EE 435

Lecture 9:

High-Gain Single-Stage Op Amps

- Folded Cascode Op Amp
- Current-mirror op amps
- OTA Applications
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)
Gain-Boosted Telescopic Cascode Op Amp
(with or w/o current mirror counterpart circuits)

Advantages:

 Significant increase in dc gain

Limitations:

- Signal swing (4VD_{\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
Laboratory Support

Offset Voltage

- Systematic Offset Voltage
- Random Offset Voltage

![Op-Amp Diagram]

$V_{ICQ}$

$V_{OUT}$
Laboratory Support

Offset Voltage

• Systematic Offset Voltage
• Random Offset Voltage

Definition: The output offset voltage is the difference between the desired output and the actual output when \( V_{id} = 0 \) and \( V_{ic} \) is the quiescent common-mode input voltage.

\[
V_{OUTOFF} = V_{OUT} - V_{OUTDES}
\]

Note: \( V_{OUTOFF} \) is dependent upon \( V_{ICQ} \) although this dependence is usually quite weak and often not specified.
Laboratory Support

Definition: The input-referred offset voltage is the differential dc input voltage that must be applied to obtain the desired output when \( V_{ic} \) is the quiescent common-mode input voltage.

Note: \( V_{OFF} \) is usually related to the output offset voltage by the expression

\[
V_{OFF} = \frac{V_{OUTOFF}}{A_C}
\]

Note: \( V_{OFF} \) is dependent upon \( V_{ICQ} \) although this dependence is usually quite weak and often not specified.
Laboratory Support

When differential input op amps are biased with symmetric supply voltages, it is generally assumed that the desired quiescent input voltage is 0V and the desired quiescent output voltage is 0V so $V_{\text{OFF}}$ is the differential input voltage needed to make $V_{\text{OUT}}=0\text{V}$.

The input offset voltage is comprised of two parts, a systematic component and a random component

$$V_{\text{OFF}} = V_{\text{OFFSYS}} + V_{\text{OSR}}$$
Laboratory Support

\[ V_{OFF} = V_{OFFSYS} + V_{OSR} \]

After fabrication there is no distinction made between \( V_{OFFSYS} \) and \( V_{OSR} \) and simply \( V_{OFF} \) is of concern

\( V_{OSR} \) is determined entirely by random variations in component values from their ideal value and will only be seen in a simulation if deviations are intentionally introduced (Monte Carlo Analysis if often used for predicting \( V_{OSR} \))

It is expected that \( V_{OFFSYS} \) should be small (much smaller than \( V_{OSR} \)) and it is the designer’s responsibility to make this small.
It is not necessary to make $V_{OFFSYS} = 0$ although this can and is often done by making a minor tweak of matching critical parameters after the design of the op amp is almost complete.

$V_{OFFSYS}$ can also be set to 0 by using a degree of freedom of the amplifier design variables but this is generally an unwise use of degrees of freedom (although some textbooks including Martin and Johns in Sec 5.1 do this!)
Laboratory Support

By symmetry, to force $V_{OUT} = 0$, it is necessary to have $V_{D3} = 0$

- Making $V_{D3} = 0$ sets $|V_{EB3}| = V_{DD} + V_{Tp}$ and results in the use of one degree of freedom!
- Making $V_{EB3}$ so large will severely limit the voltage swing at $V_{OUT}$
- This shows why it is not wise to use a degree of freedom to make the systematic offset voltage 0

(If no mismatch is introduced, will be seeing only effects of systematic offset)
Can sweep a voltage in simulator at gate of $M_1$ to make $V_{OUT} = 0$

This is the systematic offset voltage

Can simply add the systematic offset voltage to input throughout rest of the design phase and then remove after design is complete or tweak at end of design to eliminate systematic offset.
Laboratory Support

Usually $V_{OFF}$ will change if changes in any design variables are made so re-simulation will be needed to get the correct value of $V_{OFF}$.

If $V_{OFF}$ is not included, ac simulation of open-loop amplifier will usually not give desired results because small-signal models will be developed in simulator at incorrect operating point (often even in incorrect region of operation).

Alternative is to do ac simulations by embedding op amp into a FB configuration that will inherently compensate for offset voltage but issue of compensation must be addressed for amplifiers with two or more poles.
Are there other useful high output impedance circuits that can be used for the quarter circuit?

\[
A_{VO} = \frac{-G_{M1}}{2(G_1 + G_2)}
\]

\[
BW = \frac{G_1 + G_2}{C_L}
\]

\[
GB = \frac{G_{M1}}{2C_L}
\]
What circuit is this?

Cascode Amplifier
Often termed a “Folded Cascode Amplifier”
Same small-signal performance as other
But a biasing problem!!
What circuit is this?

Folded Cascode Amplifier

Biased Folded Cascode
What circuit is this?

