EE 435

Lecture 6:

Current Mirrors
Signal Swing
Telescopc Cascode Op Amp
Review from last lecture:
Performance with Common-Mode Input

Consider tail-current bias amplifier

\[ v_{OUTC} = 0 \] thus \( A_C = 0 \)
Performance with Common-Mode Input

Consider tail-voltage bias amplifier

\[ v_{\text{OUTC}} = v_{\text{C}} \]

Solving, we obtain

\[ \frac{v_{\text{OUTC}}}{v_{\text{C}}} = A_C = \frac{-G_{M1}}{sC + G_1 + G_2} \]

This circuit has a rather large common-mode gain and will not reject common-mode signals.
Applications of Quarter-Circuit Concept to Op Amp Design

Consider initially the basic single-ended amplifier

Review from last lecture:
Review from last lecture:

Single-stage single-input low-gain op amp

Basic Structure

Quarter Circuit

Counterpart Circuit

Practical Implementation
Review from last lecture:

Single-stage low-gain differential op amp

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

\[
A_o = \frac{g_{m1}}{2g_{o1} + g_{o3}}
\]

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

What are the number of degrees of freedom?
(assume \(V_{DD}, C_L\) fixed)

Natural Parameters:
\[
\left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, V_{B1}, V_{B3} \right\}
\]

Constraints: \(I_{D5} \approx 2I_{D3}\)

Net Degrees of Freedom: 4

Practical Parameters:
\[
\left\{ V_{EB1}, V_{EB3}, V_{EB5}, P \right\}
\]

Need a CMFB circuit to establish \(V_{b1}\)
Review from last lecture:
Expressions valid for both tail-current and tail-voltage op amp

So which one should be used?

- Common-mode input range large for tail current bias
- Improved rejection of common-mode signals for tail current bias
- Extra design degree of freedom for tail current bias
- Improved output signal swing for tail voltage bias (will show later)
Definition: The slew rate of an amplifier is the maximum rate of change that can occur at an output node.

SR is a nonlinear large-signal characteristic. Input is over-driven hard (some devices in amplifier usually leave normal operating region). Magnitude of SR⁺ and SR⁻ usually same and called SR (else SR⁺ and SR⁻ must be given).
With step input on $V_{\text{IN}}^+$, all tail current ($I_T$) will go to $M_1$ thus turning off $M_2$ thus current through $M_4$ which is $\frac{1}{2}$ of $I_T$ will go to load capacitor $C_L$.

The I-V characteristics of any capacitor is

$$I = C \frac{dV}{dt}$$

Substituting $I = I_T/2$, $V = V_{\text{OUT}}^+$ and $C = C_L$ obtain a voltage ramp at the output thus

$$SR^+ = \frac{dV_{\text{OUT}}^+}{dt} = \frac{I_T}{2C_L} = \frac{P}{V_{DD}2C_L}$$
Review from last lecture:

**Slew Rate**

![Slew Rate Diagram]

It can be similarly shown that putting a negative step on the input steer all current to $M_2$ thus the current to the capacitor $C_L$ will be $I_T$ minus the current from $M_2$ which is still $I_T/2$. This will cause a negative ramp voltage on $V_{OUT}^+$ of value

$$SR^- = \frac{dV_{OUT}^+}{dt} = -\frac{I_T}{2C_L} = -\frac{P}{V_{DD}2C_L}$$

Since the magnitude of $SR^+$ and $SR^-$ are the same, obtain a single SR for the amplifier of value

$$SR = \frac{P}{V_{DD}2C_L}$$
**Review from last lecture:**

**Single-stage low-gain differential op amp**

Consider single-ended output performance:

Will term this the **reference op amp**

Will make performance comparisons of other op amps relative to this

\[ A(s) = \frac{1}{sC_L + g_{o1} + g_{o3}} \]

**mixed parameters**

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

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

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

**practical parameters**

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

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

\[ SR = \frac{P}{2V_{DD} C_L} \]

Need a CMFB circuit to establish \( V_{b1} \)
Reference Op Amp

Review from last lecture:

Need a CMFB circuit to establish $V_{b1}$
### Amplifier Structure Summary

#### Small Signal Parameter Domain

<table>
<thead>
<tr>
<th>Common Source</th>
<th>$A_{vo} = \frac{g_m}{g_o}$</th>
<th>$GB = \frac{g_m}{C_L}$</th>
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#### Practical Parameter Domain

