EE 435

Lecture 6:

Current Mirrors
Signal Swing
Basic Op Amp Design

- Fundamental Amplifier Design Issues
- Single-Stage Low Gain Op Amps
- Single-Stage High Gain Op Amps
- Two-Stage Op Amp
- Other Basic Gain Enhancement Approaches
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:
\[
\{V_{EB1}, V_{EB3}, V_{EB5}, P\}
\]

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)
Slew Rate

Definition: The slew rate of an amplifier is the maximum rate of change that can occur at an output node.

Amplifier

\[ \text{Slope} = \text{SR}^+ \]

\[ \text{Slope} = \text{SR}^- \]

SR is a nonlinear large-signal characteristic.
Input is over-driven hard (some devices in amplifier usually leave normal operating region).
Magnitude of \( \text{SR}^+ \) and \( \text{SR}^- \) usually same and called SR (else \( \text{SR}^+ \) and \( \text{SR}^- \) must be given).
The Reference Op Amp
(CMFB not shown)

The Reference Op Amp
(CMFB not shown)

This is probably the simplest differential input op amp and is widely used.
Will go to more complicated structures only if better performance is required.

Review from last lecture:

Reference Op Amp
single-ended output

$V_{DD}$

$V_{B1}$

$V_{B2}$

$V_{IN}$

$V_{OUT}$

$C_L$

$M_1$

$M_2$

$M_3$

$M_4$

$M_9$

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

mixed parameters

practical parameters

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

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

$GB = \frac{g_{m1}}{2C_L}$

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

$SR = \frac{I_r}{2C_L}$

$SR = \frac{P}{2V_{DD}C_L}$
## 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>
</tr>
</thead>
</table>

### Practical Parameter Domain

<table>
<thead>
<tr>
<th>Common Source</th>
<th>$A_{vo} = \left(\frac{2}{\lambda}\right) \left(\frac{1}{V_{EB}}\right)$</th>
<th>$GB = \left(\frac{2P}{V_{DD}C_L}\right) \left(\frac{1}{V_{EB}}\right)$</th>
</tr>
</thead>
</table>

### Small Signal Parameter Domain

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<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>$SR = \frac{g_{01}}{\lambda C_L}$</th>
</tr>
</thead>
</table>

### Practical Parameter Domain

<table>
<thead>
<tr>
<th>Reference Op Amp</th>
<th>$A_{vo} = \left[\frac{1}{\lambda_1 + \lambda_3}\right] \left(\frac{1}{V_{EB1}}\right)$</th>
<th>$GB = \left(\frac{P}{2V_{DD}C_L}\right) \left[\frac{1}{V_{EB1}}\right]$</th>
<th>$SR = \frac{P}{2V_{DD}C_L}$</th>
</tr>
</thead>
</table>

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

Often apply to only fraction of transistor
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?
Operation of Op Amp – A different perspective

Small signal differential half-circuit

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!

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

$$BW = \frac{G_1 + G_2}{C_L}$$

$$GB = \frac{G_{M1}}{2C_L}$$
Operation of Op Amp – A different perspective

If the input impedance to the counterpart circuit is infinite and the quiescent values of the left and right drain voltages are the same, connecting the bias port of the quarter circuit to $V_{O^-}$ 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 steered 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 $I_{IN}$, and the current $I_{IN}$ is nearly independent of the voltage across $P$, 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 provided the voltages across the circuits are the same!
Consider using single n-mos transistor as quarter circuit

Note counterpart circuits can be recognized as the basic current mirror
Current Mirrors

• Current mirrors are really just a current amplifier
• Current mirror can be used to eliminate CMFB and double gain in basic op amp
• Many different current mirrors exist with varying levels of performance
• Current mirror not necessarily from counterpart of quarter circuit but often is
Basic Current Mirror

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

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

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

n-channel
Basic Current Mirror

\[ I_{\text{IN}} \rightarrow I_{\text{OUT}} \]

M1 \quad M2

n-channel

Small-signal two-port model

\[ \begin{align*}
\text{gm1} + g_{01} & \quad \frac{g_{m2}}{g_{m1} + g_{01}} i_1 \\
g_{02} & \quad g_{02}
\end{align*} \]

Simplified small-signal two-port model

\[ \begin{align*}
g_{m1} & \quad \frac{g_{m2}}{g_{m1}} i_1 \\
g_{02} & \quad g_{02}
\end{align*} \]

OR equivalently

\[ \begin{align*}
g_{m1} & \quad \frac{W_2 L_1}{W_1 L_2} i_1 \\
g_{02} & \quad g_{02}
\end{align*} \]
Basic Current Mirror

\[ I_{IN} = \frac{\mu C_{OX} W_{1}}{2L_{1}} (V_{GS1} - V_{T})^2 \]

\[ I_{OUT} = \frac{\mu C_{OX} W_{2}}{2L_{2}} (V_{GS2} - V_{T})^2 \]

\[ \frac{I_{OUT}}{I_{IN}} = \frac{W_{2}}{W_{1}} \frac{L_{1}}{L_{2}} \]
Current Mirrors

- More advanced current mirrors exist
- Several of these are discussed in the text
Current Mirrors

\[ I_{\text{OUT}} = K I_{\text{IN}} \]

- Quarter circuits with high output impedance are useful for building current mirrors.
- Replication of K copies is often simply denoted as a device sizing or scaling factor.

