EE 435

Lecture 7:

High-Gain Single-Stage Op Amps
How do the transfer characteristics relate to the signal swing?

For this circuit, high gain and large output signal swing for small $V_{EB1}$. 

Review from last lecture:
Review from last lecture:

Signal Swing of Single-Stage Op Amp

For high-gain amplifiers, $V_d$ is inherently very small so are only concerned about output signal swing vs $V_{iC}$

Generally large swings come at expense of other desirable characteristics
Review from last lecture:
Signal Swing of Single-Stage Op Amp

What type of signal swing is needed?

Wide $V_{iC}$ and $V_{OUT}$ range

Expected for catalog parts and overall I/O in many applications

Narrow $V_{iC}$ and wide $V_{OUT}$ range

Acceptable when $V_{iC}$ is fixed

Narrow $V_{OUT}$ and wide $V_{iC}$ range

Acceptable when followed by high-gain stage

Narrow $V_{iC}$ and $V_{OUT}$ range

Acceptable when $V_{iC}$ fixed and followed by high-gain stage
Review from last lecture:
Signal Swing of Single-Stage Op Amp
Review from last lecture:

**Design space for single-stage op amp**

Performance Parameters in Practical Parameter Domain \( \{ V_{EB1}, V_{EB2}, V_{EB5}, P \} \):

\[
A_0 = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{2}{V_{EB1}} \right)
\]

\[
GB = \left( \frac{P}{V_{DD}C_L} \right) \left( \frac{2}{V_{EB1}} \right)
\]

\[
SR = \frac{P}{(V_{DD} - V_{SS})C_L}
\]

\[
V_{OUT} < V_{DD} - |V_{EB3}|
\]

\[
V_{OUT} > V_{iC} - V_{T2}
\]

\[
V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|
\]

\[
V_{iC} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}
\]

**Simple Expressions in Practical Parameter Domain**
Review from last lecture:

Design space for single-stage op amp

Performance Parameters in Natural Parameter Domain \{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, I_T \}:

\[
A_{V0} = \left[ \frac{4\mu_n C_{OX}}{\lambda_1 + \lambda_3} \right] \left[ \frac{W_1}{L_1} \right] \left[ \frac{\sqrt{I_T}}{L_1} \right]
\]

\[
SR = \frac{I_T}{C_L}
\]

\[
GB = \left[ \frac{\sqrt{\mu_n C_{OX}}}{C_L} \right] \left[ \frac{W_1}{L_1} \right] \left[ \frac{\sqrt{I_T}}{L_1} \right]
\]

\[
V_{OUT} < V_{DD} - \frac{\sqrt{I_T}}{\sqrt{\mu_n C_{OX}}} \sqrt{\frac{W}{L}}
\]

\[
V_{OUT} > V_{ic} - V_{T2}
\]

Complicated Expressions in Practical Parameter Domain
Review from last lecture:

Basic Op Amp Design

• Fundamental Amplifier Design Issues
• Single-Stage Low Gain Op Amps
• Single-Stage High Gain Op Amps
• Other Basic Gain Enhancement Approaches
• Two-Stage Op Amp
Review from last lecture:

Single-Stage High Gain Op Amps

How can the gain of the op amp be increased?

Recall from Quarter-Circuit Concept

\[ A_{VO} = \frac{1}{2} \frac{-G_{M1}}{G_1 + G_2} \]

A possible strategy:

Increase \( G_{M1} \) or Decrease \( G_1 \) (and \( G_2 \)) in Quarter Circuit or Both
Review from last lecture:

Single-Stage High-Gain Op Amps

• If the output conductance can be decreased without changing the transconductance, the gain can be enhanced

• Will concentrate on quarter-circuits and extend to op amps
Background

Determination of 2-port parameters

Method 1  Open-Short Termination Approach

Method 2  Load Termination Approach
Determination of 2-port parameters

Determination of \( \{g_{o1}, g_{o2}, g_{M1}, g_{M2}\} \)

Method 1  Open-Short Termination Approach

By structural symmetry, repeat to obtain \( g_{m1} \) and \( g_{o1} \)
Background