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<th>Common Source</th>
<th>$A_{vo} = \left( \frac{2}{\lambda} \right) \left( \frac{1}{V_{EB}} \right)$</th>
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#### Reference Op Amp

| | $A_{vo} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}$ | $GB = \frac{g_{m1}}{2C_L}$ | $SR = \frac{I_T}{2C_L}$ |

#### Practical Parameter Domain

| Reference Op Amp | $A_{vo} = \left( \frac{1}{\lambda_1 + \lambda_3} \right) \left( \frac{1}{V_{EB1}} \right)$ | $GB = \left( \frac{P}{2V_{DD}C_L} \right) \left( \frac{1}{V_{EB1}} \right)$ | $SR = \frac{P}{2V_{DD}C_L}$ |

**Review from last lecture:**
Review from last lecture:

Single-stage low-gain differential op amp

Need a CMFB circuit to establish $V_{B1}$ or $V_{B2}$

CMFB amplifies difference between $V_{B1}$ and average of two signal inputs

Can apply to either $V_{B1}$ or $V_{B2}$ but not both
Single-stage low-gain differential op amp

Need a CMFB circuit to establish $V_{b1}$

The CMFB circuit is often quite large and requires considerable design effort!

Can the CMFB be removed?
The signal dependent current in quarter circuit is steered to output node and drives the parallel output conductances of the quarter circuit and counterpart circuit.

If the signal-dependent current could be doubled, the gain would be doubled as well!

- The differential gain $A_{VO}$ is given by:
  \[ A_{VO} = \frac{-G_{M1}}{2(G_1 + G_2)} \]
- The bandwidth $BW$ is given by:
  \[ BW = \frac{G_1 + G_2}{C_L} \]
- The gain-bandwidth product $GB$ is given by:
  \[ GB = \frac{G_{M1}}{2C_L} \]
Operation of Op Amp – A different perspective

Small signal differential half-circuit

Connecting the bias port of the quarter circuit to $V_0^-$ instead of to $V_{BB}$ will cause the signal current in the right counterpart circuit to be equal to that in the left counterpart circuit.

This will double the signal current to $V_o^+$ and thus double the voltage gain!

This will also eliminate the need for a CMFB circuit!
Current Mirrors

If the current \( I_{BB} \) is small compared to \( I_{IN} \), then \( I_{OUT} \approx I_{IN} \)

Circuits with this property are called Current Mirrors

If multiple copies of the right circuit are placed in parallel, the current will be scaled by the number of copies

These scaled circuits are also called Current Mirrors

As long as \( I_{BB} \ll I_{IN} \), this scaling in currents occurs even if the circuits are highly nonlinear!
Operation of Op Amp – A different perspective
Current Mirrors

- Current mirrors are really just a current amplifier
- Simple current mirror was used to eliminate CMFB and double gain in basic op amp
- Many different current mirrors exist with varying levels of performance
Basic Current Mirror

\[ I_{IN} = \frac{\mu C_{OX} W_1}{2L_1} (V_{GS1} - V_T)^2 \]

\[ I_{OUT} = \frac{\mu C_{OX} W_2}{2L_2} (V_{GS2} - V_T)^2 \]

\[ \frac{I_{OUT}}{I_{IN}} = \frac{W_2}{W_1} \frac{L_1}{L_2} \]

n-channel

At the output port, small signal equivalent is a one-port

\[ g_{out} = g_{02} \]
Basic Current Mirror

At the output port, small signal equivalent is a one-port

\[ g_{\text{out}} = g_{02} \]
Current Mirrors

• More advanced current mirrors exist

• Several of these are discussed in the text
Current Mirrors

Properties of Current Mirrors of Interest:

- Mirror Gain Accuracy
- Signal Swing at Output
- Output Impedance (ideally infinite)

More advanced current mirrors usually offer improvements in one or more of these properties
More Advanced Current Mirrors

- **Cascode Current Mirror**
  - $I_{IN} \rightarrow M_3 \rightarrow M_4 \rightarrow I_{OUT}$
  - $M_1 \leftarrow M_2$

- **Wilson Current Mirror**
  - $I_{IN} \rightarrow M_3 \rightarrow M_4 \rightarrow I_{OUT}$
  - $M_1 \leftarrow M_2$

- **Modified Wilson Current Mirror**
  - $I_{IN} \rightarrow M_4 \rightarrow I_{OUT}$
  - $M_1 \leftarrow M_2$
USPTO search on Jan 25, 2009
433 patents with “current and mirror” in title since 1976

Searching US Patent Collection...

