Advanced Current Mirrors and Opamps

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Wide-Swing Current Mirrors

It is proven that if both of the following conditions are satisfied, then all transistors will be biased in the saturation region.

\[
\begin{align*}
V_{out} & \geq (n+1)V_{eff} \\
V_{in} & \geq nV_{eff}
\end{align*}
\]

Typically, \( n \) is chosen identical to 1. So the output swing will be:

\[
V_{out} \geq 2V_{eff}
\]
Enhanced Output-Impedance Current Mirrors

\[ R_{out} \approx g_{m1} r_{ds1} r_{ds2} (1 + A) \]
Implementation of Enhanced Output-Impedance Current Mirror

\[ R_{out} \approx g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2} \]

\[ V_{out} \geq V_{tn} + V_{eff3} + V_{eff1} \]

Advantage:
• High Output-Impedance

Disadvantages:
• Low Output-Swing
• Imprecise Current Mirror
Implementation of Enhanced Output-Impedance Current Mirror

\[ R_{out} \approx g_{m1}r_{ds1}r_{ds2}g_{m3} \frac{r_{ds3}}{2} \]

\[ V_{out} \geq V_{tn} + V_{eff3} + V_{eff1} \]

Advantages:
- High Output-Impedance
- Precise Current Mirror

Disadvantage:
- Low Output-Swing
Implementation of Enhanced Output-Impedance Current Mirror

\[
R_{\text{out}} \approx g_{m1} r_{ds1} r_{ds2} g_{m3} \frac{r_{ds3}}{2}
\]

\[
V_{\text{out}} \geq 2V_{\text{eff}}
\]

Advantages:
- High Output-Impedance
- High Output-Swing

Disadvantage:
- Imprecise Current Mirror
Wide-Swing Current Mirror with Enhanced Output-Impedance

Advantages:
• High Output-Impedance
• Precise Current Mirror
• High Output-Swing

Disadvantage:
• High Power Consumption

\[ R_{out} \approx g_m r_{ds1} r_{ds2} g_m \frac{I_{ds3}}{2} \]

\[ V_{out} \geq 2V_{eff1} \]
Modified Wide-Swing Current Mirror with Enhanced Output-Impedance

\[
R_{out} \approx g_m r_{ds1} r_{ds2} g_m \frac{r_{ds3}}{2} \quad V_{out} \geq 2V_{eff}
\]

Advantages:
- High Output-Impedance
- Precise Current Mirror
- High Output-Swing
Current Mirror Symbol

1:K

1

K

1

K
• This opamp is useful when we want to drive capacitive loads.
• One of the most important parameters of this modern opamp is its transconductance value.
• Therefore, some designers refer to this modern opamp as Operational Transconductance Amplifier (OTA).
Remember the wide-swing current mirror

\[ I_{\text{bias}} \quad I_{\text{in}} \quad V_{\text{bias}} \quad V_{\text{out}} \]

\[ \frac{W/L}{(n+1)^2} \quad \frac{W/L}{n^2} \quad \frac{W/L}{n^2} \]

\[ Q_5 \quad Q_4 \quad Q_1 \quad Q_3 \quad Q_2 \]

\[ I_{\text{out}} = I_{\text{in}} \]
\[ i = g_{m2} \frac{V_i}{2} \Rightarrow i_{sc} = g_{m2} V_i \]

\[ i_{sc} = 2i \]

\[ r_{out} \approx g_{m8} r_{ds8} r_{ds10} \parallel g_{m6} r_{ds6} \left( r_{ds3} \parallel r_{ds1} \right) \]

\[ v_o = r_{out} i_{sc} \Rightarrow A_V = g_{m1} r_{out} \]
Competition between Two Current Sources

Assume that:

\[
\left( \frac{W}{L} \right)_1 = \left( \frac{W}{L} \right)_2 \\
\left( \frac{W}{L} \right)_3 = \left( \frac{W}{L} \right)_4
\]

If \( I_{bias1} > I_{bias2} \) \( \Rightarrow \) Q1:Triode Q3:Active \( I = I_{bias2} \)

If \( I_{bias2} > I_{bias1} \) \( \Rightarrow \) Q1:Active Q3:Triode \( I = I_{bias1} \)
Slew Rate

