OTA circuits

Cascaded Amplifiers

-- Stability Issues

-- Two-Stage Op Amp Design
Review from last lecture:

Current Mirror Op Amp W/O CMFB

Often termed an OTA

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

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

**Voltage Controlled Amplifier**

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

Voltage Controlled Inverting Amplifier

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

Voltage Controlled Resistances

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

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

Noninverting Voltage Controlled Amplifier

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

Inverting Voltage Controlled Amplifier

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

Extremely large gain adjustment is possible

Voltage Controlled Resistorless Amplifiers
OTA Applications

Noninverting Voltage Controlled Integrator

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

Inverting Voltage Controlled Integrator

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

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

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

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

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

\[ SR = \frac{M_{IT}}{C_L} \]

And can use higher output impedance current mirrors to decrease \( g_{OEQ} \)
SR of Current Mirror Op Amp

\[ \text{SR} = \frac{M_I T}{2C_L} \]

\[ \text{SR} = \frac{M_I T}{C_L} \]
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

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

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

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?

\[ A_{VO} = -\frac{M \cdot g_{m1}}{2 + \frac{1}{g_{o6} + g_{o8}}} \]

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

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?

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

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

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?
Reference Op Amp

Consider single-ended output performance:

\[ A(s) = \frac{g_{m1}}{2} \frac{2}{sC_L + g_{O1} + g_{O3}} \]

\[ A_{VO} = \frac{1}{2} \frac{g_{m1}}{g_{O1} + g_{O3}} \]

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

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

\[ A_{V0} = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{1}{V_{EB1}} \right) \]

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

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

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

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

$$M = \frac{WL_6}{WL_4}$$

$$M = \frac{g_{m6}}{g_{m4}}$$

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?

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

Consider how the gain appears in the practical parameter domain

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

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?

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

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

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_{Ref\ Op\ Amp} = \frac{I_T}{2C_L}

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

SR Improved by factor of M!

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

SR = \frac{P}{2V_{DD} C_L} \begin{bmatrix} M \\ 1 + M \end{bmatrix}

SR_{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

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: \( g_{OQC} \)

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

\[ g_{M_{QC}} = g_{m1} M \]

\( g_m \) 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: \( g_{oQC} \)
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 \( A_{V0} \)

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:

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

\[ A_{vO} = -\frac{g_{m1}}{2} \left( \frac{g_{m6}}{g_{O6} + g_{O8}} \right) \]

Cascade of n-channel common source amplifier with p-channel common-source amplifier!
Comparison of Different Circuit Designs

• An objective comparison of different design approaches is often a critical part of the design process

• Different objective functions or different comparison approaches often lead to different conclusions

• Textbooks and the technical literature do not always identify the most appropriate objective functions

• Critical to identify metrics that capture the important characteristics of a design when making comparisons but this is often a challenging task
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:

\[
A_{vo} = -\frac{M \cdot g_{m1}}{2} = -\frac{g_{m6} \cdot g_{m1}}{g_{O6} + g_{O8}}
\]

Cascade of n-channel common source amplifier with p-channel common-source amplifier!
Current Mirror Op Amp Summary

- Current-mirror op amp offers no improvement in performance over the reference op amp.
- Current-mirror op amp can be viewed as a cascade of two common-source amplifiers, one with a low gain and the other with a larger gain.
- Current-mirror op amp is useful as an open-loop programmable transconductance amplifier (OTA).
- Current-mirror op amp will work in feedback applications as well, but performance would often be better with alternative Op Amp architectures.
End of Lecture 11