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**
  - $I_{IN}$ to $I_{OUT}$
  - $M_1 M_2 M_3 M_4$

- **Wilson Current Mirror**
  - $I_{IN}$ to $I_{OUT}$
  - $M_1 M_2 M_3 M_4$

- **Modified Wilson Current Mirror**
  - $I_{IN}$ to $I_{OUT}$
  - $M_1 M_2 M_4$
Current Mirrors

- The concept of the current mirror was first introduced in about 1969 (not certain who introduced it but probably Wheatley and Wittlinger)

- Many of the basic current mirror circuits were introduced within a few years after the concept first appeared

- How many current mirror circuits are there?

- Have any current mirrors been introduced recently?

- Is there still an opportunity to contribute to the current mirror field?
# USPTO search on Jan 21, 2018

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

<table>
<thead>
<tr>
<th>PAT. NO.</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>9,864,395</td>
<td>Base current compensation for a BJT current mirror</td>
</tr>
<tr>
<td>9,857,824</td>
<td>Calibration of a resistor in a current mirror circuit</td>
</tr>
<tr>
<td>9,829,066</td>
<td>Current mirror circuit and receiver using the same</td>
</tr>
<tr>
<td>9,787,178</td>
<td>Current mirror circuit and charge pump circuit</td>
</tr>
<tr>
<td>9,746,871</td>
<td>Noise canceling current mirror circuit for improved PSR</td>
</tr>
<tr>
<td>9,740,232</td>
<td>Current mirror with tunable mirror ratio</td>
</tr>
<tr>
<td>9,728,256</td>
<td>Methods and apparatuses having a voltage generator with an adjustable voltage drop for representing a voltage drop</td>
</tr>
<tr>
<td>9,713,212</td>
<td>Current mirror circuit and method</td>
</tr>
<tr>
<td>9,693,417</td>
<td>LED mains voltage measurement using a current mirror</td>
</tr>
<tr>
<td>9,680,483</td>
<td>Current mirror circuit and charge pump circuit</td>
</tr>
<tr>
<td>9,671,228</td>
<td>Floating current mirror for RLG discharge control</td>
</tr>
<tr>
<td>9,641,167</td>
<td>Current mirror circuits with narrow bandwidth bias noise reduction</td>
</tr>
<tr>
<td>9,638,584</td>
<td>Differential temperature sensor with sensitivity set by current-mirror and resistor ratios without limiting DC bias</td>
</tr>
<tr>
<td>9,632,522</td>
<td>Current mirror bias circuit with voltage adjustment</td>
</tr>
<tr>
<td>9,622,303</td>
<td>Current mirror and constant-current LED driver system for constant-current LED driver IC device</td>
</tr>
<tr>
<td>9,595,310</td>
<td>Circuits for control of time for read operation, using a current mirror circuit to mirror a reference current into the du</td>
</tr>
<tr>
<td>9,563,223</td>
<td>Low-voltage current mirror circuit and method</td>
</tr>
<tr>
<td>9,559,641</td>
<td>Current mirror, control method, and image sensor</td>
</tr>
<tr>
<td>9,548,022</td>
<td>Pixel and organic light emitting display device including current mirror</td>
</tr>
<tr>
<td>9,497,402</td>
<td>Image lag mitigation for buffered direct injection readout with current mirror</td>
</tr>
</tbody>
</table>
USPTO search on Jan 26, 2014
509 patents with “current and mirror” in title since 1976

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 509 patents.
Hits 1 through 50 out of 509

<table>
<thead>
<tr>
<th>PAT. NO.</th>
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<tbody>
<tr>
<td>1 8,618,787</td>
<td>Current mirror and high-compliance single-stage amplifier</td>
</tr>
<tr>
<td>2 8,598,953</td>
<td>System and method for pre-charging a current mirror</td>
</tr>
<tr>
<td>3 8,598,914</td>
<td>Comparator circuit with current mirror</td>
</tr>
<tr>
<td>4 8,587,287</td>
<td>High-bandwidth linear current mirror</td>
</tr>
<tr>
<td>5 8,575,971</td>
<td>Current mirror and current cancellation circuit</td>
</tr>
<tr>
<td>6 8,569,674</td>
<td>Multiplexed photocurrent monitoring circuit comprising current mirror circuits</td>
</tr>
<tr>
<td>7 8,537,868</td>
<td>Laser diode write driver feedback, current mirror, and differential-pair circuitry</td>
</tr>
<tr>
<td>8 8,531,226</td>
<td>Current mirror arrangement and method for switching on a current</td>
</tr>
<tr>
<td>9 8,519,794</td>
<td>Current mirror with low headroom and linear response</td>
</tr>
<tr>
<td>10 8,511,842</td>
<td>Eddy current based mirror wavefront control</td>
</tr>
<tr>
<td>11 8,502,751</td>
<td>Pixel driver circuit with load-balance in current mirror circuit</td>
</tr>
<tr>
<td>12 8,471,631</td>
<td>Bias circuit, power amplifier, and current mirror circuit</td>
</tr>
<tr>
<td>13 8,456,227</td>
<td>Current mirror circuit</td>
</tr>
<tr>
<td>14 8,450,992</td>
<td>Wide-swing cascode current mirror</td>
</tr>
<tr>
<td>15 8,441,381</td>
<td>Gate leakage compensation in a current mirror</td>
</tr>
</tbody>
</table>
USPTO search on Jan 22, 2012
475 patents with “current and mirror” in title since 1976

