Fully Differential Single-Stage Amplifier Design

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

- General Differential Analysis
- 5T Op Amp from simple quarter circuit
- Biasing with CMFB circuit
- Common-mode and differential-mode analysis
- Common Mode Gain
- Overall Transfer Characteristics
Review from last lecture:
Determination of op amp characteristics from quarter circuit characteristics

--- The “differential” gain ---

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

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

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

\[ GB = \frac{G_{M1}}{2C_L} \]

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

Single-stage low-gain differential op amp

-- The “differential” gain --

Quarter Circuit

Single-Ended Output : Differential Input Gain

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

$$A_o = \frac{2}{g_{o1} + g_{o3}}$$

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

Need a CMFB circuit to establish $V_{b1}$
Consider any output voltage for any linear circuit with two inputs

\[ V_{OUT} = A_1 V_1 + A_2 V_2 \]

\[ A_c = A_1 + A_2 \]

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

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

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

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 \( V_d = V_1 - V_2 \)

Theorem: The differential output for any linear network can be expressed equivalently as

\[ V_{\text{OUT}} = A_1 V_1 + A_2 V_2 \]

or as

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

and superposition can be applied to either \( V_1 \) and \( V_2 \) to obtain \( A_1 \) and \( A_2 \) or to \( V_c \) and \( V_d \) to obtain \( A_c \) and \( A_d \)
Today’s Outline

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

\[ \mathcal{V}_{\text{OUT}} = \mathcal{V}_c A_c + \mathcal{V}_d A_d \]

- 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.
- Analysis to this point have focused only on the circuit on the left.
• General Differential Analysis
• 5T Op Amp from simple quarter circuit
• Biasing with CMFB circuit
• Common-mode and differential-mode analysis
• Common Mode Gain
• Overall Transfer Characteristics
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 with $i_c=0$

Solving, we obtain

$$\nu_{\text{OUTC}}=0 \quad \text{thus } A_C=0$$

(Note: Have assumed an ideal tail current source in this analysis

$A_C$ will be small but may not vanish if tail current source is not ideal)
Performance with Common-Mode Input
Consider tail-voltage bias amplifier with $i_c=0$

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

Consider tail-voltage bias amplifier with $i_c=0$

Common-Mode Half-Circuit

\[ V_{BB} \]

\[ v_{OUTC} \]

\[ v_c \]

\[ i_c \]

\[ V_{DD} \]

\[ V_{SS} \]

Solving, we obtain

\[ \frac{v_{OUTC}}{v_c} = A_C = \frac{-G_{M1}}{sC + G_1 + G_2} \]

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

Not a very good differential amplifier.
• General Differential Analysis
• 5T Op Amp from simple quarter circuit
• Biasing with CMFB circuit
• Common-mode and differential-mode analysis
• Common Mode Gain

Overall Transfer Characteristics
Overall Small-Signal Analysis

As stated earlier, with common-mode gain and difference-mode gains available

\[ v_{\text{OUT}} = v_c A_c + v_d A_d \]
Today’s Outline

• Common-mode operation

Design of basic differential op amp

• Slew Rate

• The Reference Op Amp
Recall

Single-stage low-gain differential op amp

Quarter Circuit

Single-Ended Output : Differential Input Gain

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

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

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

Need a CMFB circuit to establish \(V_{B1}\)
Design of Basic
Single-stage low-gain differential op amp

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

\[ A_o = \frac{g_{m1}}{2g_{o1} + g_{o3}} \]

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

What are the number of degrees of freedom?
(assume \(V_{DD}, C_L \) fixed, Symmetry)

Natural Parameters:
\[ \left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, V_{B1}, V_{B2} \right\} \]

Constraints: \( I_{D5} \approx 2I_{D3} \)
Net Degrees of Freedom: 4

- Expressions for \( A_0 \) and GB were obtained from quarter-circuit
- Expressions for \( A_0 \) and GB in terms of natural parameters for quarter circuit were messy
- Can be shown that expressions for \( A_0 \) and GB in terms of natural parameters are also messy

Can a set of practical design parameters be identified?
Design of Basic Single-stage low-gain differential op amp

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

\[
A_o = \frac{g_{m1}}{2} \frac{2}{g_{o1} + g_{o3}}
\]

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

What are the number of degrees of freedom?
(assume \(V_{DD}, C_L\) fixed, Symmetry)

Natural Parameters:
\[
\left\{ \frac{W_1}{L_4}, \frac{W_3}{L_3}, \frac{W_5}{L_5}, V_{B1}, V_{B2} \right\}
\]

Constraints: \(I_{D5} \approx 2I_{D3}\)
Net Degrees of Freedom: 4

Practical Parameters:
\[
\left\{ V_{EB1}, V_{EB3}, V_{EB5}, P \right\}
\]

Will now express performance characteristics in terms of Practical Parameters

Need a CMFB circuit to establish \(V_{B1}\)
Single-Ended Output : Differential Input Gain

$$A(s) = \frac{-g_{m1}}{2} \frac{1}{sC_L + g_{o1} + g_{o3}}$$

$$A_o = \frac{2}{g_{o1} + g_{o3}}$$

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

Practical Parameters:
$$\{V_{EB1}, V_{EB3}, V_{EB5}, P\}$$

Have 4 degrees of freedom but only two practical variables impact $A_0$ and $GB$. So still have 2 DOF after meet $A_0$ and $GB$ requirements

Need a CMFB circuit to establish $V_{B1}$
Single-stage low-gain differential I/O op amp

Quarter Circuit

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

**Differential Output : Differential Input Gain**

\[
\begin{align*}
A(s) &= \frac{g_{m1}}{sC_L + g_{o1} + g_{o3}} \\
A_0 &= \frac{g_{m1}}{g_{o1} + g_{o3}} \\
GB &= \frac{g_{m1}}{C_L}
\end{align*}
\]

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

Have 4 degrees of freedom but only two practical variables impact \( A_0 \) and GB, so still have 2 DOF after meet \( A_0 \) and GB requirements.

Need a CMFB circuit to establish \( V_{B1} \) or \( V_{B2} \)
Expressions valid for both tail-current and tail-voltage op amp

Recall:

\[ \left\{ \frac{W_1}{L_1}, \frac{W_3}{L_3}, V_{B1} \right\} \]

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
- Two extra design degree of freedom for tail current bias
- Improved output signal swing for tail voltage bias (will show later)
Today’s Outline

- Common-mode operation
- Design of basic differential op amp
- Slew Rate
- The Reference Op Amp
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 (some devices in amplifier usually leave normal operating region).
- Hard input overdrive depicted in this figure.
- 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

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

Practical parameter domain
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

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

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

$$SR = \frac{P}{V_{DD}2C_L}$$
Today’s Outline

• Common-mode operation
• Design of basic differential op amp
• Slew Rate

The Reference Op Amp
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**

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

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

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

**practical parameters**

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

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

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

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
## Amplifier Structure Summary

<table>
<thead>
<tr>
<th>Small Signal Parameter Domain</th>
<th></th>
</tr>
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<tbody>
<tr>
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What basic type of amplifier is this op amp?

Reference Op Amp

single-ended output

A(s) = \frac{g_{m1}}{2sC_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

What basic type of amplifier is this op amp?

Voltage Transconductance

Does it really matter?

Transresistance

Current

A(s) = \frac{g_{m1}}{2} \frac{1}{sC_L + g_{o1} + g_{o3}}
End of Lecture 5