EE 435

Lecture 7:

High-Gain Single-Stage Op Amps
Review from last lecture:

Signal Swing

How do the transfer characteristics relate to the signal swing?

For this circuit, high gain and large output signal swing for small $V_{EB1}$. 
Review from last lecture:

Signal Swing of Single-Stage Op Amp

For high-gain amplifiers, $V_d$ is inherently very small so are only concerned about output signal swing vs $V_{iC}$.

Generally large swings come at expense of other desirable characteristics.
Review from last lecture:
Signal Swing of Single-Stage Op Amp

What type of signal swing is needed?

Wide $V_{ic}$ and $V_{out}$ range
Expected for catalog parts and overall I/O in many applications

Narrow $V_{ic}$ and wide $V_{out}$ range
Acceptable when $V_{ic}$ is fixed

Narrow $V_{out}$ and wide $V_{ic}$ range
Acceptable when followed by high-gain stage

Narrow $V_{ic}$ and $V_{out}$ range
Acceptable when $V_{ic}$ fixed and followed by high-gain stage
Review from last lecture:

Signal Swing of Single-Stage Op Amp

\[ V_{OUT} \]

\[ V_{SS} \]

\[ V_{DD} \]

\[ V_{iC} \]
Review from last lecture:
Design space for single-stage op amp

Performance Parameters in Practical Parameter Domain \{ V_{EB1}, V_{EB2}, V_{EB5}, P \}:

\[
A_0 = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left[ \frac{2}{V_{EB1}} \right]
\]
\[
GB = \left( \frac{P}{V_{DD} C_L} \right) \left[ \frac{2}{V_{EB1}} \right]
\]
\[
SR = \frac{P}{(V_{DD} - V_{SS}) C_L}
\]
\[
V_{OUT} < V_{DD} - |V_{EB3}|
\]
\[
V_{OUT} > V_{iC} - V_{T2}
\]
\[
V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|
\]
\[
V_{iC} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}
\]

Simple Expressions in Practical Parameter Domain
Review from last lecture:

Design space for single-stage op amp

Performance Parameters in Natural Parameter Domain \{ W_1/L_1, W_3/L_3, W_5/L_5, I_T \}:

\[
V_{iC} < V_{DD} + V_{T1} - |V_{T3}| - \frac{\sqrt{I_T}}{\sqrt{\mu_p C_{OX} L_3}} \sqrt{\frac{W_3}{L_3}}
\]

\[
V_{ic} > V_{T1} + \frac{\sqrt{I_T}}{\sqrt{\mu_n C_{OX} L_1}} + \frac{\sqrt{I_T}}{\sqrt{\mu_n C_{OX} L_5}} + V_{SS}
\]

\[
A_{V0} = \frac{\sqrt{4 \mu_n C_{OX}}}{\lambda_1 + \lambda_3} \left( \frac{W_1}{\sqrt{L_1}} \right)
\]

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

\[
GB = \left[ \frac{\sqrt{\mu_n C_{OX}}}{C_L} \right] \frac{W_1}{\sqrt{L_1}} \sqrt{I_T}
\]

\[
V_{OUT} < V_{DD} - \frac{\sqrt{I_T}}{\sqrt{\mu_p C_{OX} L}} \sqrt{\frac{W}{L}}
\]

\[
V_{OUT} > V_{ic} - V_{T2}
\]

Complicated Expressions in Practical Parameter Domain
Measurement and Simulation of Op Amps

- Measurement of $A_v$ is challenging
  - Because it is so large
  - Even harder as $A_{v0}$ becomes larger
  - Offset voltage causes a problem
  - Embed in Feedback Network to Stabilize Operating Point
    - Stability must be managed
    - Use time varying input to distinguish signal information from offset
    - Must be well below first pole frequency
  - Measurement challenges often parallel simulation challenges

- Measurement of GB is easy
- Measurement of $R_0$ is challenging
Single-stage op amps

Question – is the gain achievable with the single-stage op amps considered so far adequate?

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

If \( \lambda_1 = \lambda_3 = 0.01 \text{V}^{-1} \) and \( V_{EB1} = 0.15 \text{V} \), then

\[ A_{V0} \approx \frac{1}{(0.01 + 0.01) \times 0.15} = 333 \]

or, in db, \( A_{V0db} = 20 \log_{10} 333 = 50 \text{db} \)

This is inadequate for many applications!

