EE 435

Lecture 10:

Folded-Cascode Amplifiers
Current Mirror Op Amps
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

Where we are at:
Review from last lecture:

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
- Assume biased with a dc current source (not shown) at drain of $M_3$
Gain-Boosted Telescopic Cascode Op Amp
(with or w/o current mirror counterpart circuits)

Advantages:

Significant increase in dc gain

Limitations:

• Signal swing \(4V_{D_{\text{SAT}}}+V_T\) between \(V_{\text{DD}}\) and \(V_{\text{SS}}\)
• 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
Review from last lecture:

Are there other useful high output impedance circuits that can be used for the quarter circuit?

\[
A_{V0} = \frac{-G_{M1}}{2(G_1 + G_2)} \\
BW = \frac{G_1 + G_2}{C_L} \\
GB = \frac{G_{M1}}{2C_L}
\]
Review from last lecture:

Implementation of Biased Folded Cascode Amplifier?

Biased Folded Cascode

Implementation of Biased Folded Cascode
How can this be seen by inspection?

- First observe if all \( g_o \)'s are 0, \( G_M = g_{m1} \)
- Then observe \( M_3 \) “cascodes” the impedance \( g_{o1} + g_{o5} \)

\[
\begin{align*}
V_{OUT} (g_{o3} + sC_L) + g_{m3} V_3 &= V_X g_{o3} \\
V_X (g_{o1} + g_{o3} + g_{o5}) + g_{m1} V_1 - g_{m3} V_3 &= V_{OUT} g_{o3} \\
V_3 &= -V_X \\
V_1 &= V_{IN} \\
V_{OUT} (g_{o3} + sC_L) + (g_{m3} + g_{o3}) V_3 &= 0 \\
+ g_{m1} V_{IN} &= V_3 (g_{m3} + g_{o1} + g_{o3} + g_{o5}) + V_{OUT} g_{o3} \\
\frac{V_{OUT}}{V_{IN}} &\approx -\frac{g_{m1}}{sC_L + (g_{o1} + g_{o5}) \frac{g_{o3}}{g_{m3}}} \\
\end{align*}
\]
Biased Folded Cascode Quarter Circuit

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

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

\[
GB \approx \frac{g_{m1}}{C_L}
\]
Basic Amplifier Structure Comparisons
(ideal current source biasing)

<table>
<thead>
<tr>
<th>Small Signal Parameter Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Source</strong></td>
</tr>
<tr>
<td>$A_{v0} \approx \frac{g_m}{g_o}$</td>
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<tr>
<td><strong>Cascode</strong></td>
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<td>$A_{v0} \approx \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}}$</td>
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<td><strong>Regulated Cascode</strong></td>
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<td>$A_{v0} \approx \frac{g_{m1} g_{m3} A}{g_{o1} g_{o3}}$</td>
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<tr>
<td><strong>Folded Cascode</strong></td>
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<tr>
<td>$A_{v0} \approx \frac{g_{m1} g_{m3}}{(g_{o1} + g_{o5}) g_{o3}}$</td>
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## Basic Amplifier Structure Comparisons

### Practical Parameter Domain

<table>
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<tr>
<th>Structure</th>
<th>$A_{vo}$</th>
<th>$GB$</th>
</tr>
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<tr>
<td>Common Source</td>
<td>$A_{vo} = \left( \frac{2}{\lambda} \right) \left( \frac{1}{V_{EB}} \right)$</td>
<td>$GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{1}{V_{EB}} \right)$</td>
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<td>Cascode</td>
<td>$A_{vo} = \left( \frac{4}{\lambda_1\lambda_3} \right) \left( \frac{1}{V_{EB1}V_{EB3}} \right)$</td>
<td>$GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{1}{V_{EB1}} \right)$</td>
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<tr>
<td>Regulated Cascode</td>
<td>$A_{vo} \approx \left( \frac{4}{\lambda_1\lambda_3} \right) \left( \frac{A}{V_{EB1}V_{EB3}} \right)$</td>
<td>$GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{1 - \theta}{V_{EB1}} \right)$</td>
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<tr>
<td>Folded Cascode</td>
<td>$A_{vo} \approx \left( \frac{4\theta}{(\theta\lambda_1 + \lambda_5)\lambda_3V_{EB1}V_{EB3}} \right)$</td>
<td>$GB = \left( \frac{2P}{V_{DD}C_L} \right) \left[ \frac{\theta}{V_{EB1}} \right]$</td>
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**Note:**
- $\lambda = \text{fraction of current of } M_5 \text{ that is in } M_1$
- $\Theta = \text{pct power in } A$
- $\Theta = \frac{\text{fraction of current of } M_5 \text{ that is in } M_1}$
Biased Folded-Cascode Amplifier

