EE 435

Lecture 10:

Current Mirror Op Amps
Folded Cascode Amplifier

Review from last lecture:

QUARTER CIRCUIT

Op Amp
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

Review from last lecture:
Folded Gain-boosted Cascode Amplifier

\[ A_o \approx \frac{-g_{m1}}{\left(g_{o1}\right) \frac{g_{o3}}{A g_m3}} \]

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

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

<table>
<thead>
<tr>
<th></th>
<th>Small Signal Parameter Domain</th>
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</thead>
<tbody>
<tr>
<td><strong>Common Source</strong></td>
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<tr>
<td></td>
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<tr>
<td><strong>Regulated Cascode</strong></td>
<td>$A_{vo} \approx \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}} A$</td>
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<td>--------------------------------------</td>
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<tr>
<td><strong>Practical Parameter Domain</strong></td>
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<tr>
<td>[ A_{vo} = \left( \frac{2}{\lambda} \right) \left( \frac{1}{V_{EB}} \right) ]</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>
<td>[ GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{1}{V_{EB1}} \right) ]</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 = \text{pct power in } A ]</td>
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<td>[ A_{vo} \approx \left( \frac{4\theta}{(\theta\lambda_1 + \lambda_5)\lambda_3} \right) \left( \frac{V_{EB1}V_{EB3}}{V_{EB}} \right) ]</td>
<td>[ GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{\theta}{V_{EB1}} \right) ]</td>
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<td>[ \Theta = \text{fraction of current of } M_5 \text{ that is in } M_1 ]</td>
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<tr>
<td>[ A_{vo} \approx \left( \frac{A4\theta_2}{(\theta_2\lambda_1 + \lambda_5)\lambda_3} \right) \left( \frac{V_{EB1}V_{EB3}}{V_{EB}} \right) ]</td>
<td>[ GB = \left( \frac{2P}{V_{DD}C_L} \right) \left( \frac{\theta_2(1 - \theta_1)}{V_{EB1}} \right) ]</td>
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<td>[ \Theta_1 = \text{pct of total power in } A ]</td>
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<tr>
<td>[ \Theta_2 = \text{fraction of current of } M_5 \text{ that is in } M_1 ]</td>
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Folded Gain-boosted Telescopic Cascode Op Amp

\[ A_o \approx \frac{-g_{m1}}{2} \]
\[ \frac{g_{o1} + g_{o5}}{A_3g_{m3}} + \frac{g_{o7}}{A_1g_{m9}} \]
\[ GB = \frac{g_{m1}}{2C_L} \]

- 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
## Operational Amplifier Structure Comparison

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<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_t}{2C_L} ]</th>
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<td>Telescopic Cascode</td>
<td>[ A_o = \frac{g_{m1}}{2} \frac{g_{o3}g_{o5}}{g_{o1}g_{m3}} + \frac{g_{o5}g_{o7}}{g_{m5}} ]</td>
<td>[ GB = \frac{g_{m1}}{2C_L} ]</td>
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</table>
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

Small signal differential amplifier

- $A_{VQC}(s) = \frac{-G_M}{sC_L + G}$
- $A_V = \frac{V_O}{V_d} = \frac{-G_{M1}}{2 \left( sC_L + G_1 + G_2 \right)}$

- 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

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

\[ A_V = \frac{V_O}{V_d} = \frac{-G_{M1}}{2} \frac{1}{sC_L + G_1 + G_2} \]
$g_{mEQ}$ Gain Enhancement Strategy

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

$g_m$ 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
Current Mirror Op Amps

Premise: Transconductance gain increased by mirror gain M

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

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

Premise: GB very good as well

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

**Very Simple Structure!**

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

\[ g_{mEQ} = M \frac{g_{m1}}{2} \quad \text{(for } V_{IN}^+=V_d/2) \]

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

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

\[ g_{\text{meq}} = M \frac{g_{m1}}{2} \]

\[ g_{\text{oeq}} = g_{o6} + g_{o8} \]

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

\[ A_{\text{vo}} = \frac{M \cdot g_{m1}}{2} \]

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

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

by C.F. Wheatley
H.A. Wittlinger

From:
1969 N.E.C. PROCEEDINGS
December 1969
\[ I_B - I_A = M(I_2 - I_1) \]

Original OTA

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

\[ I_B - I_A = M(I_2 - I_1) \]
\[ I_A = MI_1 \quad I_B = MI_2 \]

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

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

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

Often termed an OTA

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

Introduced by Wheatley and Whitlinger in 1969

\[ I_{OUT} = g_m V_{IN} \]
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.
OTA Applications

Voltage Controlled Inverting Amplifier

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

Voltage Controlled Resistances

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

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

Noninverting Voltage Controlled Amplifier

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

Inverting Voltage Controlled Amplifier

Extremely large gain adjustment is possible

Voltage Controlled Resistorless Amplifiers
OTA Applications

Voltage Controlled Integrators

Noninverting Voltage Controlled Integrator

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

Inverting Voltage Controlled Integrator

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

Voltage Controlled Integrators
Comparison with Op Amp Based Integrators

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

And 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

SR = \frac{MI_T}{C_L}

SR_{CMOpAmp} = \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

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

\[
SR_{CMOpAmp} = \frac{M \cdot I_T}{2C_L}
\]

Improved a factor of 2!

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

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

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

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

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?

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

\[
M = \frac{W_6 L_4}{W_4 L_6}
\]

Ask the apple comparison question!
Comparison of Current-Mirror Op Amps with Previous Structures

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

Are we comparing Apples with Apples?

- In the small-signal parameter domain?
- In the practical parameter domain?
- Does it matter if we are making a comparison?

\[
M \cdot \frac{g_{m1}}{2} \leq \frac{1}{g_{o6} + g_{o8}}
\]

\[
M = \frac{W_6 L_4}{W_4 L_6}
\]
Reference Op Amp

Consider single-ended output performance:

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

\[ A_{v0} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}} \]

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

\[ SR = \frac{I_T}{2C_L} \]

\[ A_{v0} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right) \]

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

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

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

\[ A_{VO} = -\frac{M \cdot g_{m1}}{2} \]
\[ M = \frac{W_L L_4}{W_6 L_4} \]
\[ M = \frac{g_{m6}}{g_{m4}} \]

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?

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

Consider how the gain appears in the practical parameter domain

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

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

How does the GB power efficiency compare with previous amplifiers?

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

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

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?

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

SR Improved by factor of M!

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

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

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

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!

But performance is comparable to other circuits and the circuit structure is really simple

Widely used architecture as well but maybe more for OTA applications
Gain Enhancement Strategy

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

\( g_m \) 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: \( g_{OQC} \)
Consider this quarter circuit

\[ g_{\text{MQC}} = g_{m1} M \]

\( g_m \) 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: \( g_{\text{ooc}} \)
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 \( A_{V_0} \)

So what happened with the Current Mirror approach to increasing the numerator?

Previous approaches focused on decreasing denominator

Consider now increasing numerator
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

From Current Mirror Analysis:

\[ A_v = -\frac{1}{2} \left( \frac{g_{m2}}{g_{m4}} \right) \left( \frac{g_{m6}}{g_{o6} + g_{o8}} \right) \]

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

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