Determination of 2-port parameters

Determination of \{g_{o1}, g_{o2}, g_{M1}, g_{M2}\}

Method 2  Load Termination Approach

express the gain \( A(s) \) as in form

\[
A(s) = \frac{a_0}{sC_L + b_0}
\]

observe

\[
v_2(g_{o2} + sC_L) + g_{M2} V_{TST} = 0
\]

\[
A(s) = \frac{v_2(s)}{V_{TST}(s)} = -\frac{g_{M2}}{sC_L + g_{o2}}
\]
Background

Analysis Cascode Amplifier

\[ V_{OUT}(g_{o2} + sC_L) + g_{m2}V_2 = V_Xg_{o2} \]
\[ V_X(g_{o1} + g_{o2}) + g_{m1}V_1 - g_{m2}V_2 = V_{OUT}g_{o2} \]
\[ V_2 = -V_X \]
\[ V_1 = V_{IN} \]

\[ V_X, V_1 \text{ and } V_2 \text{ can be eliminated from these 4 equations} \]
Analysis of Cascode Amplifier

Background

\[
V_{OUT}(g_{o2} + sC_L) + g_{m2}V_2 = V_xg_{o2}
\]
\[
V_x(g_{o1} + g_{o2}) + g_{m1}V_1 - g_{m2}V_2 = V_{OUT}g_{o2}
\]
\[
V_2 = -V_x
\]
\[
V_1 = V_{IN}
\]

\[
V_{OUT}(g_{o2} + sC_L) - g_{m2}V_x = V_xg_{o2}
\]
\[
V_x(g_{o1} + g_{o2}) + g_{m1}V_{IN} + g_{m2}V_x = V_{OUT}g_{o2}
\]

\[
\frac{V_{OUT}}{V_{IN}} = \frac{-g_{m1}(g_{o2} + g_{m2})}{sC_L(g_{o1} + g_{o2} + g_{m2}) + g_{o1} + g_{o2}} \approx \frac{-g_{m1}g_{m2}}{sC_Lg_{m2} + g_{o1}g_{o2}}
\]

for A large:

\[
\frac{V_{OUT}}{V_{IN}} \approx \frac{g_{m1}}{sC_L + g_{o1}\left(\frac{g_{o2}}{g_{m2}}\right)}
\]

\[g_{MEQ}\]

\[g_{OEQ}\]
High output impedance quarter-circuits

\[
g_{o\text{EQ}} \approx g_{o1} \left[ \frac{g_{o3}}{g_{m3}} \right]
\]

\[
g_{m\text{EQ}} \approx g_{m1}
\]

Output conductance has been decreased!

\[
A_v(s) \approx \frac{-g_{m1}}{sC_L + g_{o1} \left[ \frac{g_{o3}}{g_{m3}} \right]}
\]

\[
A_{V0} \approx \left( \frac{g_{m1}}{g_{o1}} \right) \left[ \frac{g_{o3}}{g_{o2}} \right]
\]

\[
GB \approx \frac{g_{m1}}{C_L}
\]
High output impedance quarter-circuits

\[ A_v0 = \left[ \frac{2}{\lambda_1 V_{EB1}} \right] \cdot \left[ \frac{2}{\lambda_3 V_{EB3}} \right] \]

\[ GB = \left( \frac{2P}{V_{DD} C_L} \right) \cdot \left( \frac{1}{V_{EB1}} \right) \]

How does this compare with previous amplifier?

\[ A_v0 = \left[ \frac{2}{\lambda V_{EB}} \right] \]

\[ GB = \left( \frac{2P}{V_{DD} C_L} \right) \cdot \left( \frac{1}{V_{EB}} \right) \]

Substantial increase in dc gain

No improvement in GB but also no deterioration in GB!
High output impedance quarter-circuits

Cascode Amplifier
(small-signal equiv)
High output impedance quarter-circuits

Cascode Amplifier

Quarter Circuit

Counterpart Circuit
Telescopic Cascode Op Amp

Needs CMFB Circuit for $V_{B1}$ or $V_{B5}$
Either single-ended or differential outputs
Can connect counterpart as current mirror to eliminate CMFB
Recall:

