EE 435

Lecture 7:

- Signal Swing
- Measurement/Simulation of High Gain Circuits
- High Gain Single-Stage Op Amps
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!
Basic Current Mirror

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

\[ g_{out} = g_{02} \]
Review from last lecture:

More Advanced Current Mirrors

1. **Cascode Current Mirror**
   - $I_{IN}$
   - $I_{OUT}$
   - $M_1$, $M_2$, $M_3$, $M_4$

2. **Wilson Current Mirror**
   - $I_{IN}$
   - $I_{OUT}$
   - $M_1$, $M_2$, $M_3$, $M_4$

3. **Modified Wilson Current Mirror**
   - $I_{IN}$
   - $I_{OUT}$
   - $M_1$, $M_2$, $M_4$
USPTO search on Jan 26, 2014

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

34 patents with “current and mirror” in title in 2012 and 2013

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?
Review from last lecture:

Signal Swing

To keep $M_1$ out of Triode Region

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

To keep $M_1$ out of Cutoff

$L_2: \quad V_{\text{iN}} > V_{Tn}$

To keep $M_2$ out of Triode Region

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

\[
V_{\text{XX}} - V_{Tp} > V_{\text{OUT}}
\]
Review from last lecture:

**Signal Swing**

\[ L_1 : \quad V_{OUT} > V_{IN} - V_{Tn} \]
\[ L_2 : \quad V_{IN} > V_{Tn} \]
\[ L_3 : \quad V_{XX} - V_{Tp} > V_{OUT} \]
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 $V_{EB1}$
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 \( V_{OUT} \) and wide \( V_{iC} \) range

Acceptable when followed by high-gain stage

Narrow \( V_{iC} \) and wide \( V_{OUT} \) range

Acceptable when \( V_{iC} \) is fixed

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 $M_2$ in Saturation:

$\mathcal{L}_1$: \[ V_{\text{OUT}} > V_{ic} - V_{T2} \]

To keep $M_4$ in Saturation:

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

To keep $M_1$ in Saturation:

$\mathcal{L}_3$: \[ V_{ic} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}| \]

To keep $M_5$ in Saturation:

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

To keep $M_2$ in Saturation:

$L_1$: $V_{\text{OUT}} > V_{\text{ic}} - V_{T2}$

To keep $M_4$ in Saturation:

$L_2$: $V_{\text{OUT}} < V_{DD} - |V_{EB4}|$

To keep $M_1$ in Saturation:

$L_3$: $V_{\text{ic}} < V_{DD} + V_{T1} - |V_{T3}| - |V_{EB3}|$

To keep $M_5$ in Saturation:

$L_4$: $V_{\text{ic}} > V_{T1} + V_{EB1} + V_{EB5} + V_{SS}$
Signal Swing of Single-Stage Op Amp

Constraining Equations:

\[ L_1: \quad V_{\text{OUT}} > V_{\text{iC}} - V_{T2} \]

\[ L_2: \quad V_{\text{OUT}} < V_{\text{DD}} - |V_{\text{EB4}}| \]

\[ L_3: \quad V_{\text{iC}} < V_{\text{DD}} + V_{T1} - |V_{T3}| - |V_{\text{EB3}}| \]

\[ L_4: \quad V_{\text{iC}} > V_{T1} + V_{\text{EB1}} + V_{\text{EB5}} + V_{SS} \]
Signal Swing of Single-Stage Op Amp

The diagram shows the signal swing of a single-stage operational amplifier. The key points are:

- **$V_{SS}$** and **$V_{DD}$** are the supply voltages.
- **$V_{OUT}$** is the output voltage.
- **$V_{T1} + V_{EB1} + V_{EB5}$** is the voltage swing on the $V_{SS}$ side.
- **$V_{EB4}$** is the collector-emitter voltage.
- **$|V_{EB3}| + |V_{T3}| - V_{T1}$** is the voltage swing on the $V_{DD}$ side.
- **$V_{T2}$** is the voltage swing on the $V_{SS}$ side.

The diagram illustrates the limits of the signal swing and the operational boundaries of the amplifier.
Signal Swing of Single-Stage Op Amp

Constraining Equations:

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

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 \}:

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

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

\[
GB = \left[ \frac{\mu_n C_{OX}}{C_L} \right] \sqrt{\frac{W_1}{L_1}} \frac{\sqrt{I_T}}{L_3}
\]

\[
V_{OUT} < V_{DD} - \frac{\sqrt{I_T}}{\sqrt{\mu_p C_{OX} L_3}}
\]

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

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?

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

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

\[ A_{v0} \approx \frac{1}{(0.01 + 0.01)} \frac{1}{0.15} = 333 \]

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

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

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

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

How can the gain of the op amp be increased?

Recall from Quarter-Circuit Concept

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

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 7