EE 330
Lecture 33

- High Gain Amplifiers
- Current Sources and Mirrors
- The Cascode Configuration
Review from Last Lecture

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?
How can we build the dc current source?

What is the small-signal model of an actual current source?
Model of dc Current Source

"Reasonable dc Current Source"

$I_{xx}$ independent of $V_1$ and $t$, $R_S$ large

Small-signal model of dc current source

want $R_{IN}$ large

Ideal dc Current Source

$I_{xx}$ independent of $V_1$ and $t$
Current Sources/Mirrors

Will show circuit in red behaves as a current source
Current Sources/Mirrors

If the base currents are neglected:

\[ I_0 \approx \frac{(V_{CC} - 0.6V)}{R} \]
Current Sources/Mirrors

Behaves as a current source! So is ideal with this model!!
Actually termed a “sink” current since coming out of load
And does not require an additional dc voltage source !!!

\[ I_0 \approx \frac{(V_{CC} - 0.6V)}{R} \]

If the base currents are neglected

\[ I_0 = J_S A_{E0} e^{\frac{V_{BE0}}{V_t}} \]
\[ I_t = J_S A_{E1} e^{\frac{V_{BE1}}{V_t}} \]

since \( V_{BE1} = V_{BE2} \)

\[ I_1 \approx \left( \frac{A_{E1}}{A_{E0}} \right) I_0 = \left( \frac{A_{E1}}{A_{E0}} \right) \frac{V_{CC} - 0.6V}{R} \]

Note \( I_1 \) is not a function of \( V_1 \)
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
Current Sources/Mirrors

Multiple-Output Bipolar Current Sink

\[ I_k = \begin{bmatrix} \frac{A_{E_k}}{A_{E0}} \end{bmatrix} I_0 \]
Current Sources/Mirrors

Multiple-Output Bipolar Current Source

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

Multiple-Output Bipolar Current Source and Sink

\[ I_{nk} = ? \quad I_{pk} = ? \]
Current Sources/Mirrors

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

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

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

But $I_{in}$ and $I_{out}$ must be positive!
Current Sources/Mirrors

n-p-n current mirror amplifier

\[ I_{BS} \downarrow i_{in} \quad i_{out} \downarrow M I_{BS} \]

\[ Q_0 \quad A_{E0} \quad Q_1 \quad A_{E1} \]

\[ M = \frac{A_{E1}}{A_{E0}} \]

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

npn current mirror amplifier

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

Amplifiers both positive and negative currents (provided \( i_{in} > -I_{BS} \))

\[ I_{BS} \quad \downarrow \quad i_{in} \quad i_{out} \quad MI_{BS} \]

\[ Q_0 \quad A_{E0} \quad Q_1 \quad A_{E1} \]

\[ M = \frac{A_{E1}}{A_{E0}} \]
Current Sources/Mirrors

npn Current Mirror

n-channel Current Mirror

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

If process parameters are matched, it follows that

\[
\begin{align*}
I_{in} &= \frac{\mu C_{OX} W_0}{2L_0} (V_{GS0} - V_{T0})^2 \\
I_{out} &= \frac{\mu C_{OX} W_1}{2L_1} (V_{GS1} - V_{T1})^2
\end{align*}
\]

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

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

n-p-n Current Mirror

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

n-channel Current Mirror

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

Example with $M = 2$

Standard layout

Gate area after fabrication depicted
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Better Layout

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

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

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

Example with $M = 2$

Standard layout

Better Layout

Even Better Layout

This is termed a common-centroid layout

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

$M = \left[ \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \cdot \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] = 2$

$M = \left[ \frac{2W_1 + 4\Delta W}{W_1 + 2\Delta W} \cdot \frac{L_1 + 2\Delta L}{L_1 + 2\Delta L} \right] = 2$
n-channel current mirror current amplifier

\[ M = \frac{W_2 \cdot L_1}{W_1 \cdot L_2} \]

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

Amplifies both positive and negative currents
Current Sources/Mirrors

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

multiple output n-channel current sink array

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

multiple sourcing and sinking current outputs

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

\[
M = \frac{W_{nj}}{L_{nj}} \cdot \frac{L_0}{W_0}
\]

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

\[
I = \frac{W_{nj}}{L_{nj}} \cdot \frac{L_0}{W_0} I_0
\]

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

Bipolar Mirror-Based Current Source

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

\[ I_x = J_S A e^{\frac{V_{xx}}{V_t}} \]

\[ I_x \approx \frac{V_{CC} - 0.6V}{R} \]

Basic Bipolar Current Sources

\[ V_{CC} \]

Current Mirrors often used for generating sourcing and sinking currents

Very practical methods for biasing the BJTs (or MOSFETs) can be used

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

\[ \frac{g_m}{g_0} = \frac{V_{AF}}{V_t} \approx 8000 \]

