EE 435

Lecture 8:

High-Gain Single-Stage Op Amps

-folded cascode structures
Review from last lecture:

Telescopic Cascode Op Amp

![Circuit Diagram]

Single-ended operation

\[
A_o = \frac{-g_{m1}}{2} \left( \frac{g_{o1}}{g_{m3}} + \frac{g_{o3}}{g_{m5}} + \frac{g_{o7}}{g_{m7}} \right)
\]

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

This circuit is widely used!!
Review from last lecture:

Telescopic Cascode Op Amp

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

\[ V_{IN} \]

\[ M_1 \]

\[ V_{OUT} \]

\[ C_L \]

\[ V_{OUT} \]

\[ V_X \]

\[ g_{M2} V_2 \]

\[ g_{o2} \]

\[ g_{M1} V_1 \]

\[ g_{o1} \]

\[ V_{OUT} (g_{o2} + sC_L) + g_{m2} V_2 = V_X g_{o2} \]

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

\[ V_2 = -AV_X - V_X \]

\[ V_1 = V_{IN} \]

\[ V_X, V_1 \text{ and } V_2 \text{ can be eliminated from these 4 equations} \]
Background

Analysis of Regulated Cascode Amplifier

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

\[
V_{\text{OUT}}(g_{o2} + sC_L) - g_{m2}V_X(1 + A) = V_Xg_{o2}
\]
\[
V_X(g_{o1} + g_{o2}) + g_{m1}V_{\text{IN}} + g_{m2}V_X(1 + A) = V_{\text{OUT}}g_{o2}
\]

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{-g_{m1}(g_{o2} + g_{m2}[1 + A])}{sC_L(g_{o1} + g_{o2} + g_{m2}[1 + A]) + g_{o1}g_{o2}} \approx \frac{-g_{m1}g_{m2}[1 + A]}{sC_Lg_{m2}[1 + A] + g_{o1}g_{o2}} = \frac{-g_{m1}}{sC_L + \frac{g_{o1}g_{o2}}{g_{m2}[1 + A]}}
\]

for A large:

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx \frac{g_{m1}}{sC_L + g_{o1}\left(\frac{g_{o2}}{g_{m2}}\right)\left(\frac{1}{A}\right)}
\]

\[g_{\text{MEQ}}\]

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

Regulated Cascode Amplifier
or “Gain Boosted Cascode”

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

\[ g_{\text{mEQ}} \approx g_{m1} \]

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

\[ g_{OQC} = \quad \]  

\[ g_{OCC} = \quad \]  

\[ g_{mQC} = \quad \]
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.

\[ A_o = \frac{-g_{m1}}{2g_{o1}A_1g_{o3} + g_{o5}A_3g_{o7}} \]

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

\[ A_o = \frac{-g_{m1}}{g_{o1}A_1g_{o3} + g_{o5}A_3g_{o7}g_{m3}} \]

\[ GB = \frac{g_{m1}}{C_L} \]
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 ($4V_{DSAT} + V_T$ 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
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.

\[
A_o = \frac{-g_{m1}}{2} + \frac{A_1 g_{o3}}{g_{m3}} + g_{o5} \frac{A_3 g_{o7}}{g_{m7}}
\]

\[
GB = \frac{g_{m1}}{2C_L}
\]
End of Lecture 8
Laboratory Support

Offset Voltage

- Systematic Offset Voltage
- Random Offset Voltage
Laboratory Support

Offset Voltage

- Systematic Offset Voltage
- Random Offset Voltage

**Definition:** The output offset voltage is the difference between the desired output and the actual output when $V_{id}=0$ and $V_{ic}$ is the quiescent common-mode input voltage.

\[ V_{OUTOFF} = V_{OUT} - V_{OUTDES} \]

Note: $V_{OUTOFF}$ is dependent upon $V_{ICQ}$ although this dependence is usually quite weak and often not specified.
Laboratory Support

Definition: The input-referred offset voltage is the differential dc input voltage that must be applied to obtain the desired output when $V_{ic}$ is the quiescent common-mode input voltage.

Note: $V_{OFF}$ is usually related to the output offset voltage by the expression

$$V_{OFF} = \frac{V_{OUTOFF}}{A_C}$$

Note: $V_{OFF}$ is dependent upon $V_{ICQ}$ although this dependence is usually quite weak and often not specified.
When differential input op amps are biased with symmetric supply voltages, it is generally assumed that the desired quiescent input voltage is 0V and the desired quiescent output voltage is 0V so $V_{OFF}$ is the differential input voltage needed to make $V_{OUT}=0V$.