Quarter Circuit

Counterpart Circuit
Folded-Cascode Operational Amplifier

QUARTER CIRCUIT

Op Amp
Folded-Cascode Operational 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)

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

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

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

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

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

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

\[ GB = \frac{g_{m1}}{C_L} \]
# Operational Amplifier Structure Comparison

## Small Signal Parameter Domain

<table>
<thead>
<tr>
<th>Reference Op Amp</th>
<th>( A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}} )</th>
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<th>( SR = \frac{I_r}{2C_L} )</th>
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<td>Telescopic Cascode</td>
<td>( A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{m3}} + \frac{g_{o7}}{g_{m5}} )</td>
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<td>Regulated Cascode</td>
<td>( A_o \approx \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1}g_{m3}A_1} + \frac{g_{o7}}{g_{m9}A_3} )</td>
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<td>$A_{V0} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right)$</td>
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<td>$GB = \left( \frac{P}{2V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right]$</td>
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<td>$SR = \frac{P}{2V_{DD}C_L}$</td>
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| **Telescopic Cascode**     |
| $A_{V0} = \frac{2}{V_{EB1} \left( \frac{\lambda_1 \lambda_3 V_{EB3}}{A_1} + \frac{\lambda_5 \lambda_7 V_{EB5}}{A_3} \right)}$ |
| $GB = \left( \frac{P}{2V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right]$ |
| $SR = \frac{P}{2V_{DD}C_L}$ |

| **Regulated Cascode**      |
| $\Theta = \text{pct power in } A$ |
| $A_{V0} \approx \frac{2}{V_{EB1} \left( \frac{\lambda_1 \lambda_3 V_{EB3}}{A_1} + \frac{\lambda_5 \lambda_7 V_{EB7}}{A_3} \right)}$ |
| $GB = \left( \frac{P(1-\Theta)}{2V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right]$ |
| $SR = \frac{P(1-\Theta)}{2V_{DD}C_L}$ |

| **Folded Cascode**         |
| $\Theta = \text{fraction of current of } M_5 \text{ that is in } M_1$ |
| $A_{V0} = \frac{2\Theta}{V_{EB1} \left( (\theta \lambda_1 + \lambda_5) V_{EB3} + (1-\theta) \lambda_5 \lambda_7 V_{EB9} \right)}$ |
| $GB = \left( \frac{P}{2V_{DD}C_L} \right) \cdot \left[ \frac{\Theta}{V_{EB1}} \right]$ |
| $SR = \frac{\Theta P}{2V_{DD}C_L}$ |
Folded Cascode Op Amp
(Single-ended Output)

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

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

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 \( \theta = I_T / (I_T + I_{T2}) \)
Textbook reference:

Some of the material we have been discussing appears in Chapter 3, some in Chapter 5, and some in Chapter 6 of the Martin and Johns text.

In particular, the telescopic and folded cascode structures are referred to as advanced op amps and appear in later chapters of the text.
Folded Gain-boosted Cascode Amplifier

\[ A_o \approx \frac{-g_{m1}}{(g_{o1})^2 g_{o3} g_{m3}} \]

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

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

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

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

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

modest improvement in output swing
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<td>[ A_{vo} \approx \left( \frac{A4\theta_2}{\left( \theta_2 \lambda_1 + \lambda_5 \right) \lambda_3 V_{EB1} V_{EB3}} \right) ]</td>
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<td>[ GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{\theta_2 \left( 1-\theta_1 \right)}{V_{EB1}} \right) ]</td>
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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 $4 \, V_{DS\, SAT}$)
• + Can directly feed output back to input to create buffer
• - Deterioration in $A_{V0}$ (maybe 30% or more)
• - Deterioration in GB power efficiency (can be significant)
• - Minor increase in circuit size
Other Methods of Gain Enhancement

Recall:

\[ A_{V_0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC}} \]

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

Two Strategies:

1. Decrease denominator of \( A_{V_0} \)
2. Increase numerator of \( A_{V_0} \)

Previous approaches focused on decreasing denominator

Consider now increasing numerator
Determination of op amp characteristics from quarter circuit characteristics

Small signal Quarter Circuit

\[ A_{\text{VQc}}(s) = \frac{-G_M}{sC_L + G} \]

Small signal differential amplifier

\[ A_V = \frac{V_O}{V_d} = \frac{-G_{M1}}{sC_L + G_1 + G_2} \]

