Fully Differential Single-Stage Amplifier Design

- Common-mode operation
- Design of basic differential op amp
- Slew Rate
- The Reference Op Amp
Review from last lecture:

Determination of op amp characteristics from quarter circuit characteristics

Small signal Quarter Circuit

\[
 A_{voqc} = - \frac{G_M}{G} \\
 BW = \frac{G}{C_L} \\
 GB = \frac{G_M}{C_L}
\]

Small signal differential amplifier

\[
 A_vo = \frac{-G_{M1}}{2(G_1 + G_2)} \\
 BW = \frac{G_1 + G_2}{C_L} \\
 GB = \frac{G_{M1}}{2C_L}
\]

Note: Factor of 4 reduction of gain
Review from last lecture:

Single-stage low-gain differential op amp

Quarter Circuit

Single-Ended Output : Differential Input Gain

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

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

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

Need a CMFB circuit to establish \( V_{b1} \)
Consider any output voltage for any linear circuit with two inputs:

\[ V_{OUT} = V_1 + V_2 \]

\[ A_c = A_1 + A_2 \]

\[ A_d = \frac{A_1 - A_2}{2} \]

\[ V_{OUT} = V_c A_c + V_d A_d \]

\[ V_{OUT} = V_c (A_1 + A_2) + V_d \left( \frac{A_1 - A_2}{2} \right) \]

Implication: Can solve a linear two-input circuit by applying superposition with \( V_1 \) and \( V_2 \) as inputs or by applying \( V_c \) and \( V_d \) as inputs.

Implication: In a circuit with \( A_2 = -A_1 \), \( A_c = 0 \) we obtain

\[ V_{OUT} = V_d A_d \]
Review from last lecture:
Common-Mode and Differential-Mode Analysis
Extension to differential outputs and symmetric circuits

Theorem: The symmetric differential output voltage for any symmetric linear network excited at symmetric nodes can be expressed as:

\[ V_{\text{OUT}} = A_d V_d \]

where \( A_d \) is the differential voltage gain and the voltage \( V_d = V_1 - V_2 \).
Common-Mode and Differential-Mode Analysis

Consider any output voltage for any linear circuit with two inputs

\[ v_{OUT} = A_1 v_1 + A_2 v_2 \]

\[ v_{OUT} = v_c A_c + v_d A_d \]

Single-Ended Superposition

Difference-Mode/Common-Mode Superposition
Common-Mode and Differential-Mode Analysis

Consider an output voltage for any linear circuit with two inputs

\[ V_{OUT} = V_c A_c + V_d A_d \]

Difference-Mode/Common-Mode Superposition is almost exclusively used for characterizing Amplifiers that are designed to have a large differential gain and a small common-mode gain.
Performance with Common-Mode Input

Single-Ended Outputs
Tail-Current Bias

Differential Output
Tail Current Bias

Single-Ended Outputs
Tail-Voltage Bias

Differential Output
Tail Voltage Bias
Performance with Common-Mode Input

Consider tail-current bias amplifier
Performance with Common-Mode Input

Consider tail-current bias amplifier

Common-Mode Half-Circuit

\[ \nu_{\text{OUTC}}(sC+G_1+G_2)+G_{M1}\nu_1 = G_1\nu_X \]
\[ \nu_C = \nu_1 + \nu_X \]
\[ \nu_XG_1 - G_{M1}\nu_1 = \nu_{\text{OUTC}}G_1 \]

Solving, we obtain

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

Consider tail-voltage bias amplifier

Common-Mode Half-Circuit

No current flows across axis of symmetry in a symmetric circuit
Performance with Common-Mode Input

Consider tail-voltage bias amplifier

Common-Mode Half-Circuit

\[
\begin{align*}
\nu_{\text{OUTC}} &= \frac{\nu_{\text{OUTC}}(sC+G_1+G_2) + G_{M1}v_1}{\nu_C} = 0 \\
\nu_C &= v_1
\end{align*}
\]

Solving, we obtain

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

This circuit has a rather large common-mode gain and will not reject common-mode signals.

Not a very good differential amplifier.
Recall

Single-stage low-gain differential op amp

Quarter Circuit

Single-Ended Output : Differential Input Gain

\[
A(s) = \frac{-g_{m1}}{2 \left( \frac{1}{sC_L} + g_{o1} + g_{o3} \right)}
\]

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

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

Need a CMFB circuit to establish \( V_{b1} \)
Design of Basic
Single-stage low-gain differential op amp

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

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:
\[ \{ V_{EB1}, V_{EB3}, V_{EB5}, P \} \]

Will now express performance characteristics in terms of Practical Parameters

Need a CMFB circuit to establish \( V_{b1} \)
Design of Basic
Single-stage low-gain differential op amp

Quarter Circuit

Single-Ended Output : Differential Input Gain

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

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

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

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

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

Need a CMFB circuit to establish \( V_{b1} \)
Single-stage low-gain differential op amp

Quarter Circuit

\[ V_{OD} = V_O^+ - V_O^- \]

Differential Output : Differential Input Gain

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

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

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

\[
A_0 = \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left( \frac{2}{V_{EB1}} \right) \quad GB = \left( \frac{P}{V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right]
\]

Need a CMFB circuit to establish \( V_{B1} \) or \( V_{B2} \).
Operational Amplifier Small Signal Differential Input Characteristics in Terms of Quarter Circuit Performance

Assumptions: Bias current in quarter circuits same as in Op Amps and $C_L$ is load capacitance on each side of op amp

### Single-ended Output

$$A(s) = \frac{2 - g_{MN}}{sC_L + g_{ON} + g_{OP}}$$

$$A_0 = \frac{1}{2} \frac{g_{MN}}{g_{ON} + g_{OP}}$$

$$GB = \frac{1}{2} \frac{g_{MN}}{C_L}$$

### Differential Output

$$A(s) = \frac{-g_{MN}}{sC_L + g_{ON} + g_{OP}}$$

$$A_0 = \frac{g_{MN}}{g_{ON} + g_{OP}}$$

$$GB = \frac{g_{MN}}{C_L}$$

Expressions valid for both tail-current and tail-voltage op amp
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.

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

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

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

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

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

$$\text{SR} = \frac{P}{V_{DD}2C_L}$$
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

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

mixed parameters

\[
A_{V0} = \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}}
\]

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

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

practical parameters

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

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

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

single-ended output

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

mixed parameters

practical parameters

\[ \begin{align*}
A_{V0} &= \frac{1}{2} \frac{g_{m1}}{g_{o1} + g_{o3}} \\
GB &= \frac{g_{m1}}{2C_L} \\
SR &= \frac{I_T}{2C_L} \\
A_{V0} &= \left[ \frac{1}{\lambda_1 + \lambda_3} \right] \left[ \frac{1}{V_{EB1}} \right] \\
GB &= \left( \frac{P}{2V_{DD}C_L} \right) \cdot \left[ \frac{1}{V_{EB1}} \right] \\
SR &= \frac{P}{2V_{DD}C_L}
\end{align*} \]
# 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

<table>
<thead>
<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>
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</table>

## Practical Parameter Domain

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

single-ended output

What basic type of amplifier is this op amp?

A(s) = \frac{g_{m1}}{sC_L + g_{o1} + g_{o3}}
Reference Op Amp

single-ended output

What basic type of amplifier is this op amp?

Does it really matter?

Transconductance

Voltage

Transresistance

Current

\[ A(s) = \frac{g_{m1}}{sC_L + g_{o1} + g_{o3}} \]
End of Lecture 5