EE 330
Lecture 32

• High-Gain Amplifiers
  – Current Source Load on Common Emitter
  – Cascode
  – Cascades

• Current Sources
Review from Last Time

High-gain amplifier

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

\[ A_V = \frac{-I_{CQ}}{V_t I_{CQ}/V_{AF}} = -\frac{V_{AF}}{V_t} \]

\[ A_V = -\frac{V_{AF}}{V_t} \approx \frac{200V}{25mV} = -8000 \]

This gain is very large!
Review from Last Time

Current Sources/Mirrors

If the base currents are neglected

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

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

\[ I_1 = J_S A_{E1} e^{\frac{V_{BE1}}{V_t}} \]

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

\[ I_1 \approx \left( \frac{A_{E1}}{A_{E0}} \right) I_0 \]

Behaves as a current source!
Current Sources/Mirrors

- Multiple Outputs Possible
- Can be built at sourcing or sinking currents
- Also useful as a current amplifier
- MOS counterparts work very well and are not plagued by base current
Review from Last Time

High-gain amplifier

\[ A_V \approx -8000 \]

How can we build the ideal current source?

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

Basic Bipolar Current Sinks

Basic Bipolar Current Sources

Very practical methods for biasing the BJTs can be used. Current Mirrors often used for generating sourcing and sinking currents.
Basic Current Sources and Sinks

Small-signal Model of BJT Current Sinks and Sources

Review from Last Time

Small-signal model of all other BJT Sinks and Sources are the same
Review from Last Time

High-gain amplifier

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

\[ A_V = \frac{-g_{m1}}{g_{01} + g_{02}} \approx \frac{-g_{m1}}{2g_{01}} \]
Nonideal current source decreased the gain by a factor of 2

But the voltage gain is still quite large

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

Can the gain be made even larger?

The Cascode Configuration

\[ V_{XX} \rightarrow Q_2 \rightarrow Q_1 \rightarrow V_{YY} \]

\[ V_{XX} \rightarrow M_2 \rightarrow M_1 \rightarrow V_{YY} \]
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
The Cascode Amplifier (consider npn BJT version)
The Cascode Amplifier (consider npn BJT version)

Instead of just determining the voltage gain, we will obtain the two-port model for the cascode amplifier.
The Cascode Amplifier (consider npn BJT version)

From the two-port model of the cascode, the $A_V$ in the model is simply the voltage gain of the cascode amplifier and $g_{0CC}$ is the output conductance of the cascode amplifier. Instead of just determining the voltage gain, we will obtain the two-port model for the cascode amplifier.
The Cascode Amplifier (consider npn BJT version)
Observing $V_1 = V_{IN}$ and eliminating $V_2$, we obtain

$$V_X = \frac{-g_{m1}(g_{o2} + g_{m2})}{g_{o2}(g_{\pi2} + g_{o1})} V_1 + \frac{g_{o1} + g_{o2} + g_{\pi2} + g_{m2}}{g_{o2}(g_{o1} + g_{\pi2})} I_X$$
Cascode Configuration

Two-port model of cascode amplifier

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

It thus follows for the npn bipolar structure that:

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

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

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

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

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

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

\[ V_{SS} \rightarrow V_{XX} \rightarrow V_{YY} \rightarrow V_{CC} \]

\[ V_{IN} \rightarrow Q_1 \rightarrow Q_2 \rightarrow Q_3 \rightarrow V_{OUT} \]
High-gain amplifier comparisons

It thus follows that

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

But $g_{0CC} \approx g_{03}/\beta$

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

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
• It only requires one additional transistor
• But its 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?
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

\[
\begin{align*}
Q_1 & \quad V_{XX} \quad V_{YY} \quad V_{SS} \\
Q_2 & \quad V_{XX} \quad V_{YY} \quad V_{SS} \\
M_1 & \quad V_{XX} \quad V_{YY} \quad V_{SS} \\
M_2 & \quad V_{XX} \quad V_{YY} \quad V_{SS} \\
\end{align*}
\]
Cascode current sources