The input offset voltage is comprised of two parts, a systematic component and a random component

$$V_{OFF} = V_{OFFSYS} + V_{OSR}$$
Laboratory Support

\[ V_{OFF} = V_{OFFSYS} + V_{OSR} \]

After fabrication there is no distinction made between \( V_{OFFSYS} \) and \( V_{OSR} \) and simply \( V_{OFF} \) is of concern.

\( V_{OSR} \) is determined entirely by random variations in component values from their ideal value and will only be seen in a simulation if deviations are intentionally introduced (Monte Carlo Analysis is often used for predicting \( V_{OSR} \)).

It is expected that \( V_{OFFSYS} \) should be small (much smaller than \( V_{OSR} \)) and it is the designer’s responsibility to make this small.
Laboratory Support

\[ V_{\text{OFF}} = V_{\text{OFFSYS}} + V_{\text{OSR}} \]

It is not necessary to make \( V_{\text{OFFSYS}} = 0 \) although this can and is often done by making a minor tweak of matching critical parameters after the design of the op amp is almost complete.

\( V_{\text{OFFSYS}} \) can also be set to 0 by using a degree of freedom of the amplifier design variables but this is generally an unwise use of degrees of freedom (although some textbooks including Martin and Johns in Sec 5.1 do this!)
Laboratory Support

By symmetry, to force $V_{\text{OUT}} = 0$, it is necessary to have $V_{D3} = 0$

(If no mismatch is introduced, will be seeing only effects of systematic offset)

- Making $V_{D3} = 0$ sets $|V_{E3}| = V_{DD} + V_{Tp}$ and results in the use of one degree of freedom!
- Making $V_{E3}$ so large will severely limit the voltage swing at $V_{\text{OUT}}$
- This shows why it is not wise to use a degree of freedom to make the systematic offset voltage 0
Laboratory Support

Can sweep a voltage in simulator at gate of $M_1$ to make $V_{OUT} = 0$

This is the systematic offset voltage

Can simply add the systematic offset voltage to input throughout rest of the design phase and then remove after design is complete or tweak at end of design to eliminate systematic offset.
Laboratory Support

Usually $V_{OFF}$ will change if changes in any design variables are made so re-simulation will be needed to get the correct value of $V_{OFF}$

If $V_{OFF}$ is not included, ac simulation of open-loop amplifier will usually not give desired results because small-signal models will be developed in simulator at incorrect operating point (often even in incorrect region of operation)

Alternative is to do ac simulations by embedding op amp into a FB configuration that will inherently compensate for offset voltage but issue of compensation must be addressed for amplifiers with two or more poles
Are there other useful high output impedance circuits that can be used for the quarter circuit?

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

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

\[ GB = \frac{G_{M1}}{2C_L} \]
What circuit is this?

Cascode Amplifier
Often termed a “Folded Cascode Amplifier”
Same small-signal performance as other
But a biasing problem!!
What circuit is this?

Folded Cascode Amplifier

Biased Folded Cascode
What circuit is this?

Biased Folded Cascode

Implementation of Biased Folded Cascode
Biased Folded Cascode Quarter Circuit

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx -\frac{g_{m1}}{sC_L + (g_{o1} + g_{o5}) \left( \frac{g_{o3}}{g_{m3}} \right)}
\]

\[
A_{V0} = \frac{g_{m1}}{ (g_{o1} + g_{o5}) g_{o3}} \cdot \frac{g_{m3}}{g_{o3}}
\]