Results of Search in US Patent Collection db for:
TTL/(current AND mirror): 475 patents.
Hits 1 through 50 out of 475

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<tr>
<td>8,026,757</td>
<td>Current mirror circuit, in particular for a non-volatile memory device</td>
</tr>
<tr>
<td>7,994,861</td>
<td>System and method for pre-charging a current mirror</td>
</tr>
<tr>
<td>7,973,488</td>
<td>Constant current driver circuit with voltage compensated current sense mirror</td>
</tr>
<tr>
<td>7,933,138</td>
<td>F-RAM device with current mirror sense amp</td>
</tr>
<tr>
<td>7,932,712</td>
<td>Current-mirror circuit</td>
</tr>
<tr>
<td>7,923,942</td>
<td>Constant current source mirror tank dimmable ballast for high impedance lamps</td>
</tr>
<tr>
<td>7,915,948</td>
<td>Current mirror circuit</td>
</tr>
<tr>
<td>7,911,870</td>
<td>Fuse data read circuit having control circuit between fuse and current mirror circuit</td>
</tr>
<tr>
<td>7,907,012</td>
<td>Current mirror with low headroom and linear response</td>
</tr>
<tr>
<td>7,894,235</td>
<td>F-RAM device with current mirror sense amp</td>
</tr>
<tr>
<td>7,889,106</td>
<td>Current mirror circuit and digital-to-analog conversion circuit</td>
</tr>
<tr>
<td>7,868,808</td>
<td>Phase-locked loop circuitry using charge pumps with current mirror circuitry</td>
</tr>
<tr>
<td>7,859,135</td>
<td>Internal power supply circuit having a cascode current mirror circuit</td>
</tr>
<tr>
<td>7,858,966</td>
<td>Protected qubit based on superconducting current mirror</td>
</tr>
<tr>
<td>7,851,834</td>
<td>Cascode current mirror and method</td>
</tr>
<tr>
<td>7,839,670</td>
<td>F-RAM device with current mirror sense amp</td>
</tr>
<tr>
<td>7,834,694</td>
<td>Differential current mirror circuit</td>
</tr>
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USPTO search on Jan 21, 2018

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

26 patents with “current and mirror” in title in 2016 and 2017

• Averaged 12.4 patents/year from 1976 to 2006
• Averaged 17 patents/year in 2012 and 2013
• Averaged 13 patents/year in 2016 and 2017
USPTO search on Jan 21, 2018

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

26 patents with “current and mirror” in title in 2016 and 2017

Number of patents/year is about at the 3-decade average

Is there still an opportunity to contribute to the current mirror field?
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

Assume left and right sides matched

Slew Rate?

When \( V_d \) large and negative,

\[
I_C = -I_T
\]

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

When \( V_d \) large and positive,

\[
I_C = I_T
\]

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

In terms of practical parameter set

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

\[
V_d = V^{+}_{IN} - V^{-}_{IN}
\]
Single-stage low-gain differential op amp

Current-Mirror Connected Counterpart Circuit

No CMFB Circuit Needed

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

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

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

In terms of practical design space parameters

\[ A_0 = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{2}{V_{EB1}} \right) \]

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

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

Consider single-input amplifier first

To keep $M_1$ out of Triode Region

$L_1$: $V_{OUT} > V_{iN} - V_{Tn}$

To keep $M_1$ out of Cutoff

$L_2$: $V_{iN} > V_{Tn}$

To keep $M_2$ out of Triode Region

$L_3$: $|V_{OUT} - V_{DD}| > |V_{XX} - V_{DD} - V_{Tp}|$

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

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

\[ \mathcal{L}_2 : \quad V_{iN} > V_{Tn} \]

\[ \mathcal{L}_3 : \quad V_{XX} - V_{Tp} > V_{OUT} \]
Signal Swing

\[ \mathcal{L}_1: \quad V_{OUT} > V_{IN} - V_{Tn} \]
\[ \mathcal{L}_2: \quad V_{IN} > V_{Tn} \]
\[ \mathcal{L}_3: \quad V_{XX} - V_{Tp} > V_{OUT} \]
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
End of Lecture 6