EE 435

Lecture 9:

High-Gain Single-Stage Op Amps

- Regulated Folded Cascode Op Amp
- Current-mirror op amps
- OTA Applications
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.
What circuit is this?

Folded Cascode Amplifier

Biased Folded Cascode
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 Telescopic Cascode Op Amp

\[ A_o \approx \frac{g_{m1}}{2} \left( \frac{g_{o1} + g_{o5}}{A_3 g_m} + \frac{g_{o7}}{A_4 g_{m9}} \right) \]

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

- Needs CMFB Circuit for \( V_{B4} \)
- Either single-ended or differential outputs
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## Operational Amplifier Structure Comparison

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<th>Reference Op Amp</th>
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### Small Signal Parameter Domain
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
Folded Gain-boosted Cascode Amplifier

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

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

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

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

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

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

modest improvement in output swing
## Basic Amplifier Structure Comparisons

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<tr>
<th>Small Signal Parameter Domain</th>
<th>Common Source</th>
<th>Cascode</th>
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<td>$A_{vo}$</td>
<td>$A_{vo} = \frac{g_m}{g_o}$</td>
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## Basic Amplifier Structure Comparisons

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<td><strong>Common Source</strong></td>
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<tr>
<td>$A_{vo} = \frac{2}{\lambda \frac{1}{V_{EB}}}$</td>
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<td>$A_{vo} = \frac{4}{\lambda_{1} \lambda_{3}} \frac{1}{V_{EB1}V_{EB3}}$</td>
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<td>$A_{vo} \approx \frac{4}{\lambda_{1} \lambda_{3}} \frac{A}{V_{EB1}V_{EB3}}$</td>
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<td>$A_{vo} \approx \frac{4\theta}{(\theta \lambda_{1} + \lambda_{5}) \lambda_{3} V_{EB1}V_{EB3}}$</td>
<td>$GB = \frac{2P}{V_{DD}C_{L}} \left[ \frac{\theta}{V_{EB1}} \right]$</td>
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<td>$\Theta =$ fraction of current of $M_5$ that is in $M_1$</td>
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<td>$A_{vo} \approx \frac{A4\theta_{2}}{(\theta_{2} \lambda_{1} + \lambda_{5}) \lambda_{3} V_{EB1}V_{EB3}}$</td>
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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
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# Operational Amplifier Structure Comparison

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Summary of Folded Amplifier Performance

• + Modest improvement in output signal swing (from $5 \, V_{\text{DS SAT}}$ to $4 \, V_{\text{DS SAT}}$)

• - 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:

\[ A_{v0} = \frac{-g_{MQC}}{g_{OQC} + g_{OCC}} \]

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

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
$g_{mEQ}$ Gain Enhancement Strategy
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 $I_B$

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

\[
A_{v0} = -\frac{g_{mEQ}}{g_{DEQ}}
\]

\[
GB = \frac{g_{mEQ}}{C_L}
\]
Need CMFB to establish \( V_{B2} \)

Can use higher output impedance current mirrors

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

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

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

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

\[ A_{Vo} = -\frac{M \cdot g_{m1}}{2 \left( g_{O6} + g_{O8} \right)} \]

\[ SR = \frac{M \cdot I_T}{2C_L} \]
• Current-Mirror Op Amp offers strategy for $g_m$ enhancement
• Very Simple Structure
• Has applications as an OTA
• 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

\[ I_B - I_A = M(I_z - I_I) \]

\[ I_A = I_3 \]

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

\[ I_4 = I_3 \]

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

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

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

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

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

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

\[ g_{m\text{EQ}} = Mg_{m1} \]

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

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

Voltage Controlled Inverting Amplifier
OTA Applications

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

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

Voltage Controlled Resistances
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

Noninverting Voltage Controlled Integrator

Inverting Voltage Controlled Integrator

Voltage Controlled Integrators
Comparison with Op Amp Based Integrators

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

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

Need CMFB circuit and requires modest circuit modification to provide CMFB insertion point.

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

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

Improved a factor of 2!

but …
Fully Differential Current Mirror Op Amp with Improved Slew Rate

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

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

Improved a factor of 2!

but ...

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

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

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

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

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?

\[ \text{A}_{vo} = -\frac{2}{g_{o6} + g_{o8}} \]

\[ M = \frac{W_6 L_4}{W_4 L_6} \]
Consider single-ended output performance:

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

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

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

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

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

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

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

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

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

\[ A_{vo} = -\frac{g_{m6} \cdot g_{m1}}{2} \cdot \frac{g_{m4}}{g_{o6} + g_{o8}} \]

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?

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

Consider how the gain appears in the practical parameter domain

\[ A_{V0} = \frac{\frac{1}{2} \left( \frac{1}{2} + \frac{1}{M} \right)}{V_{EB1} \left( \lambda_{M6} + \lambda_{M8} \right)} \]

\[ = \frac{L}{2} \frac{I_{T} M}{V_{EB1} \left( \lambda_{M6} + \lambda_{M8} \right)} \]

\[ = \frac{1}{2} \frac{1}{V_{EB1}} \]

\[ \approx \frac{1}{2\lambda V_{EB1}} \]

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?

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

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

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?

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

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

SR Improved by factor of M!

but …

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

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

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

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!
End of Lecture 9