\[
G_B = \frac{g_{m1}}{C_L}
\]
## Basic Amplifier Structure Comparisons

<table>
<thead>
<tr>
<th>Structure</th>
<th>Small Signal Parameter Domain</th>
</tr>
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<tbody>
<tr>
<td>Common Source</td>
<td>( A_{VO} = \frac{g_m}{g_o} )</td>
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<tr>
<td>Cascode</td>
<td>( A_{VO} = \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}} )</td>
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<td>Regulated Cascode</td>
<td>( A_{VO} \approx \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}} A )</td>
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<tr>
<td>Folded Cascode</td>
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<td>$A_{vo} = \left( \frac{2}{\lambda} \right) \left( \frac{1}{V_{EB}} \right)$</td>
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<td><strong>Cascode</strong></td>
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<td>$A_{vo} = \left( \frac{4}{\lambda_1 \lambda_3} \right) \left( \frac{1}{V_{EB1} V_{EB3}} \right)$</td>
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<tr>
<td><strong>Regulated Cascode</strong></td>
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<td>$A_{vo} \approx \left( \frac{4}{\lambda_1 \lambda_3} \right) \left( \frac{A}{V_{EB1} V_{EB3}} \right)$</td>
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<td>$\Theta =$ pct power in A</td>
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<td>$A_{vo} \approx \left( \frac{4\theta}{(\theta \lambda_1 + \lambda_5) \lambda_3 V_{EB1} V_{EB3}} \right)$</td>
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<td>$\Theta =$ fraction of current of $M_5$ that is in $M_1$</td>
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Biased Cascode Amplifier

Quarter Circuit

Counterpart Circuit
Folded Cascode Amplifier

QUARTER CIRCUIT

Op Amp
Folded Cascode Amplifier (redrawn)

These transistors pair-wise form a current source and one in each pair can be removed
Folded Cascode Op Amp

- Needs CMFB Circuit for $V_{B4}$
- Either single-ended or differential outputs
- Can connect counterpart as current mirror to eliminate CMFB
- Folding caused modest deterioration of $A_{V0}$ and GB energy efficiency
- Modest improvement in output swing
Folded Cascode Op Amp
(Single-ended Output)

\[ A_v(s) \approx -\frac{g_{mEQ}}{sC_L + g_{OEQ}} \]

\[ A_{v0} \approx \frac{g_{mEQ}}{g_{OEQ}} \]

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

\[ g_{mEQ} = g_{m1} \]

\[ g_{OEQ} \approx (g_{o1} + g_{o5})\frac{g_{o3}}{g_{m3}} + (g_{o7})\frac{g_{o9}}{g_{m9}} \]

\[ A_{v0} \approx \frac{g_{m1}}{(g_{o1} + g_{o5})\frac{g_{o3}}{g_{m3}} + (g_{o7})\frac{g_{o9}}{g_{m9}}} \]

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

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# Operational Amplifier Structure Comparison

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Folded Cascode Op Amp
(Single-ended Output)

\[ A_{v0} \approx \frac{g_{m1}}{(g_{o1} + g_{o5}) g_{o3} g_{m3} + (g_{o7}) g_{o9} g_{m9}} \]

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

How many degrees of freedom are there?
What is a practical design parameter set?

DOF ? 9 DOF
\{I_T, W_1/L_1, W_5/L_5, W_3/L_3, W_9/L_9, W_7/L_7, V_{B1}, V_{B2}, V_{B3}\}

Practical Design Parameters
\{P, \theta, V_{EB1}, V_{EB3}, V_{EB5}, V_{EB7}, V_{EB9}, V_{B2}, V_{B3}\}
where \( \theta = \frac{I_T}{I_T + I_{T2}} \)
Folded Gain-boosted Cascode Amplifier

\[ A_o \approx \frac{-g_{m1}}{\left(g_{o1}\right) g_{o3} A g_{m3}} \]

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

- with ideal current source bias
- modest improvement in output swing
Folded Gain-boosted Cascode Amplifier

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx -\frac{g_{m1}}{sC_L + \frac{(g_{o1} + g_{o5})g_{o3}}{g_{m3}A}}
\]

\[
A_0 \approx -\frac{g_{m1}g_{m3}A}{(g_{o1} + g_{o5})g_{o3}}
\]

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

modest improvement in output swing
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Folded Gain-boosted Telescopic Cascode Op Amp

\[ A_o \approx \frac{-g_{m1}}{2} \left( g_{o1} + g_{o5} \right) \frac{g_{o3}}{A_3 g_{m3}} + g_{o7} \frac{g_{o9}}{A_1 g_{m9}} \]

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

- Needs CMFB Circuit for \( V_{B4} \)
- Either single-ended or differential outputs
- Can connect counterpart as current mirror to eliminate CMFB
- Folding caused modest deterioration in GB efficiency and gain
- Modest improvement in output swing
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Summary of Folded Amplifier Performance

- + Modest improvement in output signal swing (from $5 \, V_{DS \, SAT}$ to $4 \, V_{DS \, SAT}$)
- - Deterioration in $A_{v0}$ (maybe 30% or more)
- - Deterioration in GB power efficiency (can be significant)
- - Minor increase in circuit size