What can be done about it?
Basic Op Amp Design

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Other Basic Gain Enhancement Approaches
- Two-Stage Op Amp
Determination of op amp characteristics from quarter circuit characteristics

\[ A_v = \frac{V_o^+}{V_d} = \frac{-G_{M1}}{2sC_L + G_1 + G_2} \]

Small signal differential half-circuit

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

\[ BW = \frac{G_1 + G_2}{2C_L} \]

\[ GB = \frac{G_{M1}}{2C_L} \]
How can the gain of the op amp be increased?

Recall from Quarter-Circuit Concept

\[ A_{VO} = \frac{1}{2} \frac{-G_{M1}}{G_1 + G_2} \]

A possible strategy:

Increase \( G_{M1} \) or Decrease \( G_1 \) (and \( G_2 \)) in Quarter Circuit or Both
Single-Stage High-Gain Op Amps

• If the output conductance can be decreased without changing the transconductance, the gain can be enhanced

• Will concentrate on quarter-circuits and extend to op amps
Determination of 2-port parameters

Background

Determination of \{g_{o1}, g_{o2}, g_{M1}, g_{M2}\}

Method 1  Open-Short Termination Approach

Method 2  Load Termination Approach
Background

Determination of 2-port parameters

Determination of \{g_{o1}, g_{o2}, g_{M1}, g_{M2}\}

Method 1  Open-Short Termination Approach

\[
\begin{align*}
g_{M2} &= \frac{-I_{TST}}{V_{TST}} \\
g_{o2} &= \frac{I_{TST}}{V_{TST}}
\end{align*}
\]

By structural symmetry, repeat to obtain \(g_{m1}\) and \(g_{o1}\)
Background

**Determination of 2-port parameters**

**Method 2**  Load Termination Approach

Express the gain $A(s)$ as in form

$$A(s) = \frac{a_0}{sC_L + b_0}$$

Observe

$$V_2(g_{o2} + sC_L) + g_{M2}V_{TST} = 0$$

$$A(s) = \frac{V_2(s)}{V_{TST}(s)} = -\frac{g_{M2}}{sC_L + g_{o2}}$$
Analysis: Cascode Amplifier

\[
\begin{align*}
V_{IN} & = V_1 \\
V_2 & = g_{m2} V_2 \\
V_X & = V_{OUT} \left( g_{o2} + sC_L \right) + g_{m2} V_2 = V_X g_{o2} \\
V_1 & = V_{IN} \\
V_2 & = -V_X \\
V_{OUT} & = V_1 + V_2 \\
V_X & = \frac{V_2}{g_{m1}} \\
V_{OUT} & = V_{IN} + V_2 \\
\end{align*}
\]

\[V_X, V_1 \text{ and } V_2 \text{ can be eliminated from these 4 equations}\]
Background

Analysis of Cascode Amplifier

\[
\begin{align*}
V_{\text{OUT}} (g_{o2} + sC_L) + g_{m2} V_2 &= V_x g_{o2} \\
V_x (g_{o1} + g_{o2}) + g_{m1} V_1 - g_{m2} V_2 &= V_{\text{OUT}} g_{o2} \\
V_2 &= -V_x \\
V_1 &= V_{\text{IN}}
\end{align*}
\]

\[
\begin{align*}
V_{\text{OUT}} (g_{o2} + sC_L) - g_{m2} V_x &= V_x g_{o2} \\
V_x (g_{o1} + g_{o2}) + g_{m1} V_{\text{IN}} + g_{m2} V_x &= V_{\text{OUT}} g_{o2}
\end{align*}
\]

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} = \frac{-g_{m1} (g_{o2} + g_{m2})}{sC_L (g_{o1} + g_{o2} + g_{m2}) + g_{o1}g_{o2}} \approx \frac{-g_{m1}g_{m2}}{sC_L g_{m2} + g_{o1}g_{o2}}
\]

for \(A\) large:

\[
\frac{V_{\text{OUT}}}{V_{\text{IN}}} \approx \frac{g_{m1}}{sC_L + g_{o1} \left(\frac{g_{o2}}{g_{m2}}\right)}
\]
High output impedance quarter-circuits

\[ V_{DD} \]
\[ I_{DB} \]
\[ V_{OUT} \]
\[ M_3 \]
\[ C_L \]
\[ M_1 \]
\[ V_{BB} \]
\[ V_{IN} \]
\[ V_{SS} \]