Assuming $\text{I}_{\text{bias}_2} > \text{I}_{D4}$ and $V_{\text{in}}^+ >> V_{\text{in}}^-$ ➔ $SR^+ = \frac{\text{I}_{D4}}{C_L}$

Assuming $\text{I}_{\text{bias}_2} > \text{I}_{D4}$ and $V_{\text{in}}^- >> V_{\text{in}}^-$ ➔ $SR^- = \frac{\text{I}_{D4}}{C_L}$
Lemma

\[ R \approx \frac{1}{g_{m9}} \]

Wide-swing current mirror
Frequency Response

\[ \omega_{p1} \approx \frac{1}{r_{\text{out}} C_L} \]  
\[ \Rightarrow \omega_{ta} = \frac{g_{m1}}{C_L} \]

\[ A_0 = g_{m1} r_{\text{out}} \]  

\[ \omega_{p2} \approx \frac{1}{\frac{1}{g_{m5} C_{p1}} + \frac{1}{g_{m9} C_{p2}} + \frac{1}{g_{m8} C_{p3}}} \]
Another Schematic for Folded-Cascode Opamp

Output swing:

\[ V_{B2} - V_{tn} \leq V_{out} \leq V_{B1} + |V_{tp}| \]

Input common-mode range:

\[ V_{tn} + V_{eff1} + V_{eff12} \leq V_{cmi} \leq V_{B1} + |V_{tp}| + |V_{eff6}| + V_{tn} \]
Folded-Cascode Opamp without wide-swing current source

conventional cascode current mirror
Folded-Cascode Opamp
(pmos-input)
Folded-Cascode Opamp
(pmos-input)
What is the DC voltage of the output node?

In a single-ended opamp, the DC voltage of the output node is determined by the feedback circuit around the opamp.

\[ V_{\text{out}} = V_{\text{bias}} + \frac{R_2}{R_1} (V_{\text{bias}} - V_{\text{in}}) \]
The bias voltages Vb1, Vb4, and Vb5 must be chosen so that the following relation is satisfied!!!

\[ I_{D9} = 0.5I_{D12} + I_{D3} \]

The opamp is completely symmetric. So we can use the half-circuit of the opamp for AC analysis.
Fully Differential Folded-Cascode Opamp
(half-circuit)

\[
\begin{align*}
\omega_{p1} & \approx \frac{1}{r_{out} C_L} \\
A_0 & = g_{m_i} r_{out} \\
\omega_{p2} & \approx \frac{1}{\frac{1}{g_{m7}} C_p}
\end{align*}
\]

\[
\Rightarrow \omega_{ta} = \frac{g_{m_i}}{C_L}
\]
What is the DC voltage of the output nodes?

In a single-ended opamp, the DC voltage of the output node is determined by the feedback circuit around the opamp.

\[ V_{i+} = V_{i-} = V_{CM} \]

\[
\begin{align*}
I &= \frac{V_{CM} - V_x}{R} \\
V_{CM} - V_o &= 2RI \\
\Rightarrow V_{CM} - V_o &= 2(V_{CM} - V_x) \\
\Rightarrow V_{o+} &= V_{o-} = V_o = 2V_x - V_{CM}
\end{align*}
\]

The DC voltage of the output nodes cannot be determined!!!
Common-Mode Feedback Circuit
(CMFB Circuit)

In a fully differential opamp, the CMFB circuit is employed inside the opamp to adjust the common-mode voltage of the output nodes identical to a predetermined voltage, $V_{\text{ref}}$.

\[ \text{CMFB Circuit} \Rightarrow \frac{V_{o+} + V_{o-}}{2} = V_{\text{ref}} \]

\[ KVL \ and \ KCL \Rightarrow V_o = 2V_x - V_{CM} \]

\[ V_x = \frac{V_{\text{ref}} + V_{CM}}{2} \]
Vref denotes the desired output common-mode voltage.

\[ V_y = \frac{V_{o+} + V_{o-}}{2} \]

\[ V_{err} = V_y - V_{\text{ref}} \]

\[ K \times V_{err}, \quad K > 0 \]

Vb4-estimated
Ideal CMFB Circuit (2)

Vref denotes the desired output common-mode voltage.

