EE 435

Lecture 10:

Current Mirror Op Amps
Folded Cascode Amplifier

QUARTER CIRCUIT

Op Amp

Review from last lecture:
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 Gain-boosted Cascode Amplifier

- with ideal current source bias
- modest improvement in output swing
## Basic Amplifier Structure Comparisons

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

Review from last lecture:
# Basic Amplifier Structure Comparisons

## Practical Parameter Domain

<table>
<thead>
<tr>
<th>Structure</th>
<th>$A_{vO}$</th>
<th>$GB$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Source</strong></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>
</tr>
<tr>
<td><strong>Cascode</strong></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>
</tr>
<tr>
<td><strong>Regulated Cascode</strong></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>
</tr>
<tr>
<td><strong>Folded Cascode</strong></td>
<td>$A_{vO} \approx \left(\frac{4\theta}{(\theta\lambda_1 + \lambda_5)\lambda_3 V_{EB1}V_{EB3}}\right)$</td>
<td>$GB = \left(\frac{2P}{V_{DD}C_L}\right) \left[\frac{\theta}{V_{EB1}}\right]$</td>
</tr>
<tr>
<td><strong>Folded Regulated Cascode</strong></td>
<td>$A_{vO} \approx \left(\frac{A4\theta_2}{(\theta_2\lambda_1 + \lambda_5)\lambda_3 V_{EB1}V_{EB3}}\right)$</td>
<td>$GB = \left(\frac{2P}{V_{DD}C_L}\right) \left[\frac{\theta_2(1-\theta_1)}{V_{EB1}}\right]$</td>
</tr>
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</table>

### Review from last lecture:

- $\Theta_1 = \text{pct of total power in A}$
- $\Theta_2 = \text{fraction of current of } M_5 \text{ that is in } M_1$
Review from last lecture:
Folded Gain-boosted Telescopic Cascode Op Amp

\[ A_o \approx \frac{-g_{m1}}{2} \]

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

- 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
## Operational Amplifier Structure Comparison

<table>
<thead>
<tr>
<th>Reference Op Amp</th>
<th>Small Signal Parameter Domain</th>
</tr>
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<tbody>
<tr>
<td>$A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$</td>
<td>$GB = \frac{g_{m1}}{2C_L}$</td>
</tr>
<tr>
<td><strong>Telescopic Cascode</strong></td>
<td></td>
</tr>
<tr>
<td>$A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1}} + \frac{g_{o7}}{g_{m3}}$</td>
<td>$GB = \frac{g_{m1}}{2C_L}$</td>
</tr>
<tr>
<td><strong>Regulated Cascode</strong></td>
<td></td>
</tr>
<tr>
<td>$A_o \approx \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1}} + \frac{g_{o7}}{g_{m3} A_1} \frac{g_{o9}}{g_{m9} A_3}$</td>
<td>$GB = \frac{g_{m1}}{2C_L}$</td>
</tr>
<tr>
<td><strong>Folded Cascode</strong></td>
<td></td>
</tr>
<tr>
<td>$A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1} + g_{o5}} + \frac{g_{o7}}{g_{m3}}$</td>
<td>$GB = \frac{g_{m1}}{2C_L}$</td>
</tr>
<tr>
<td><strong>Folded Regulated Cascode</strong></td>
<td></td>
</tr>
<tr>
<td>$A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1} + g_{o5}} \frac{g_{o9}}{g_{m3} A_3} + \frac{g_{o7}}{g_{m9} A_9}$</td>
<td>$GB = \frac{g_{m1}}{2C_L}$</td>
</tr>
</tbody>
</table>

Review from last lecture:
Other Methods of Gain Enhancement

Recall:

\[ A_{V0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC}} \]

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

Two Strategies:

1. Decrease denominator of \( A_{V0} \)

2. Increase numerator of \( A_{V0} \)

Previous approaches focused on decreasing denominator

Consider now increasing numerator
**$g_{mEQ}$ Gain Enhancement Strategy**

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

$g_m$ is increased by the mirror gain!

Use the quarter circuit itself to form the op amp.

Use this as a quarter circuit.

\[ V_{IN} \rightarrow M_1 \rightarrow I_B \rightarrow 1: M \rightarrow V_{OUT} \]
$g_{m\text{EQ}}$ Gain Enhancement Strategy
Current Mirror Op Amps

Premise: Transconductance gain increased by mirror gain $M$

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

Premise: $GB$ very good as well

Still need to generate the bias current $I_B$

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

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

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

Basic Current Mirror Op Amp
Is this a real clever solution?
Basic Current Mirror Op Amp

\[ g_{\text{mEQ}} = M \frac{g_{m1}}{2} \]
\[ g_{\text{OEQ}} = g_{O6} + g_{O8} \]
\[ GB = M \frac{g_{m1}}{2C_L} \]
\[ A_{\text{VO}} = -M \frac{g_{m1}}{2} \frac{I_T}{g_{O6} + g_{O8}} \]
\[ SR = \frac{M \cdot I_T}{2C_L} \]