Cascode Amplifier

\[ g_{oEQ} \approx g_{o1} \left[ \frac{g_{o3}}{g_{m3}} \right] \]

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

Output conductance has been decreased!

\[ A_v(s) \approx \left. \frac{-g_{m1}}{sC_L + g_{o1} \left[ \frac{g_{o3}}{g_{m3}} \right]} \right. \]

\[ A_{V0} \approx \left( \frac{g_{m1}}{g_{o1}} \right) \left[ \frac{g_{o3}}{g_{o2}} \right] \]

\[ GB \approx \frac{g_{m1}}{C_L} \]
High output impedance quarter-circuits

Cascode Amplifier

\[ A_{V0} = \left[ \frac{2}{\lambda_1 V_{EB1}} \right] \cdot \left[ \frac{2}{\lambda_3 V_{EB3}} \right] \]

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

How does this compare with previous amplifier?

\[ A_{V0} = \left[ \frac{2}{\lambda V_{EB}} \right] \]

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

Substantial increase in dc gain

No improvement in GB but also no deterioration in GB!
High output impedance quarter-circuits

Cascode Amplifier (small-signal equiv)
High output impedance quarter-circuits

Cascode Amplifier

Quarter Circuit

Counterpart Circuit
Telescopic Cascode Op Amp

Needs CMFB Circuit for $V_{B1}$ or $V_{B5}$
Either single-ended or differential outputs
Can connect counterpart as current mirror to eliminate CMFB
Determination of op amp characteristics from quarter circuit characteristics

Small signal Quarter Circuit

\[
A_{\text{voqc}} = -\frac{G_M}{G}
\]

\[
\text{BW} = \frac{G}{C_L}
\]

\[
\text{GB} = \frac{G_M}{C_L}
\]

Small signal differential amplifier

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

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

\[
\text{GB} = \frac{G_{M1}}{2C_L}
\]

Note: Factor of 4 reduction of gain
Telescopic Cascode Op Amp

Single-ended operation

\[ g_{OQC} = \quad \]  

\[ g_{OCC} = \quad \]  

\[ g_{mQC} = \quad \]
Telescopic Cascode Op Amp

Single-ended operation

\[ A_0 = \frac{-g_{m1}}{2} \left( \frac{g_{o1}}{g_{m3}} + \frac{g_{o5}}{g_{m7}} \right) \]

\[ GB = \frac{g_{m1}}{2C_L} \]
Telescopic Cascode Op Amp

Single-ended operation

\[ A_o = \frac{-\frac{g_{m1}}{2}}{g_{o1} \frac{g_{o3}}{g_{m3}} + g_{o5} \frac{g_{o7}}{g_{m7}}} \]

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

This circuit is widely used!!
Telescopic Cascode Op Amp

- Tail bias current generator shown
- $I_T$ often one of many outputs for current mirror
- $I_B$ and $M_{12}$ often common to many blocks

(CMFB circuit not shown)
Telescopic Cascode Op Amp

- Current-Mirror p-channel Bias to Eliminate CMFB
- Only single-ended output available
Telescopic Cascode Op Amp

- Differential Output
- CMFB to establish $V_{B1}$ or $V_{B5}$ needed
- Tail current generally generated with current mirror
End of Lecture 7
Telescopic Cascode Op Amp

Signal Swing and Power Supply Limitations

There are a minimum of 2 $V_{DSAT}$ drops between $V_{OUT}$ and $V_{DD}$ and a minimum of 3 $V_{DSAT}$ drops between $V_{OUT}$ and $V_{SS}$

Thus, there are a minimum of 5 $V_{DSAT}$ drops between $V_{DD}$ and $V_{SS}$

This establishes a lower bound on $V_{DD}-V_{SS}$ and it will be reduced by the p-p signal swing on the output
Telescopic Cascode Op Amp

n-channel inputs

p-channel inputs
Are there other high output impedance circuits that can be used as quarter circuits?
Are there other high output impedance circuits that can be used as quarter circuits?