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

- 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
Observing $V_1 = V_{\text{IN}}$ and eliminating $V_2$ between these two equations, we obtain

$$V_{\text{IN}} = I_1 \cdot \frac{1}{g_{\pi 1}}$$

and

$$V_X = I_X \cdot \left[ \frac{g_{m1} + g_{01} + g_{m2} + g_{\pi 2}}{g_{02} \left( g_{01} + g_{\pi 2} \right)} \right] - V_{\text{IN}} \cdot \left[ \frac{g_{m1} \left( g_{02} + g_{m2} \right)}{g_{02} \left( g_{\pi 2} + g_{01} \right)} \right]$$
It thus follows for the npn bipolar structure that:

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

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

\[ g_{\pi CC} = g_{\pi 1} \]
Cascode Configuration

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

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

\[ g_{\pi CC} = g_{\pi1} \]

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

\[ g_{0CC} \approx \frac{g_{01}}{\beta} \]

- 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
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!

What happens to the gain if a transistor-level current source is used for $I_B$?
Cascode Configuration
Cascode Configuration

\[ \text{Q1} \quad \text{Q2} \quad V_{XX} \quad V_{IN} \quad V_{SS} \]

\[ V_{CC} \quad V_{YY} \quad Q_{3} \]

\[ V_{OUT} \]

\[ \text{Q1} \quad \text{Q2} \quad V_{IN} \quad V_{OUT} \]

\[ V_{CC} \quad V_{YY} \quad Q_{3} \]

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

It thus follows that

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

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

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

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

Thus

• This is still a factor of 2 better than that of the CE amplifier with transistor current source

• It only requires one additional transistor

• But it's not nearly as good as the gain the cascode circuit seemed to provide
Can we design a better current source?
In particular, one with a higher output impedance?!

Gain limited by output impedance of current source!!
Better current sources

Need a higher output impedance than $g_0$.

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
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.
Cascode Configuration Comparisons

Can we use more cascoding to further increase the gain?

\[ A_V = \frac{-g_m}{g_0} \]  
\[ A_V = \text{-8,000} \]

\[ A_V \approx \frac{-g \cdot m_1}{2g \cdot 0_1} \]  
\[ A_V = \text{-4,000} \]

\[ A_V \approx -\left[ \frac{g_{m1}}{g_{01}} \right] \beta \]  
\[ A_V = \text{-800,000} \]

\[ A_V \approx -\left[ \frac{g_{m1}}{g_{01}} \right] \frac{\beta}{2} \]  
\[ A_V = \text{-400,000} \]
High Gain Amplifiers Seldom Used Open Loop

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

\[ A_V = -8,000 \]

\[ A_V = -400,000 \]

If \( A_V = -400,000 \) and \( V_{IN} \) increases by 1mV, what would happen at the output?

\[ V_{OUT} \text{ would decrease by } 400,000 \times 1\text{mV} = -400V \]
The Cascode Amplifier (consider n-ch MOS version)

\[ V_{\text{IN}} \rightarrow M_1 \rightarrow M_2 \rightarrow V_{\text{OUT}} \]

\[ V_{\text{XX}} \]

\[ V_{\text{CC}} \]

\[ V_{\text{SS}} \]

**Discuss**

Same issues for biasing with current source as for BJT case

With cascode current source, gain only drops by a factor of 2

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

\[
g_{0CC} = \begin{bmatrix} 
\frac{g_{01}g_{02}}{g_{m2}} 
\end{bmatrix}
\]
The Cascode Amplifier (consider n-ch MOS version)

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

[Diagram of the cascode amplifier with input voltage \( V_{\text{IN}} \), output voltage \( V_{\text{OUT}} \), and power supply \( V_{\text{CC}} \).]

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

\[ A_{\text{VCC}} \approx -\frac{1}{2} \left[ \frac{g_{m1}g_{m2}}{g_{01}g_{02}} \right] \]

Discuss
Current Source Summary (BJT)

**Basic**

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

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

- $g_0 \approx g_{01}$

**Cascode**

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

- $V_{CC}$
- $V_{YY}$
- $V_{XX}$

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

**Basic**

- $V_{YY}$
- $V_{SS}$
- $M_1$
- $I_X$

**Cascode**

- $V_{XX}$
- $V_{YY}$
- $M_1$
- $M_2$
- $V_{SS}$
- $I_X$

$g_0 \approx g_{01}$

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

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

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

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

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

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

\[ A_V \approx -\frac{1}{2} \frac{g_m}{g_0} \]

\[ A_V \approx -\left( \frac{g_m}{g_0} \right) \beta \]

- 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