**Determination of op amp characteristics from quarter circuit characteristics**

Small signal Quarter Circuit

\[
A_{\text{VOQC}} = -\frac{G_M}{G}
\]

\[
BW = \frac{G}{C_L}
\]

\[
GB = \frac{G_M}{C_L}
\]

Small signal differential amplifier

\[
A_{\text{V0}} = \frac{-G_{M1}}{2(G_1 + G_2)}
\]

\[
BW = \frac{G_1 + G_2}{C_L}
\]

\[
GB = \frac{G_{M1}}{2C_L}
\]

Note: Factor of 4 reduction of gain
Telescopic Cascode Op Amp

Single-ended operation

\[ g_{OQC} = \] 

\[ g_{OCC} = \]

\[ g_{mQC} = \]
Telescopic Cascode Op Amp

Single-ended operation

\[
A_o = \frac{-g_{m1}}{2} \left( \frac{g_{o1}}{g_{m3}} + \frac{g_{o5}}{g_{m7}} \right)
\]

\[
G_B = \frac{g_{m1}}{2C_L}
\]
Telescopic Cascode Op Amp

Single-ended operation

\[
A_o = \frac{-g_{m1}}{2} + \frac{g_{o1}}{g_{m3}} + \frac{g_{o3}}{g_{m3}} + \frac{g_{o5}}{g_{m7}} + \frac{g_{o7}}{g_{m7}}
\]

\[
GB = \frac{g_{m1}}{2C_L}
\]

This circuit is widely used!!

(CMFB circuit not shown)
Telesscopic Cascode Op Amp

• Tail bias current generator shown
• $I_T$ often one of many outputs for current mirror
• $I_B$ and $M_{12}$ often common to many blocks

(CMFB circuit not shown)
Telescopic Cascode Op Amp

- Current-Mirror p-channel Bias to Eliminate CMFB
- Only single-ended output available

Standard p-channel Cascode Mirror

Wide-Swing p-channel Cascode Mirror
Telescopic Cascode Op Amp

- Differential Output
- CMFB to establish $V_{B1}$ or $V_{B5}$ needed
- Tail current generally generated with current mirror
Telescopic Cascode Op Amp

Signal Swing and Power Supply Limitations

There are a minimum of 2 $V_{DSAT}$ drops between $V_{OUT}$ and $V_{DD}$ and a minimum of 3 $V_{DSAT}$ drops between $V_{OUT}$ and $V_{SS}$.

Thus, there are a minimum of 5 $V_{DSAT}$ drops between $V_{DD}$ and $V_{SS}$.

This establishes a lower bound on $V_{DD} - V_{SS}$ and it will be reduced by the p-p signal swing on the output.
Telescopic Cascode Op Amp

n-channel inputs

p-channel inputs
Are there other high output impedance circuits that can be used as quarter circuits?
Are there other high output impedance circuits that can be used as quarter circuits?

I recall the regulated cascode circuits have this property
High output impedance quarter-circuits

Regulated Cascode Amplifier
or “Gain Boosted Cascode”

(A is usually a simple amplifier, often the reference op amp with + terminal connected to the desired quiescent voltage)
Background

Analysis of Regulated Cascode Amplifier

\[ V_{OUT} (g_{o2} + sC_L) + g_{m2} V_2 = V_X g_{o2} \]
\[ V_X (g_{o1} + g_{o2}) + g_{m1} V_1 - g_{m2} V_2 = V_{OUT} g_{o2} \]
\[ V_2 = -AV_X - V_X \]
\[ V_1 = V_{IN} \]

\( V_X, V_1 \) and \( V_2 \) can be eliminated from these 4 equations.
Background