I recall the regulated cascode circuits have this property.
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)
Background

Analysis of Regulated Cascode Amplifier

\[ V_{OUT} (g_{o2} + sC_L) + g_{m2} V_2 = V_X g_{o2} \]
\[ V_X (g_{o1} + g_{o2}) + g_{m1} V_1 - g_{m2} V_2 = V_{OUT} g_{o2} \]
\[ V_2 = -AV_X - V_X \]
\[ V_1 = V_{IN} \]

\( V_X, V_1 \) and \( V_2 \) can be eliminated from these 4 equations
Background

Analysis of Regulated Cascode Amplifier

\[ V_{OUT} \left( g_{o2} + sC_L \right) + g_{m2} V_2 = V_X g_{o2} \]
\[ V_X \left( g_{o1} + g_{o2} \right) + g_{m1} V_1 - g_{m2} V_2 = V_{OUT} g_{o2} \]
\[ V_2 = -A V_X - V_X \]
\[ V_1 = V_{IN} \]

\[ V_{OUT} \left( g_{o2} + sC_L \right) - g_{m2} V_X (1 + A) = V_X g_{o2} \]
\[ V_X \left( g_{o1} + g_{o2} \right) + g_{m1} V_{IN} + g_{m2} V_X (1 + A) = V_{OUT} g_{o2} \]

\[ \frac{V_{OUT}}{V_{IN}} = \frac{-g_{m1} \left( g_{o2} + g_{m2} [1 + A] \right)}{sC_L \left( g_{o1} + g_{o2} + g_{m2} [1 + A] \right) + g_{o1} g_{o2}} \approx \frac{-g_{m1} g_{m2} [1 + A]}{sC_L g_{m2} [1 + A] + g_{o1} g_{o2}} = \frac{-g_{m1}}{sC_L + \frac{g_{o1} g_{o2}}{g_{m2} [1 + A]}} \]

for \( A \) large:

\[ \frac{V_{OUT}}{V_{IN}} \approx \frac{g_{m1}}{sC_L + \left( \frac{g_{o2}}{g_{m2}} \right) \left( \frac{1}{A} \right)} \]

\( g_{MEQ} \)

\( g_{OEQ} \)
High output impedance quarter-circuits

Regulated Cascode Amplifier or “Gain Boosted Cascode”

\[
g_{DEQ} \approx g_{o1} \left( \frac{g_{o3}}{g_{m3}(1+A)} \right)
\]

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

Output conductance has been decreased even more!

\[
A_v(s) \approx \frac{-g_{m1}}{sC_L + g_{o1} \left( \frac{g_{o3}[1+A]}{g_{m3}} \right)}
\]

\[
A_0 \approx \left( \frac{g_{m1}}{g_{o1}} \right) \cdot \left[ \frac{g_{m3}(1+A)}{g_{o3}} \right]
\]

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

Same GB as for previous two circuits
Gain-Boosted Telescopic Cascode Op Amp

Needs CMFB Circuit for Vb1
Either single-ended or differential outputs
Can connect counterpart as current mirror to eliminate CMFB
Use differential op amp to facilitate biasing of cascode device
Gain-Boosted Telescopic Cascode Op Amp

Single-ended operation

\[ g_{OQC} = \] 

\[ g_{OCC} = \] 

\[ g_{mQC} = \]
Gain-Boosted Telescopic Cascode Op Amp

This is modestly less efficient at generating GB because now power is consumed in both the cascode devices and the boosting amplifier.
Gain-Boosted Telescopic Cascode Op Amp

\[
A_o = \frac{-g_{m1}}{g_{o1} A_1 g_{o3} + g_{o5} A_3 g_{o7} g_{m3} g_{m7}}
\]

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

This is modestly less efficient at generating GB because now power is consumed in both the cascode devices and the boosting amplifier.