All have the same small-signal model

\[ g_{0CC} = \frac{g_{02} (g_{01} + g_{\pi2})}{g_{01} + g_{02} + g_{\pi2} + g_{m2}} \]
For the BJT cascode current sources

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

\[ V_{\text{OUT}} = \frac{V_{\text{IN}} - V_{\text{SS}}}{1 + \frac{V_{\text{OUT}}}{V_{\text{ZZ}}}} \]
Thus

Recall

Thus

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

\[
A_{VCC} \approx - \left[ \frac{g_{m1}}{g_{01}} \right] \beta, \quad g_{0CC} \approx \left[ \frac{g_{02}g_{\pi2}}{g_{m2}} \right], \quad g_{03CC} = \left[ \frac{g_{02}g_{\pi2}}{g_{m2}} \right]
\]

\[
A_V = A_{VCC} \left[ \frac{g_{0CC}}{g_{03CC} + g_{0CC}} \right] = \frac{A_{VCC}}{2} = - \left[ \frac{g_{m1}}{g_{01}} \right] \beta \frac{1}{2}
\]
Cascode Configuration

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

This gain is very large and is a factor of 2 below that obtained with an ideal current source biasing.
Can we use more cascoding to further increase the gain?
Cascode Configuration

The double cascode

- Further gain enhancement
- Further output impedance increase
- Limited applications, particularly at lower voltages, because signal swings at outputs are small

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

\[ g_{0CC} \approx \frac{g_{01}}{\beta^2} \]
The Cascode Amplifier (consider n-ch MOS version)

- Same functional form for gain and output conductance except $g_{\pi}=0$
- Simplifications functionally different!

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

\[
g_{0CC} = \left[ \frac{g_{02}(g_{01}+g_{\pi2})}{g_{01}g_{02}+g_{\pi2}+g_{m2}} \right] \approx \left[ \frac{g_{01}g_{02}}{g_{m2}} \right]
\]
The Cascode Amplifier (consider n-ch MOS version)

\[ \text{Same issues for biasing with current source as for BJT case} \]
The Cascode Amplifier

- Operational amplifiers often built with basic cascode configuration
- 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
Cascade Configurations

- Large gains can be obtained by cascading
- Gains are multiplicative (when loading is included)
- Some attention is needed to biasing but it is manageable
- Minor variant of the two-stage cascade often used to built Op Amps

Compensation of two-stage cascade needed if feedback is applied to maintain stability
Three or more stages are seldom cascaded because no really good way to compensate to maintain stability
Differential Amplifiers

Basic operational amplifier circuit
Differential Amplifiers

Assume left-right matching
i.e. circuit (except for excitations) is symmetric
Differential Amplifiers

Common Mode Excitation

\[ V_{C} = \frac{V_{1} + V_{2}}{2} \]
\[ V_{D} = V_{2} - V_{1} \]

Difference Mode Excitation

\[ V_{1} = V_{C} - \frac{V_{D}}{2} \]
\[ V_{2} = V_{C} + \frac{V_{D}}{2} \]

Analysis of two circuits is generally much easier than analysis of original circuit.
Differential Amplifiers

Common Mode Excitation

\[ V_{OUTQ} = V_{DD} - R_1 \frac{I_{TAIL}}{2} \]

\[ A_C = \frac{V_{OUTC}}{V_C} = 0 \]

(A\textsubscript{C} will not be quite 0 if the tail current source is nonideal)
Theorem: The small-signal voltage of a symmetric linear network excited differentially is always 0 at every node on the axis of symmetry.
Differential Amplifiers

Difference Mode Excitation

Difference Mode Half Circuit

Theorem: The small-signal voltage of a symmetric linear network excited differentially is always 0 at every node on the axis of symmetry

\[ A_D = \frac{V_{OUT2}}{V_D} = -\frac{g_{m1} R_1}{2} \]
End of Lecture 32