EE 330
Lecture 33

- High Gain Amplifiers
- Current Sources and Mirrors
- The Cascode Configuration
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?
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

\[ I_k = \left[ \frac{A_{Ek}}{A_{E0}} \right] I_0 \]
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

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

nnpn current mirror amplifier

\[ i_{\text{out}} = ? \]
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 \( i_{\text{in}} > -I_{\text{BS}} \))
Current Sources/Mirrors

n-p-n Current Mirror

n-channel Current Mirror

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

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

If process parameters are matched, it follows that

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

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

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

npn Current Mirror

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

n-channel Current Mirror
Layout of Current Mirrors

Example with $M = 2$

Standard layout

Gate area after fabrication depicted
Layout of Current Mirrors

Example with $M = 2$

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

Standard layout

Better Layout

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

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

Example with $M = 2$

Standard layout

Better Layout

Even Better Layout

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

Amplifies both positive and negative currents

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

\[ I_k = \left[ \frac{W_k}{W_0} \frac{L_0}{L_k} \right] I_0 \]

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
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

\[ I_X = J S A E e^\frac{V_{XX}}{V_t} \]

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

Basic Bipolar Current Sources

\[ V_{CC} \]

\[ I_X \]

- 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

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

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

\[ A_V \approx \frac{-g_{m1}}{2g_{01}} \]
A gain of 8000 can be made even larger with an even better voltage gain of approximately 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

\[
\begin{align*}
(V_X + V_2)g_{02} + V_2g_m &= I_X \\
V_1g_m - V_2(g_{01} + g_{\pi2}) &= I_X
\end{align*}
\]

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

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

and

\[
V_X = I_X \cdot \left[ \frac{g_{01} + g_{02} + g_{\pi2} + g_m}{g_{02}(g_{01} + g_{\pi2})} \right] - V_{IN} \cdot \left[ \frac{g_{m1}(g_{02} + g_m)}{g_{02}(g_{\pi2} + g_{01})} \right]
\]

Discuss

Standard Form for Amplifier Two-Port

\[
\begin{align*}
V_1 &= i_1R_{IN} + A_{VR}v_2 \\
V_2 &= i_2R_O + A_{V0}v_1
\end{align*}
\]
Cascode Configuration

Two-port model of cascode amplifier

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

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

It thus follows for the npn bipolar structure that:

\[ A_{VCC} = - \left[ \frac{g_{m1} (g_{02} + g_{m2})}{g_{02} (g_{\pi 2} + g_{01})} \right] \approx \left[ \frac{g_{m1} g_{m2}}{g_{02} g_{\pi 2}} \right] \]

\[ g_{0CC} = \left[ \frac{g_{02} (g_{01} + g_{\pi 2})}{g_{01} + g_{02} + g_{\pi 2} + g_{m2}} \right] \approx \left[ \frac{g_{02} g_{\pi 2}}{g_{m2}} \right] \]

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

\[
A_{VCC} \approx - \frac{g_m1g_m2}{g_{02}g_{\pi2}}
\]

\[
g_{0CC} \approx \frac{g_{02}g_{\pi2}}{g_m2}
\]

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

\[
A_{VCC} \approx - \left[ \frac{g_m1}{g_02} \beta \right] \approx - \left[ \frac{g_m1}{g_01} \right] \beta
\]

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

A_{VCC} \approx \left[ \frac{g_{m1}}{g_{02}} \right] \beta = \left[ \frac{2V_{AF}}{V_t} \right] \beta = [-8000] \times 100

A_{VCC} \approx -800,000

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

\[ Q_1 \]
\[ Q_2 \]
\[ \text{V}_{XX} \]
\[ \text{VIN} \]
\[ \text{V}_{SS} \]
\[ \text{IB} \]
\[ \text{VCC} \]
\[ \text{V}_{OUT} \]

\[ Q_3 \]
\[ \text{V}_{YY} \]
\[ \text{VCC} \]
\[ \text{V}_{OUT} \]
Cascode Configuration

$V_{CC}$

$V_{YY}$

$Q_3$

$V_{XX}$

$Q_2$

$Q_1$

$V_{IN}$

$V_{SS}$

$V_{OUT}$

$V_{OUT}$

$V_{IN}$
High-gain amplifier comparisons

It thus follows that

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

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

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

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

\[ A_V \approx -\left( \frac{g_{m1}}{g_{01}} \right) \approx -8000 \]

- 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 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!!

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.

\[ A_V = -\left[ \frac{g_{m1}}{g_{o1}} \right] \frac{\beta}{2} \]

\[ A_V = -\left[ 8000 \right] \frac{100}{2} \approx -400,000 \]
Cascode Configuration Comparisons

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

\[ A_V = -8,000 \]

\[ A_V = -4,000 \]

\[ A_V = -800,000 \]

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

\[ A_V = -400,000 \]

Can we use more cascoding to further increase the gain?
The Cascode Amplifier (consider n-ch MOS version)

\[ V_{CC} \]
\[ I_B \]
\[ V_{OUT} \]

\[ V_{XX} \]
\[ M_1 \]
\[ M_2 \]
\[ V_{IN} \]
\[ V_{SS} \]

\[ A_{VCC} = -\left( \frac{g_m1g_m2}{g_01g_02} \right) \]
\[ g_{0CC} = \left[ \frac{g_01g_02}{g_m2} \right] \]

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)

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

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

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

Basic

Q1
V_YY
V_SS
I_x

V_CC
V_YY
Q1
I_x

Cascode

Q2
V_XX
V_YY
Q1
V_SS
I_x

Q1
V_YY
V_CC
I_x

Basic Cascode

\( g_0 \approx g_{01} \)

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

**Basic**

\[ g_0 \approx g_{01} \]

**Cascode**

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

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

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

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

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

\[ A_V = -\left[ \frac{g_{m1}}{g_{01}} \right] \frac{\beta}{2} \]
End of Lecture 33