Elimination of need for CMFB Circuit
Gain-Boosted Telescopic Cascode Op Amp

Signal Swing and Power Supply Limitations

A minimum of 5 $V_{DSAT}$ drops between $V_{DD}$ and $V_{SS}$

This establishes a lower bound on $V_{DD}$-$V_{SS}$ and it will be reduced by the p-p signal swing on the output.
Gain-Boosted Telescopic Cascode Op Amp

(with or w/o current mirror counterpart circuits)

Advantages:

- Significant increase in dc gain

Limitations:

- Signal swing (4VD_{SAT} + V_T between V_{DD} and V_{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
End of Lecture 7
Are there other useful high output impedance circuits that can be used for the quarter circuit?

\[ A_{VO} = \frac{-G_{M_1}}{2(G_1 + G_2)} \]

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

\[ GB = \frac{G_{M_1}}{2C_L} \]
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

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

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

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

<table>
<thead>
<tr>
<th>Structure</th>
<th>$A_{vo}$</th>
<th>$GB$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Source</strong></td>
<td>$g_m / g_o$</td>
<td>$g_m / C_L$</td>
</tr>
<tr>
<td><strong>Cascode</strong></td>
<td>$g_{m1} g_{m3} / g_{o1} g_{o3}$</td>
<td>$g_m / C_L$</td>
</tr>
<tr>
<td><strong>Regulated Cascode</strong></td>
<td>$g_{m1} g_{m3} / g_{o1} g_{o3} \approx A$</td>
<td>$g_m / C_L$</td>
</tr>
<tr>
<td><strong>Folded Cascode</strong></td>
<td>$g_{m1} g_{m3} / (g_{o1} + g_{o5}) g_{o3}$</td>
<td>$g_m / C_L$</td>
</tr>
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## Basic Amplifier Structure Comparisons

<table>
<thead>
<tr>
<th>Practical Parameter Domain</th>
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<tbody>
<tr>
<td><strong>Common Source</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><strong>Cascode</strong></td>
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<tr>
<td>$A_{vo} = \left( \frac{4}{\lambda_1\lambda_3} \right) \left( \frac{1}{V_{EB1}V_{EB3}} \right)$</td>
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<td><strong>Regulated Cascode</strong></td>
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<tr>
<td>$A_{vo} \approx \left( \frac{4}{\lambda_1\lambda_3} \right) \left( \frac{A}{V_{EB1}V_{EB3}} \right)$</td>
</tr>
<tr>
<td><strong>Folded Cascode</strong></td>
</tr>
<tr>
<td>$A_{vo} \approx \left( \frac{4\Theta}{(\theta\lambda_1 + \lambda_5)\lambda_3} \right) \left( \frac{V_{EB1}V_{EB3}}{} \right)$</td>
</tr>
</tbody>
</table>

$\Theta =$ fraction of current of $M_5$ that is in $M_1$
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)

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

\[ A_{V_0} \approx \frac{g_{mEQ}}{g_{OEQ}} \]

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

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

\[ g_{OEQ} \approx \left( g_{o1} + g_{o5} \right) \frac{g_{O3}}{g_{m3}} + \left( g_{o7} \right) \frac{g_{O9}}{g_{m9}} \]

\[ A_{V_0} \approx \frac{g_{m1}}{\left( g_{o1} + g_{o5} \right) \frac{g_{O3}}{g_{m3}} + \left( g_{o7} \right) \frac{g_{O9}}{g_{m9}}} \]

\[ GB = \frac{g_{m1}}{C_L} \]
### Operational Amplifier Structure Comparison

<table>
<thead>
<tr>
<th>Structure</th>
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<td><strong>Reference Op Amp</strong></td>
<td>$A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$</td>
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<td></td>
<td>$SR = \frac{I_T}{2C_L}$</td>
</tr>
<tr>
<td><strong>Telescopic Cascode</strong></td>
<td>$A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1} + \frac{g_{o3}}{g_{m3}} + \frac{g_{o5}}{g_{m5}}}</td>
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<td>$GB = \frac{g_{m1}}{2C_L}$</td>
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<td><strong>Regulated Cascode</strong></td>
<td>$A_o \approx \frac{g_{m1}}{2} \frac{g_{o3}}{g_{o1} + \frac{g_{o3}}{g_{m3} A_1} + \frac{g_{o9}}{g_{m9} A_3}}$</td>
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<tr>
<td><strong>Telescopic Cascode</strong></td>
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<tr>
<td>$A_{v0} = \frac{2}{V_{EB1} \left( \lambda_1 \lambda_3 V_{EB3} + \lambda_5 \lambda_7 V_{EB5} \right)}$</td>
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<td><strong>Regulated Cascode</strong></td>
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<td>$\theta = \text{pct power in } A$</td>
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<td>$\theta = \text{fraction of current of } M_5 \text{ that is in } M_1$</td>
</tr>
</tbody>
</table>
Folded Cascode Op Amp (Single-ended Output)