- Note that the counterpart circuit is simply serving as the biasing current source
- Could use counterpart circuits (or other circuits) from other quarter circuits for “P”
- Counterpart circuits connected as one-port
- Can think of making differential op amp directly from quarter circuit
Differential input op amp directly from quarter circuit

\[ A_{VQC}(s) = \frac{-G_M}{sC_L + G} \]

\[ A_V = \frac{V_O}{V_d} = \frac{-G_{M1}}{2} \frac{1}{sC_L + G_1 + G_2} \]

\[ A_V = \frac{V_O}{V_d} = \frac{-G_{M1}}{2} \frac{1}{sC_L + G_1 + G_{BB}} \]
$g_{mEQ}$ Gain Enhancement Strategy

Consider using the quarter circuit itself to form the op amp.

$g_{MQC} = g_{m1} M$

$g_m$ is increased by the mirror gain!

Folding is required to establish the correct bias current direction.

Consider using the quarter circuit itself to form the op amp.

Could have done this for other quarter circuits as well but there is a particularly important reason we are following this approach with this quarter circuit – What is it?

Output conductance of QC: $g_{oQC}$
$g_{mEQ}$ Gain Enhancement Strategy

$g_{MQC} = g_{M1}M$

$g_{OEQ} = g_{OQC} + g_{OI_{BB}}$

Redraw to absorb $I_B$ in the quarter circuit
$g_{mEQ}$ Gain Enhancement Strategy

\[ V_{IN} \rightarrow M_1 \rightarrow I_B \rightarrow V_{OUT} \]

\[ V_{IN}^+ \rightarrow M_1 \rightarrow I_B \rightarrow V_{OUT}^+ \]

\[ V_{IN}^- \rightarrow M_1 \rightarrow I_B \rightarrow V_{OUT}^- \]
Current Mirror Op Amps

Premise: Transconductance gain increased by mirror gain M

\[ g_{OEQ} = g_{OQC} + g_{OI_{BB}} \]

Premise: If output conductance is small, gain can be very high

Premise: GB very good as well

Still need to generate the bias current \( I_B \)

\[ A_{V0} = \frac{V_{OUT}^-}{V_{IN}^+ - V_{IN}^+} \]

\[ g_{mEQ} = M \frac{g_{m1}}{2} \]

(for \( V_{IN}^+ = V_d/2 \))

\[ A_{V0} = -\frac{g_{mEQ}}{g_{OEQ}} \]

\[ GB = \frac{g_{mEQ}}{C_L} \]
Current Mirror Op Amps

Need CMFB to establish $V_{B2}$

Can use higher output impedance current mirrors

Can use current mirror bias to eliminate CMFB but loose one output
Is this a real clever solution?
Basic Current Mirror Op Amp

\[ g_{\text{mEQ}} = \frac{Mg_{m1}}{2} \]

\[ g_{\text{OEQ}} = g_{O6} + g_{O8} \]

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

\[ A_{\text{VO}} = \frac{M \cdot g_{m1}}{2g_{O6} + g_{O8}} \]

\[ SR = \frac{M \cdot I_T}{2C_L} \]
• Current-Mirror Op Amp offers strategy for $g_m$ enhancement
• Very Simple Structure
• Has applications as an OTA
• Based upon small signal analysis, performance appears to be very good!
• But – how good are the properties of the CMOA?

Is this a real clever solution?
Seminal Work on the OTA

OTA Obsoletes Op Amp

by C.F. Wheatley
H.A. Wittlinger

From:
N.E.C. PROCEEDINGS
Seminal Work on the OTA

OTA Obsoleses Op Amp

by C.F. Wheatley
H.A. Wittlinger

From:
1969 N.E.C. PROCEEDINGS
December 1969
Original OTA

\[ I_B - I_A = M(I_2 - I_1) \]

\[ I_A = I_3 \]
\[ I_B = I_{OUT} + I_4 \]
\[ I_4 = I_3 \]
\[ I_{OUT} = M(I_B - I_A) \]
Original OTA

\[ I_B - I_A = M(I_2 - I_1) \]

\[ I_A = M I_1 \quad I_B = M I_2 \]

\[ I_{OUT} = M(I_B - I_A) \]
Original OTA

\[ I_{OUT} = M(I_B - I_A) \]
Original OTA

\[ I_{OUT} = M(I_B - I_A) \]

3-mirror OTA
Current Mirror Op Amp W/O CMFB

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

Often termed an OTA

\[ I_{OUT} = g_m V_{IN} \]

Introduced by Wheatley and Whitlinger in 1969
End of Lecture 10