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 433 patents.
Hits 1 through 50 out of 433

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36 patents with “current and mirror” in title in 2007 and 2008

Results of Search in US Patent Collection db for:
(TTL/(current AND mirror) AND ISD/20070101-20090101): 36 patents.

*Hits 1 through 36 out of 36*

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<td>7,439,480</td>
<td>Regulated current mirror</td>
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<tr>
<td>7,432,696</td>
<td>Apparatus and method for low input voltage current mirror circuit</td>
</tr>
<tr>
<td>7,429,854</td>
<td>CMOS current mirror circuit and reference current/voltage circuit</td>
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<tr>
<td>7,425,870</td>
<td>Current mirror circuit</td>
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<td>7,423,476</td>
<td>Current mirror circuit having drain-source voltage clamp</td>
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USPTO search on Jan 25, 2009

433 patents with “current and mirror” in title since 1976

36 patents with “current and mirror” in title in 2007 and 2008

Averaged 12.4 patents/year from 1976 to 2006
Averaged 18 patents in 2007 and 2008
Single-stage low-gain differential op amp

- Can eliminate CMFB circuit if only single-ended output is needed by connecting counterpart circuits as a current mirror
- This will double the voltage gain and the GB as well
- Still uses counterpart circuits but terminated in different ways
- Although not symmetric, previous analysis results with specified modifications still nearly apply
Single-stage low-gain differential op amp

Current-Mirror Connected Counterpart Circuit

No CMFB Circuit Needed

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

\[ A_o = \frac{g_{m1}}{g_{o1} + g_{o3}} \]

\[ GB = \frac{g_{m1}}{C_L} \quad SR = \frac{I_T}{C_L} \]

In terms of practical design space parameters

\[ A_o = \left[ \frac{2}{\lambda_1 + \lambda_3} \right] \left( \frac{2}{V_{EB1}} \right) \]

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

\[ SR = \frac{P}{V_{DD}C_L} \]
Signal Swing

To keep $M_1$ out of Triode Region

$\mathcal{L}_1$: $V_{\text{OUT}} > V_{iN} - V_{Tn}$

To keep $M_1$ out of Cutoff

$\mathcal{L}_2$: $V_{iN} > V_{Tn}$

To keep $M_2$ out of Triode Region

$\mathcal{L}_3$: $|V_{\text{OUT}} - V_{DD}| > |V_{XX} - V_{DD} - V_{Tp}|$

$V_{XX} - V_{Tp} > V_{\text{OUT}}$
Signal Swing

\[ L_1: \quad V_{\text{OUT}} > V_{\text{iN}} - V_{\text{Tn}} \]

\[ L_2: \quad V_{\text{iN}} > V_{\text{Tn}} \]

\[ L_3: \quad V_{XX} - V_{Tp} > V_{\text{OUT}} \]

\[ V_{\text{OUT}} \]

\[ V_{\text{iC}} \]

\[ V_{\text{CC}} \]

\[ V_{\text{Tn}} \]
$\mathcal{L}_1: \ V_{\text{OUT}} > V_{\text{iN}} - V_{\text{Tn}}$

$\mathcal{L}_2: \ V_{\text{iN}} > V_{\text{Tn}}$

$\mathcal{L}_3: \ V_{XX} - V_{TP} > V_{\text{OUT}}$
Signal Swing

How do the transfer characteristics relate to the signal swing?

Observe signal swing boundaries are same as operating region changes for transfer characteristics.
Signal Swing

How do the transfer characteristics relate to the signal swing?

For this circuit, high gain and large output signal swing for small $V_{EB1}$. 
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
Signal Swing of Single-Stage Op Amp

What type of signal swing is needed?

