Differential Amplifiers

- General Considerations
- MOS Differential Pair
- Cascode Differential Amplifiers
- Common-Mode Rejection
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Audio Amplifier Example

- An audio amplifier is constructed above that takes on a rectified AC voltage as its supply and amplifies an audio signal from a microphone.

Small-Signal Model for Bipolar Transistor

- Some examples in this chapter are explained in bipolar transistor circuits
- The small-signal model of a bipolar transistor is very similar to that of the MOSFET, except bipolar transistor has low input impedance at base
“Humming” Noise in Audio Amplifier Example

- However, $V_{CC}$ contains a ripple from rectification that leaks to the output and is perceived as a “humming” noise by the user.

Supply Ripple Rejection

- Since both node X and Y contain the ripple, their difference will be free of ripple.

Ripple-Free Differential Output

- Since the signal is taken as a difference between two nodes, an amplifier that senses differential signals is needed.

Common Inputs to Differential Amplifier

- Signals cannot be applied in phase to the inputs of a differential amplifier, since the outputs will also be in phase, producing zero differential output.
Differential Inputs to Differential Amplifier

When the inputs are applied differentially, the outputs are 180° out of phase; enhancing each other when sensed differentially.

\[ v_X = A_v v_{in} + v_r \]
\[ v_Y = -A_v v_{in} + v_r \]
\[ v_X - v_Y = 2A_v v_{in} \]

Differential Signals

- A pair of differential signals can be generated, among other ways, by a transformer.
- Differential signals have the property that they share the same average value to ground and are equal in magnitude but opposite in phase.

Single-ended vs. Differential Signals

Differential Pair

- With the addition of a tail current, the circuits above operate as an elegant, yet robust differential pair.
MOS Differential Pair’s Common-Mode Response

\[ V_x = V_y = V_{dd} - R_d \frac{I_{ss}}{2} \]

- Similar to its bipolar counterpart, MOS differential pair produces zero differential output as VCM changes.

Equilibrium Overdrive Voltage

\[ (V_{gs} - V_{th})_{equil} = \left( \frac{I_{ss}}{\mu_n C_{ox}} \right) \frac{W}{L} \]

- The equilibrium overdrive voltage is defined as the overdrive voltage seen by M1 and M2 when both of them carry a current of \( I_{ss}/2 \).

Minimum Common-mode Output Voltage

\[ V_{dd} - R_d \frac{I_{ss}}{2} > V_{cm} - V_{th} \]

- In order to maintain M1 and M2 in saturation, the common-mode output voltage cannot fall below the value above.
- This value usually limits voltage gain.

Differential Response
Virtual Ground

- For small changes at inputs, the $g_m$'s are the same, and the respective increase and decrease of $I_{D1}$ and $I_{D2}$ are the same, node P must stay constant to accommodate these changes. Therefore, node P can be viewed as AC ground.

Small-Signal Response

- Since the output changes by $-2g_m \Delta V R_D$ and input by $2\Delta V$, the small signal gain is $-g_m R_D$, similar to that of the CS stage. However, to obtain same gain as the CS stage, power dissipation is doubled.

MOS Differential Pair's Large-Signal Response

- There exists a finite differential input voltage that completely steers the tail current from one transistor to the other. This value is known as the maximum differential input voltage.
The effects of Doubling the Tail Current

- Since $I_{SS}$ is doubled and W/L is unchanged, the equilibrium overdrive voltage for each transistor must increase by $\sqrt{2}$ to accommodate this change, thus $\Delta V_{in,\text{max}}$ increases by $\sqrt{2}$ as well. Moreover, since $I_{SS}$ is doubled, the differential output swing will double.

The effects of Doubling W/L

- Since W/L is doubled and the tail current remains unchanged, the equilibrium overdrive voltage will be lowered by $\sqrt{2}$ to accommodate this change, thus $\Delta V_{in,\text{max}}$ will be lowered by $\sqrt{2}$ as well. Moreover, the differential output swing will remain unchanged since neither $I_{SS}$ nor $R_D$ has changed.

Small-Signal Analysis of MOS Differential Pair

- When the input differential signal is small compared to $4I_{SS}/\mu nC_{ox}(W/L)$, the output differential current is linearly proportional to it, and small-signal model can be applied.

Virtual Ground and Half Circuit

- Since $V_p$ is grounded, we can treat the differential pair as two CS “half circuits”, with the same small-signal gain.
MOS Differential Pair Half Circuit Example I

\[ \lambda \neq 0 \]
\[ A_v = -g_m \left( \frac{1}{g_m} r_{d3} r_{o1} \right) \]

MOS Differential Pair Half Circuit Example II

\[ \lambda = 0 \]
\[ A_v = -\frac{g_m}{g_m} \]

Extension of Virtual Ground

\[ V_X = 0 \]

- It can be shown that if \( R_1 = R_2 \), and points A and B go up and down by the same amount respectively, \( V_X \) does not move.

MOS Differential Pair Half Circuit Example III

\[ \lambda = 0 \]
\[ A_v = -\frac{R_{DD}/2}{\frac{R_{SS}}{2} + 1/g_m} \]
If finite tail impedance and asymmetry are both present, then the differential output signal will contain a portion of input common-mode signal.

Many circuits require a differential to single-ended conversion, however, the above topology is not very good.
Supply Noise Corruption

- The most critical drawback of this topology is supply noise corruption, since no common-mode cancellation mechanism exists. Also, we lose half of the signal.

MOS Differential Pair with Active Load

- This circuit topology performs differential to single-ended conversion with no loss of gain.
- The input differential pair decreases the current drawn from $R_L$ by $\Delta I$ and the active load pushes an extra $\Delta I$ into $R_L$ by current mirror action; these effects enhance each other.

Asymmetric Differential Pair

- Because of the vastly different resistance magnitude at the drains of $M_1$ and $M_2$, the voltage swings at these two nodes are different and therefore node P cannot be viewed as a virtual ground.