Biased Folded Cascode

Implementation of Biased Folded Cascode
Biased Folded Cascode Quarter Circuit

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

\[
A_{V0} = \frac{g_{m1}g_{m3}}{(g_{o1} + g_{o5})g_{o3}}
\]

\[
GB = \frac{g_{m1}}{C_L}
\]
## Basic Amplifier Structure Comparisons

<table>
<thead>
<tr>
<th>Structure</th>
<th>$A_{vo}$</th>
<th>$GB = \frac{g_m}{C_L}$</th>
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<tbody>
<tr>
<td>Common Source</td>
<td>$A_{vo} = \frac{g_m}{g_o}$</td>
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<td>Cascode</td>
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<td>Regulated Cascode</td>
<td>$A_{vo} \approx \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}} A$</td>
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# Basic Amplifier Structure Comparisons

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<tr>
<td><strong>A_{vo}</strong></td>
<td>$A_{vo} = \left(\frac{2}{\lambda}\right)\left(\frac{1}{V_{EB}}\right)$</td>
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<td>$A_{vo} \approx \left(\frac{4\theta}{(\theta \lambda_1 + \lambda_5)\lambda_3}\right)\left(\frac{V_{EB1}V_{EB3}}{V_{EB1}V_{EB3}}\right)$</td>
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<td><strong>GB</strong></td>
<td>$GB = \left(\frac{2P}{V_{DD}C_L}\right)\left(\frac{1}{V_{EB}}\right)$</td>
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<td>$GB = \left(\frac{2P}{V_{DD}C_L}\right)\left[\frac{\theta}{V_{EB1}}\right]$</td>
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- $\lambda$ = current gain
- $P$ = power
- $\theta$ = fraction of current of $M_5$ that is in $M_1$
- $\text{pct power in A}$
- $V_{DD}$ = supply voltage
- $C_L$ = load capacitance
- $V_{EB}$ = drain-source voltage

**Notes:**
- $\lambda_1$, $\lambda_3$, $\lambda_5$ are current gains of the respective transistors.
- $V_{EB1}$ and $V_{EB3}$ are voltages across the respective transistors.
Biased Cascode Amplifier

Quarter Circuit

Counterpart Circuit
Folded Cascode Amplifier

QUARTER CIRCUIT

Op Amp
Folded Cascode 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)

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

\[ A_v \approx \frac{g_{mEQ}}{g_{OEQ}} \]

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

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

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

\[ A_v \approx \frac{g_{m1}}{(g_{o1} + g_{o5}) \frac{g_{o3}}{g_{m3}} + (g_{o7}) \frac{g_{o9}}{g_{m9}}} \quad GB = \frac{g_{m1}}{C_L} \]
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<td><strong>Telescopic Cascode</strong></td>
<td>$A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1} g_{m3}} + \frac{g_{o5}}{g_{m5}}$</td>
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<td>$A_o = \frac{g_{m1}}{2} \frac{g_{o5}}{(g_{o1} + g_{o5}) g_{m3} + g_{o7} g_{o9}} \frac{g_{o3}}{g_{m5}}$</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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Folded Cascode Op Amp
(Single-ended Output)

\[ A_{v0} \approx \frac{g_{m1}}{\left(g_{o1} + g_{o5}\right)g_{o3} + \left(g_{o7}\right)^2 g_{o9} g_{m9}} \]

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

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 \(\theta = I_T/(I_T + I_{T2})\)
Folded Gain-boosted Cascode Amplifier

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

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

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

\[
A_0 \approx \frac{-g_{m1}g_{m3}A}{(g_{o1} + g_{o5})g_{o3}}
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\[
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modest improvement in output swing
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<td>$\Theta_1 = \text{pct of total power in } A$</td>
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<td>$\Theta_2 = \text{fraction of current of } M_5 \text{ that is in } M_1$</td>
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<td>$A_{vo} \approx \left( \frac{A4\theta_2}{(\theta_2 \lambda_1 + \lambda_5) \lambda_3 V_{EB1} V_{EB3}} \right)$</td>
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<td>$GB = \left( \frac{2P}{V_{DD}C_L} \right) \left[ \frac{\theta_2 (1-\theta_1)}{V_{EB1}} \right]$</td>
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Folded Gain-boosted Telescopic Cascode Op Amp

\[ A_0 \approx \frac{-g_{m1}}{2} \left( g_{o1} + g_{o5} \frac{g_{o3}}{A_3 g_{m3}} + g_{o7} \frac{g_{o9}}{A_1 g_{m9}} \right) \]

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

- 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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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
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
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 $I_B$

$$g_{mEQ} = M \frac{g_{m1}}{2}$$

$$A_{v0} = -\frac{g_{mEQ}}{g_{DEQ}}$$

$$GB = \frac{g_{mEQ}}{C_L}$$
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

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

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

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

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

\[ A_{vo} = -\frac{M \cdot g_{m1}}{2} \frac{1}{g_{O6} + g_{O8}} \]

\[ SR = \frac{M \cdot I_T}{2C_L} \]
• Current-Mirror Op Amp offers strategy for $g_m$ enhancement
• Very Simple Structure
• Has applications as an OTA
• 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
End of Lecture 9