EE 435

Lecture 6:

Current Mirrors
Signal Swing
Consider tail-current bias amplifier

Solving, we obtain

\[ V_{\text{OUTC}} = 0 \quad \text{thus} \quad A_C = 0 \]
Performance with Common-Mode Input

Consider tail-voltage bias amplifier

Review from last lecture:

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
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)
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).

Review from last lecture:
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

$$SR = \frac{P}{V_{DD}2C_L}$$
Reference Op Amp

single-ended output

The Reference Op Amp
(CMFB not shown)

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

mixed parameters

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

practical parameters

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

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

\[
A_{v0} = \frac{1}{\lambda_1 + \lambda_3} \left[ \frac{1}{V_{EB1}} \right]
\]

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

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

Review from last lecture:
Review from last lecture:
Amplifier Structure Summary

<table>
<thead>
<tr>
<th>Small Signal Parameter Domain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Common Source</strong></td>
</tr>
<tr>
<td>$A_{vo} = \frac{g_m}{g_o}$</td>
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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?
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

Small signal differential half-circuit

If the input impedance to the counterpart circuit is infinite, 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 $V_0^+$ 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

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

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

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

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

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

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

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

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

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

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

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

Replication of K copies is often simply denoted as a device sizing or scaling factor

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

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**
  - Diagram: M₁ → M₂ → M₃ → M₄
  - Function: Increases current gain

- **Wilson Current Mirror**
  - Diagram: M₁ → M₂ → M₃ → M₄
  - Function: Designed to reduce output impedance

- **Modified Wilson Current Mirror**
  - Diagram: M₁ → M₂ → M₄
  - Function: Optimized for specific applications
Current Mirrors

- The concept of the current mirror was first introduced in about 1969 (not certain who introduced it)
- 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 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

<table>
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### 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>High-speed CMOS current mirror</td>
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<tr>
<td>3 7,463,082</td>
<td>Light emitting device and current mirror thereof</td>
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<td>4 7,463,014</td>
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<td>Regulated current mirror</td>
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<tr>
<td>6 7,449,955</td>
<td>Chain-chopping current mirror and method for stabilizing output currents</td>
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<td>7 7,439,796</td>
<td>Current mirror with circuitry that allows for over voltage stress testing</td>
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<td>Regulated current mirror</td>
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<tr>
<td>9 7,432,696</td>
<td>Apparatus and method for low input voltage current mirror circuit</td>
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<td>10 7,429,854</td>
<td>CMOS current mirror circuit and reference current/voltage circuit</td>
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<td>11 7,425,870</td>
<td>Current mirror circuit</td>
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<td>12 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
USPTO search on Jan 22, 2012

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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Results of Search in US Patent Collection db for:
(TTL/(current AND mirror) AND ISD/20100101 ->20120101): 29 patents.
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<td>19 7,800,418</td>
<td>Current mirror circuit and digital-to-analog conversion circuit</td>
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<tr>
<td>20 7,781,983</td>
<td>Constant current driver circuit with voltage compensated current sense mirror</td>
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<tr>
<td>21 7,777,561</td>
<td>Robust current mirror with improved input voltage headroom</td>
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</tbody>
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USPTO search on Jan 22, 2012

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

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

Number of patents/year in this area still well above the 3-decade average

Is there still an opportunity to contribute to the current mirror field?
Google Patents search on Jan 22, 2012

<table>
<thead>
<tr>
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</table>
**Current mirror circuit and digital-to-analog conversion circuit**

www.google.com/patents/US7800418

US Pat. 7800418 - Filed Feb 10, 2009 - Issued Sep 21, 2010 - Kabushiki Kaisha Toshiba

BRIEF SUMMARY OF THE INVENTION According to a first aspect of the invention, there is provided a current mirror circuit comprising: a current mirror ...

Overview - Abstract - Drawing - Description - Claims

---

**Fuse data read circuit having control circuit between fuse and ...**

www.google.com/patents/US7911870

US Pat. 7911870 - Filed Apr 21, 2009 - Issued Mar 22, 2011 - RENESAS Electronics Corporation

3 output circuit (inverter) 17 receives an output voltage Vout supplied from the data read unit 4. As shown in FIG. 1, the data read unit 4 includes an ...

Overview - Abstract - Drawing - Description - Claims
Comparison of Search Engines

29 patents found

5 patents found
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

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

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

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

To keep $M_1$ out of Triode Region

$L_1: \quad V_{OUT} > V_{IN} - V_{Tn}$

To keep $M_1$ out of Cutoff

$L_2: \quad V_{IN} > V_{Tn}$

To keep $M_2$ out of Triode Region

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

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

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

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

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

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