Analysis of Regulated Cascode Amplifier

\[
\begin{align*}
V_{\text{OUT}}(g_{o_2} + sC_L) + g_{m_2}V_2 &= V_X g_{o_2} \\
V_X(g_{o_1} + g_{o_2}) + g_{m_1}V_1 - g_{m_2}V_2 &= V_{\text{OUT}} g_{o_2} \\
V_2 &= -AV_X - V_X \\
V_1 &= V_{\text{IN}} \\
V_{\text{OUT}}(g_{o_2} + sC_L) - g_{m_2}V_X(1 + A) &= V_X g_{o_2} \\
V_X(g_{o_1} + g_{o_2}) + g_{m_1}V_{\text{IN}} + g_{m_2}V_X(1 + A) &= V_{\text{OUT}} g_{o_2}
\end{align*}
\]

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{-g_{m_1}(g_{o_2} + g_{m_2}[1 + A])}{sC_L(g_{o_1} + g_{o_2} + g_{m_2}[1 + A]) + g_{o_1}g_{o_2}} \approx \frac{-g_{m_1}g_{m_2}[1 + A]}{sC_Lg_{m_2}[1 + A] + g_{o_1}g_{o_2}} = \frac{-g_{m_1}}{sC_L + \frac{g_{o_1}g_{o_2}}{g_{m_2}[1 + A]}}
\]

for A large:

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx \frac{g_{m_1}}{sC_L + g_{o_1}\left(\frac{g_{o_2}}{g_{m_2}}\right)\left(\frac{1}{A}\right)}
\]

\(g_{\text{MEQ}}\)

\(g_{\text{OEQ}}\)
High output impedance quarter-circuits

Regulated Cascode Amplifier
or “Gain Boosted Cascode”

\[ g_{\text{OEQ}} \approx g_{o1} \left[ \frac{g_{o3}}{g_{m3}(1+A)} \right] \]

\[ g_{m\text{EQ}} \approx g_{m1} \]

Output conductance has been decreased even more!

\[ A_v(s) \approx -\frac{g_{m1}}{sC_L + g_{o1} \left( \frac{g_{o3}[1+A]}{g_{m3}} \right)} \]

\[ A_0 \approx \left( \frac{g_{m1}}{g_{o1}} \right) \cdot \left[ \frac{g_{m3}(1+A)}{g_{o3}} \right] \]

\[ GB \approx \frac{g_{m1}}{C_L} \]

Same GB as for previous two circuits
Gain-Boosted Telescopic Cascode Op Amp

Needs CMFB Circuit for $V_{b1}$
Either single-ended or differential outputs
Can connect counterpart as current mirror to eliminate CMFB
Use differential op amp to facilitate biasing of cascode device
Gain-Boosted Telescopic Cascode Op Amp

Single-ended operation

\[ g_{OQC} = \] 

\[ g_{OCC} = \] 

\[ g_{mQC} = \]
Gain-Boosted Telescopic Cascode Op Amp

This is modestly less efficient at generating GB because now power is consumed in both the cascode devices and the boosting amplifier.
Gain-Boosted Telescopic Cascode Op Amp

Elimination of need for CMFB Circuit

This is modestly less efficient at generating GB because now power is consumed in both the cascode devices and the boosting amplifier

\[ A_o = \frac{-g_{m1}}{g_{o1} A_1 g_{o3} + g_{o5}} \frac{A_3 g_{o7}}{g_{m7}} \]

\[ GB = \frac{g_{m1}}{C_L} \]
Gain-Boosted Telescopic Cascode Op Amp

Signal Swing and Power Supply Limitations

A minimum of 5 $V_{DSAT}$ drops between $V_{DD}$ and $V_{SS}$

This establishes a lower bound on $V_{DD}-V_{SS}$ and it will be reduced by the p-p signal swing on the output.
Gain-Boosted Telescopic Cascode Op Amp
(with or w/o current mirror counterpart circuits)

Advantages:

Significant increase in dc gain

Limitations:

- Signal swing (4VD_{SAT} + V_T between V_{DD} and V_{SS})
- Reduction in GB power efficiency
  - some current required to bias “A” amplifiers
- additional pole in “A” amplifier
  -may add requirements for some compensation
- Area Overhead for 4 transistors and 4 amplifiers
  -actually minor concern since performance will usually justify these resources
End of Lecture 7