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

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

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

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

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

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

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

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

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

modest improvement in output swing
<table>
<thead>
<tr>
<th>Basic Amplifier Structure Comparisons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small Signal Parameter Domain</strong></td>
</tr>
<tr>
<td><strong>Common Source</strong></td>
</tr>
<tr>
<td>$A_{vo} = \frac{g_m}{g_o}$</td>
</tr>
<tr>
<td>$GB = \frac{g_m}{C_L}$</td>
</tr>
<tr>
<td><strong>Cascode</strong></td>
</tr>
<tr>
<td>$A_{vo} = \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}}$</td>
</tr>
<tr>
<td>$GB = \frac{g_{m1}}{C_L}$</td>
</tr>
<tr>
<td><strong>Regulated Cascode</strong></td>
</tr>
<tr>
<td>$A_{vo} \approx \frac{g_{m1} g_{m3}}{g_{o1} g_{o3}} A$</td>
</tr>
<tr>
<td>$GB = \frac{g_{m1}}{C_L}$</td>
</tr>
<tr>
<td><strong>Folded Cascode</strong></td>
</tr>
<tr>
<td>$A_{vo} = \frac{g_{m1} g_{m3}}{(g_{o1} + g_{o5}) g_{o3}}$</td>
</tr>
<tr>
<td>$GB = \frac{g_{m1}}{C_L}$</td>
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<tr>
<td><strong>Folded Regulated Cascode</strong></td>
</tr>
<tr>
<td>$A_{vo} = \frac{g_{m1} g_{m3}}{(g_{o1} + g_{o5}) g_{o3}} A$</td>
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<tr>
<td>$GB = \frac{g_{m1}}{C_L}$</td>
</tr>
</tbody>
</table>
# Basic Amplifier Structure Comparisons

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

\[ A_o \approx \frac{-g_{m1}}{2} \left( g_{o1} + g_{05} \right) + g_{o7} \frac{g_{o9}}{A_3 g_{m3}} + g_{o7} \frac{g_{o9}}{A_1 g_{m9}} \]

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

- 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

<table>
<thead>
<tr>
<th>Reference Op Amp</th>
<th>[ A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}} ]</th>
<th>[ GB = \frac{g_{m1}}{2C_L} ]</th>
<th>[ SR = \frac{I_T}{2C_L} ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescopic Cascode</td>
<td>[ A_o = \frac{g_{m1}}{2} \frac{g_{o3}}{g_{m3}} + \frac{g_{o7}}{g_{m5}} ]</td>
<td>[ GB = \frac{g_{m1}}{2C_L} ]</td>
<td>[ SR = \frac{I_T}{2C_L} ]</td>
</tr>
<tr>
<td>Regulated Cascode</td>
<td>[ A_o \approx \frac{g_{m1}}{2} \frac{g_{o3}}{g_{m3} A_1} + \frac{g_{o7}}{g_{m9} A_3} ]</td>
<td>[ GB = \frac{g_{m1}}{2C_L} ]</td>
<td>[ SR = \frac{I_T}{2C_L} ]</td>
</tr>
<tr>
<td>Folded Cascode</td>
<td>[ A_o = \frac{g_{m1}}{2} \frac{(g_{o1} + g_{o5}) g_{o3}}{g_{m3} A_3} + \frac{g_{o7}}{g_{m9} A_3} ]</td>
<td>[ GB = \frac{g_{m1}}{2C_L} ]</td>
<td>[ SR = \frac{I_T}{2C_L} ]</td>
</tr>
<tr>
<td>Folded Regulated Cascode</td>
<td>[ A_o = \frac{g_{m1}}{2} \frac{(g_{o1} + g_{o5}) g_{o3}}{g_{m3} A_3} + \frac{g_{o7}}{g_{m9} A_3} ]</td>
<td>[ GB = \frac{g_{m1}}{2C_L} ]</td>
<td>[ SR = \frac{I_T}{2C_L} ]</td>
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</tbody>
</table>
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 $I_B$

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

\[ A_{v0} = -\frac{g_{m\text{EQ}}}{g_{\text{DEQ}}} \]

\[ GB = \frac{g_{m\text{EQ}}}{C_L} \]
Current Mirror Op Amps

Need CMFB tp 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

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

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

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

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

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