_{\text{out}} = \left[ \frac{W_1}{W_0} \frac{L_0}{L_1} \right] I_{\text{in}} \]
Example with $M = 2$

Standard layout

Gate area after fabrication depicted

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

$M = \begin{bmatrix} \frac{W_2 + 2\Delta W}{W_1 + 2\Delta W} & \frac{L_1 + 2\Delta L}{L_2 + 2\Delta L} \end{bmatrix}$

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

Example with $M = 2$

Standard layout

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

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

Better Layout

$$M = \begin{bmatrix} \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \cdot \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \end{bmatrix} = 2$$
Layout of Current Mirrors

Example with $M = 2$

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

Standard layout

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

Better Layout

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

Even Better Layout

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

Amplifies both positive and negative currents
Current Sources/Mirrors

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

multiple output n-channel current sink array

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

multiple sourcing and sinking current outputs

\[ I_p = \left[ \frac{W_{pj} \cdot L_{p0}}{W_{p0}} \right] M_{l0} \]

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

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

\[ M_0, W_0, L_0 \]

\[ M_{n0}, W_{n0}, L_{n0} \]

\[ M_{n1}, W_{n1}, L_{n1} \]

\[ M_{n2}, W_{n2}, L_{n2} \]

\[ M_{nk}, W_{nk}, L_{nk} \]

\[ m \text{ and } k \text{ may be different} \]

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

Bipolar Mirror-Based Current Source

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

- $I_x = J_S A e^{V_{xx}/V_t}$
- $I_x \approx \frac{V_{CC}-0.6V}{R}$

Basic Bipolar Current Sources

- $V_{CC} - I_x R$
- $V_{YY}$

- 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
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.

Not Diode Connected!
Basic Current Sources and Sinks

Small-signal Model of MOS 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
Two-port model of cascode amplifier

\[
\begin{align*}
(V_X + V_2) g_{02} + V_2 g_{m2} &= I_X \\
V_1 g_{m1} - V_2 (g_{01} + g_{\pi 2}) &= I_X
\end{align*}
\]

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

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

and

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

It thus follows for the npn bipolar structure that:

$$A_{VCC} = -\frac{g_{m1}(g_{02}+g_{m2})}{g_{02}(g_{\pi2}+g_{01})} \approx -\frac{g_{m1}g_{m2}}{g_{02}g_{\pi2}}$$

$$g_{0CC} = \frac{g_{02}(g_{01}+g_{\pi2})}{g_{01}g_{02}+g_{\pi2}g_{m2}} \approx \frac{g_{02}g_{\pi2}}{g_{m2}}$$

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

$$A_{VCC} \approx -\frac{g_{m1}g_{m2}}{g_{02}g_{\pi2}}$$

$$g_{0CC} \approx \frac{g_{02}g_{\pi2}}{g_{m2}}$$

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

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

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

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!

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

$g_{0CC} \approx \frac{g_{02}}{\beta}$

$A_{VCC} \approx -\left[ \frac{g_{m1}}{g_{01}} \right] \beta = \frac{2V_{AF}}{V_t} \beta = [-8000]100$

$A_{VCC} \approx -800,000$
Cascode Configuration
Cascode Configuration

\[ V_{IN} \rightarrow Q_1 \rightarrow Q_2 \rightarrow Q_3 \rightarrow V_{OUT} \]

\[ V_{CC} \]

\[ V_{YY} \]

\[ V_{XX} \]

\[ V_{SS} \]

\[ V_{OUT} \]

\[ V_{OUT} \]
High-gain amplifier comparisons

It thus follows that

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

But \( g_{0CC} \approx \frac{g_{03}}{\beta} \)

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

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

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

But recall

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

Thus

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

\[ A_V \approx - \left[ \frac{I_{CQ}/V_t}{I_{CQ}/V_{AF}} \right] = - \left[ \frac{V_{AF}}{V_t} \right] \approx -8000 \]

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

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

Discuss
Cascode Configuration

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.

\[
A_V = \left(\frac{g_m}{g_{01}}\right) \frac{\beta}{2} \\
A_V = -\left[\frac{8000}{2}\right] \frac{100}{2} \approx -400,000
\]
Can we use more cascoding to further increase the gain?
The Cascode Amplifier (consider n-ch MOS version)

\[
\begin{align*}
A_{VCC} & = - \begin{bmatrix} g_{m1} g_{m2} \\ g_{01} g_{02} \end{bmatrix} \\
g_{0CC} & = \begin{bmatrix} g_{01} g_{02} \\ g_{m2} \end{bmatrix}
\end{align*}
\]

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)

Discuss

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

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

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

**Basic**

- $V_{YY}$
- $V_{SS}$
- $Q_1$
- $I_x$

**Cascode**

- $V_{XX}$
- $V_{YY}$
- $Q_1$
- $Q_2$
- $I_x$

$g_0 \approx g_{01}$

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

**Basic**

\[ V_{YY} \rightarrow M_1 \]

\[ V_{SS} \]

\[ V_{YY} \rightarrow M_1 \]

\[ V_{DD} \]

\[ g_0 \]

\[ g_0 \approx g_{01} \]

**Cascode**

\[ V_{XX} \rightarrow M_2 \]

\[ V_{YY} \rightarrow M_1 \]

\[ V_{SS} \]

\[ V_{DD} \]

\[ g_0 \]

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

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

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

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

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

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

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

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

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

- 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
End of Lecture 33