Wide $V_{iC}$ and $V_{OUT}$ range

Narrow $V_{iC}$ and wide $V_{OUT}$ range

Narrow $V_{OUT}$ and wide $V_{iC}$ range

Narrow $V_{iC}$ and $V_{OUT}$ range
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
Signal Swing of Single-Stage Op Amp

Constraining Equations:

To keep M₂ in Saturation:

\[ \mathcal{L}_1: \quad V_{\text{OUT}} > V_{\text{i}c} - V_{T2} \]

To keep M₄ in Saturation:

\[ \mathcal{L}_2: \quad V_{\text{OUT}} < V_{\text{DD}} - |V_{EB4}| \]

To keep M₁ in Saturation:

\[ \mathcal{L}_3: \quad V_{\text{i}c} < V_{\text{DD}} + V_{T1} - |V_{T3}| - |V_{EB3}| \]

To keep M₅ in Saturation:

\[ \mathcal{L}_4: \quad V_{\text{i}c} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS} \]
Signal Swing of Single-Stage Op Amp

To keep M2 in Saturation:
\[ \mathcal{L}_1: \quad V_{\text{OUT}} > V_{\text{ic}} - V_{T2} \]

To keep M4 in Saturation:
\[ \mathcal{L}_2: \quad V_{\text{OUT}} < V_{\text{DD}} - |V_{\text{EB4}}| \]

To keep M1 in Saturation:
\[ \mathcal{L}_3: \quad V_{\text{ic}} < V_{\text{DD}} + V_{T1} - |V_{T3}| - |V_{\text{EB3}}| \]

To keep M5 in Saturation:
\[ \mathcal{L}_4: \quad V_{\text{ic}} > V_{T1} + V_{\text{EB1}} + V_{\text{EB5}} + V_{\text{SS}} \]
Signal Swing of Single-Stage Op Amp

Constraining Equations:

- $\mathcal{L}_1$: $V_{\text{OUT}} > V_{\text{ic}} - V_{T2}$
- $\mathcal{L}_2$: $V_{\text{OUT}} < V_{DD} - |V_{EB4}|$
- $\mathcal{L}_3$: $V_{\text{ic}} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$
- $\mathcal{L}_4$: $V_{\text{ic}} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$
Signal Swing of Single-Stage Op Amp

\[ V_{OUT} \]

\[ \mathcal{L}_1 \quad \mathcal{L}_2 \quad \mathcal{L}_3 \quad \mathcal{L}_4 \]

\[ V_{SS} \quad V_{DD} \quad V_{EB4} \quad V_{EB3} \]

\[ V_{T1} + V_{EB1} + V_{EB5} \]

\[ |V_{EB3}| + |V_{T3}| - V_{T1} \]
Signal Swing of Single-Stage Op Amp

Constraining Equations:

\[
\begin{align*}
V_{OUT} &> V_{ic} - V_{T2} \\
V_{OUT} &< V_{DD} - |V_{EB4}| \\
V_{ic} &< V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}| \\
V_{ic} &> V_{T1} + V_{EB1} + V_{EB5} + V_{SS}
\end{align*}
\]

Signal swings are Important Performance Parameters!!
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
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 \}:

\[
A_{V_0} = \left[ \frac{4\mu_n C_{OX}}{\lambda_1 + \lambda_3} \right] \frac{W_1}{\sqrt{L_1}}
\]

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

\[
G_B = \left[ \frac{\mu_n C_{OX}}{L} \right] \sqrt{\frac{W_1}{L_1}} \sqrt{\frac{1}{I_T}}
\]

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

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

Complicated Expressions in Practical Parameter Domain
End of Lecture 6
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
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 \( \lambda_1 = \lambda_3 = .01 V^{-1} \) and \( V_{EB1} = .15 V \), then

\[
A_{v0} \approx \frac{1}{(.01 + .01)} \times \frac{1}{.015} = 333
\]

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

\[ A_V = \frac{V_O^+}{V_d} = \frac{-G_{M1}}{2} \frac{1}{sC_L + G_1 + G_2} \]

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

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

\[ GB = \frac{G_{M1}}{2C_L} \]
Single-Stage High Gain Op Amps

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
End of Lecture 6
Background

Determination of 2-port parameters

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

\[
\begin{align*}
V_TST^+ & \quad V_1 \quad g_{o1} \quad g_{M1} V_2 \quad g_{M2} V_1 \quad g_{o2} \quad V_2 \quad I_{TST}^- \\
\end{align*}
\]

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

**Determination of 2-port parameters**

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

**Method 2**  Load Termination Approach

Express the gain \( A(s) \) as in form:

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

Observe:

\[
V_2(g_{o2} + sC_L) + g_{M2}V_{TST} = 0
\]

\[
A(s) = \frac{V_2(s)}{V_{TST}(s)} = -\frac{g_{M2}}{sC_L + g_{o2}}
\]
Background

Analysis  Cascode Amplifier

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

$V_X, V_1$ and $V_2$ can be eliminated from these 4 equations.