\[ V_y = \frac{V_{in} + V_{in}}{2} \]

\[ V_{err} = V_y - V_{ref} \]

\[ K \times V_{err}, K > 0 \]
Ideal CMFB Circuit (3)

Vref denotes the desired output common-mode voltage.

\[ V_y = \frac{V_{o+} + V_{o-}}{2} \]

\[ V_{err} = V_y - V_{ref} \]

\[ K \times V_{err}, K > 0 \]
Single-ended Telescopic Opamp

\[ i_{sc} = g_{m1}v_i \]

\[ r_{out} \approx g_{m4}r_{ds4}r_{ds2} \parallel g_{m6}r_{ds6}r_{ds8} \]

\[ v_o = r_{out}i_{sc} \Rightarrow A_V = g_{m1}r_{out} \]
Slew Rate

\[ SR^+ = SR^- = \frac{I_{ss}}{C_L} \]
Frequency Response

\[ \omega_{p_1} \approx \frac{1}{r_{out} C_L} \Rightarrow \omega_{i_a} = \frac{g_{m_i}}{C_L} \]

\[ A_0 = g_m r_{out} \]

\[ \omega_{p_2} \approx \frac{1}{\frac{1}{g_{m_3}} C_{p_1} + \frac{1}{g_{m_7}} C_{p_2} + \frac{1}{g_{m_6}} C_{p_3}} \]
Output swing:

\[ V_{B1} - V_{tn} \leq V_{out} \leq V_{B2} + |V_{tp}| \]

Input common-mode range:

\[ V_{tn} + V_{eff1} + V_{eff9} \leq V_{cmi} \leq V_{B1} - V_{eff3} \]
Telescopic Opamp without wide-swing current source
The bias voltages \( V_{b3} \) and \( V_{b4} \) must be chosen so that the following relation is satisfied!!!

\[ I_{D7} = 0.5 I_{D9} \]

The opamp is completely symmetric. So we can use the half-circuit of the opamp for AC analysis.
\[ \omega_{p1} \approx \frac{1}{r_{out} C_L} \] \Rightarrow \omega_{ia} = \frac{g_{m1}}{C_L} \\
A_0 = g_{m1} r_{out} \\
\omega_{p2} \approx \frac{1}{\frac{1}{g_{m3}} C_p} \]
Ideal CMFB Circuit (1)

$V_{\text{ref}}$ denotes the desired output common-mode voltage.

$V_y = \frac{V_{\text{out}} + V_{\text{in}}}{2}$

$V_{\text{err}} = V_y - V_{\text{ref}}$

$K \times V_{\text{err}}, K > 0$

Vb4-estimated
Ideal CMFB Circuit (2)

$V_{ref}$ denotes the desired output common-mode voltage.

$$V_y = \frac{V_{o+} + V_{o-}}{2}$$

$$V_{err} = V_y - V_{ref}$$

$V_{b3}$

$$K \times V_{err}, \quad K > 0$$

$V_{b3}$-estimated
Fully Differential Two-Stage Opamp (nmos input)

\[ A_0 = g_{m1} R_1 g_{m5} R_2 \]

\[ \omega_{ta} = \frac{g_{m1}}{C_M} \]

\[ \omega_{p2} \approx \frac{g_{m5}}{C_1 + C_L} \]

C1 denotes the parasitic capacitance.
Fully Differential Two-Stage Opamp (pmos input)
Fully Differential Two-Stage Opamp
(First Stage: Telescopic Cascode)

\[ A_0 = g_{m1} R_1 g_{m9} R_2 \]

\[ \omega_{ta} = \frac{g_{m1}}{C_M} \]

\[ \omega_{p2} \approx \frac{g_{m9}}{C_1 + C_L} \]

C1 denotes the parasitic capacitance at node X. Miller compensation method is utilized.
Gain-Boosting Opamp

It is proven that the auxiliary amplifier will not affect the performance of the main amplifier if the following relation is satisfied.

\[ U_{\text{GBW}}^{\text{Auxiliary Amplifier}} > U_{\text{GBW}}^{\text{Main Amplifier}} \]
Gain-Boosting Opamp
Differential Pair as an Auxiliary Opamp
Folded-Cascode Circuit as an Auxiliary Opamp
### Comparison of Performance of Various Opamp Topologies

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