CMFB not shown
• Current-Mirror Op Amp offers strategy for $g_m$ enhancement
• Very Simple Structure
• Has applications as an OTA
• 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 Obsoletes Op Amp

by C.F. Wheatley
H.A. Wittlinger

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

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

\[ I_A = I_3 \]

\[ I_B = I_{\text{OUT}} + I_4 \]

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

\[ I_b - I_a = M(I_2 - I_1) \]

\[ I_a = MI_1 \quad I_b = MI_2 \]

\[ I_{OUT} = M(I_b - I_a) \]
Original OTA

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

3-mirror OTA

$\mathbf{I_{OUT}} = \mathbf{M}(\mathbf{I_B} - \mathbf{I_A})$
Current Mirror Op Amp W/O CMFB

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

Often termed an OTA

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

Introduced by Wheatley and Whitlinger in 1969
OTA Circuits

- OTA often used open loop
- Excellent High Frequency Performance
- Gain can be made programmable with dc current
- Large or very large adjustment ranges possible

\[
g_m = \begin{cases} 
K \cdot I_{ABC} & \text{for BJT circuits} \\
K \sqrt{I_{ABC}} & \text{for MOS circuits}
\end{cases}
\]

2 to 3 decades of adjustment for MOS

5 to 6 decades of adjustment for BJT
OTA Applications

Voltage Controlled Amplifier

Note: Technically current-controlled, control variable not shown here and on following slides

\[ V_{OUT} = g_m R \cdot V_{IN} \]

\( g_m \) is controllable with \( I_{ABC} \)
OTA Applications

Voltage Controlled Inverting Amplifier

\[ V_{OUT} = -g_m R \cdot V_{IN} \]
OTA Applications

Voltage Controlled Resistances

\[ R_{IN} = \frac{1}{g_m} \]

\[ R_{IN} = -\frac{1}{g_m} \]
OTA Applications

Noninverting Voltage Controlled Amplifier

\[ V_{\text{OUT}} = \frac{g_{m1}}{g_{m2}} V_{\text{in}} \]

Inverting Voltage Controlled Amplifier

\[ V_{\text{OUT}} = -\frac{g_{m1}}{g_{m2}} V_{\text{in}} \]

Extremely large gain adjustment is possible

Voltage Controlled Resistorless Amplifiers
OTA Applications

Voltage Controlled Integrators

Noninverting Voltage Controlled Integrator

\[ V_{\text{OUT}} = \frac{g_m}{sC} V_{\text{in}} \]

Inverting Voltage Controlled Integrator

\[ V_{\text{OUT}} = -\frac{g_m}{sC} V_{\text{in}} \]
Comparison with Op Amp Based Integrators

\[ V_{OUT} = \left[ -\frac{1}{sRC} \right] V_{IN} \]

OTA-based integrators require less components and significantly less for realizing the noninverting integration function!
Properties of OTA-Based Circuits

- Can realize arbitrarily complex functions
- Circuits are often simpler than what can be obtained with Op Amp counterparts
- Inherently offer excellent high frequency performance
- Can be controlled with a dc voltage or current
- Often used open-loop rather than in a feedback configuration (circuit properties depend directly on $g_m$)
- Other high output impedance op amps can also serve as OTA
- Linearity is limited
- Signal swing may be limited but can be good too
- Circuit properties process and temperature dependent
• Current-Mirror Op Amp offers strategy for $g_m$ enhancement
• Very Simple Structure
• Has applications as an OTA
• But – how good are the properties of the CMOA?

Is this a real clever solution?
Current Mirror Op Amp W/O CMFB

Can use higher output impedance current mirrors to decrease $g_{OEQ}$

$$g_{OEQ} = g_{O6} + g_{O8}$$

$$g_{mEQ} = Mg_{m1}$$

$$A_{vo} = -\frac{M \cdot g_{m1}}{g_{O6} + g_{O8}}$$

$$SR = \frac{MI_T}{C_L}$$
SR of Current Mirror Op Amp

\[ SR = \frac{MI_T}{2C_L} \]
Fully Differential Current Mirror Op Amp with Improved Slew Rate

Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point
Fully Differential Current Mirror Op Amp with Improved Slew Rate

This circuit was published because of the claim for improved SR (Fig 6.15 MJ)

Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point
Fully Differential Current Mirror Op Amp with Improved Slew Rate

\[ \text{SR} = \frac{MI_T}{C_L} \]

\[ \text{SR}_{\text{CMOp Amp}} = \frac{M \cdot I_T}{2C_L} \]

Improved a factor of 2!

but …

Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point
Fully Differential Current Mirror Op Amp with Improved Slew Rate

SR = \frac{MI_T}{C_L}

SR_{CMOp Amp} = \frac{M \cdot I_T}{2C_L}

Improved a factor of 2!

P_{CMOp Amp} = V_{DD} I_T (1 + M)

P = V_{DD} I_T (1 + 2M)

SR_{CMOp Amp} = \left(\frac{P}{V_{DD} C_L}\right) \left[\frac{M}{2[1 + M]}\right]

SR = \left(\frac{P}{V_{DD} C_L}\right) \left[\frac{M}{1 + 2M}\right]

SR actually about the same for “improved SR circuit” and basic OTA
Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an “almost free” gain enhancement?

\[ A_{VO} = - \frac{M \cdot g_{m1}}{2 \left( g_{o6} + g_{o8} \right)} \]

\[ M = \frac{W_6 L_4}{W_A L_6} \]
Reference Op Amp

Consider single-ended output performance:

$$A(s) = \frac{g_{m1}}{2sC_L + g_{o1} + g_{o3}}$$

$$A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$$

$$GB = \frac{g_{m1}}{2C_L}$$

$$SR = \frac{I_T}{2C_L}$$

$$A_{vo} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right)$$

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

$$SR = \frac{P}{2V_{DD}C_L}$$
Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an “almost free” gain enhancement?

\[
A_{vo} = - \frac{M \cdot g_{m1}}{2 g_{o6} + g_{o8}}
\]

\[
M = \frac{WL_6}{WL_4}
\]

\[
M = \frac{g_{m6}}{g_{m4}}
\]

\[
A_{vo} = - \frac{g_{m6} \cdot g_{m1}}{2 g_{o6} + g_{o8}}
\]

Gain Enhancement Potential Less Apparent but still Improved by \( g_{m6}/g_{m4} \) ratio
Comparison of Current-Mirror Op Amps with Previous Structures

Does the simple mirror gain really provide an “almost free” gain enhancement?

\[ A_{V0} = -\frac{M \cdot g_{m1}}{2 g_{o6} + g_{o8}} \]

Consider how the gain appears in the practical parameter domain

\[ A_{V0} = \frac{\frac{1}{2} \left( \frac{I_T}{2} M \right)}{V_{EB1} (\lambda_{M6} + \lambda_{M8})_{D \& Q}} = \frac{\frac{I_T}{2} M}{V_{EB1} (\lambda_{M6} + \lambda_{M8}) M \frac{I_T}{2}} = \frac{1}{V_{EB1} (\lambda_{M6} + \lambda_{M8}) \approx \frac{1}{2 \lambda V_{EB1}}} \]

This is exactly the same as was obtained for the simple differential amplifier! For a given \( V_{EB1} \), there is NO gain enhancement!
Comparison of Current-Mirror Op Amps with Previous Structures

How does the GB power efficiency compare with previous amplifiers?

GB = \frac{g_{mEQ}}{C_L} = \frac{Mg_{m1}}{2C_L} = \frac{MI_T}{2V_{EB1}C_L}

P = V_{DD}I_T(1 + M)

GB for Telescopic Cascode and Ref Op Amp!

GB efficiency decreased for small M!!
Comparison of Current-Mirror Op Amps with Previous Structures

How does the SR compare with previous amplifiers?

\[
\text{SR}_{\text{Ref Op Amp}} = \frac{I_T}{2C_L}
\]

\[
\text{SR} = \frac{M \cdot I_T}{2C_L}
\]

SR Improved by factor of M !

but ...

\[
P = V_{DD} I_T (1 + M)
\]

\[
\text{SR} = \frac{P}{2V_{DD} C_L} \left[ \frac{M}{1 + M} \right]
\]

\[
\text{SR}_{\text{Ref Op Amp}} = \frac{P}{2V_{DD} C_L}
\]

SR Really Less than for Ref Op Amp !!
Comparison of Current-Mirror Op Amps with Previous Structures

How does the Current Mirror Op Amp really compare with previous amplifiers or with reference amplifier?

Perceived improvements may appear to be very significant.

Actual performance is not as good in almost every respect!
Current-Mirror Op Amps – Another Perspective!

Differential Half-Circuit
Current-Mirror Op Amps – Another Perspective!

Differential Half-Circuit

Cascade of n-channel common source amplifier with p-channel common-source amplifier!
Current-Mirror Op Amps – Another Perspective!

Differential Half-Circuit

\[ A_v = -\frac{1}{2} \left( \frac{g_{m2}}{g_{m4}} \right) \left( \frac{g_{m6}}{g_{O6} + g_{O8}} \right) \]

From Current Mirror Analysis:

\[ A_{vo} = -\frac{1}{2} \left( \frac{g_{m1}}{g_{O6} + g_{O8}} \right) = -\frac{g_{m4}}{g_{O6} + g_{O8}} \left( \frac{g_{m1}}{2} \right) \]

Cascade of n-channel common source amplifier with p-channel common-source amplifier!
End of Lecture 10