Studio 7 Overview

• Differential Amplifier, Current Mirror Load
  – Textbook Razavi 4.1-4.3, 5.3
Circuit: Differential Amplifier (Resistive Load)

Differential input voltage controls “split” of \( I_{BIAS} \) to \( I_{D1}, I_{D2} \)
Qualitative V-I Characteristic: "Connect the dots"

- General shape for any differential pair: MOSFET, BJT, JFET, ...
- Specifics depend on bias, technology, etc.
\[ V_{O1} = V_{DD} - I_{D1} R_D \quad \text{and} \quad V_{O2} = V_{DD} - I_{D2} R_D \]
Differential Voltage Output: $V_{OD} = V_{O1} - V_{O2}$
Differential Voltage Output

• Slope of plot at operating point (origin):
  Small signal differential gain $a_{v(diff)}$
Differential Gain

- Need to improve ⇒ need to be quantitative
- Analytic tool: Bartlett's Bisection Theorem
- Applies for symmetrical circuits
- Simplifies analysis: Allows splitting of circuit into separate halves
Bartlett's Bisection Theorem

- Two completely symmetrical circuits
  a, b, c are connected points of symmetry
Common mode: Symmetric excitation

- If $V_1 = V_2 = V_{CM}$ (same input to both circuits)
- No current at connected points of symmetry
- Imagine mirror reversal: $I_a = -I_a \Rightarrow I_a = 0$
Common mode: Symmetric excitation

- We can open all leads between connected points of symmetry without affecting circuit operation
- Applies for any circuit (linear or nonlinear)
Differential mode: Antisymmetric excitation

If $V_1 = -V_2$: “See-Saw”:
Fixed voltage at connected points of symmetry
Differential mode: Antisymmetric excitation

- All leads between connected points of symmetry can be tied to small signal ground without affecting circuit operation
- Requires linearity
Bartlett's Bisection Theorem

- Applies to symmetric circuits
- Common mode (symmetric) excitation
  - Open connected points of symmetry
- Differential (antisymmetric) excitation
  - Connected points of symmetry tied to signal ground
  - Requires linearity
Any two signals!

Can be expressed as sum of common mode, differential mode:
Any two signals!

- Define: \[ V_{CM} = \frac{V_1 + V_2}{2} \]
  \[ V_{dm} = V_1 - V_2 \]

- Can verify: \[ V_1 = V_{CM} + \frac{V_{dm}}{2} \]
  \[ V_2 = V_{CM} - \frac{V_{dm}}{2} \]
Half circuit analysis technique

1) Represent inputs in terms of $V_{dm}$, $V_{CM}$
2) Redraw circuit to emphasize symmetry
3) Use superposition to find output:
   – DC bias: $V_1, V_2 = 0$ (all inputs suppressed)
   – CM Response: keep $v_{CM}$, set $v_{dm} = 0$
   – DM response: keep $v_{dm}$, set $v_{CM} = 0$
   – Add results for total output

• Split circuit using bisection theorem:
  – Analyze each half separately
1) Represent inputs in terms of $V_{dm}$, $V_{cm}$
2) Redraw to show symmetry

- $I_{BIAS}$ equivalent: two $I_{BIAS}/2$ in parallel
DC bias: $V_1, V_2 = 0$ (all signal inputs suppressed)

$$V_{O1(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D$$

$$V_{O2(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D$$

- Symmetric excitation:
  open connected points of symmetry
Common Mode Response: $v_{dm} = 0$

- Open connected points of symmetry
Note "supernode": $i_d = 0$

\[
V_{o1(cm)} = -i_d R_D = 0 \quad V_{o2(cm)} = 0
\]
Differential mode response: $v_{cm} = 0$

- Connected points of symmetry to signal ground
Small signal model of half-circuit

\[ V_{o1}(dm) = -g_m R_D \frac{v_{dm}}{2} \]

\[ V_{o2}(dm) = -g_m R_D \frac{-v_{dm}}{2} \]

- Common source amplifier!
- Note: \( g_{m1} = g_{m2} = g_m \)
Summary: Output “parts”

- **DC bias**
  \[
  V_{O1(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D \quad V_{O2(DC)} = V_{DD} - \frac{I_{BIAS}}{2} R_D
  \]

- **Common mode**
  \[
  V_{o1(cm)} = 0 \quad V_{o2(cm)} = 0
  \]

- **Differential mode**
  \[
  V_{o1(dm)} = \frac{-g_m R_D}{2} v_{dm} \quad V_{o2(dm)} = \frac{g_m R_D}{2} v_{dm}
  \]
Summary: Total output sum of components

\[ V_{O1} = V_{DD} - \frac{I_{BIAS}}{2} R_D + \frac{0}{C_M} + \frac{-g_m R_D}{2} v_{dm} \]

\[ V_{O2} = V_{DD} - \frac{I_{BIAS}}{2} R_D + \frac{0}{C_M} + \frac{g_m R_D}{2} v_{dm} \]
Studio 7 Exercise

• $I_{\text{BIAS}} = 250\mu\text{A}$, $R_D = 20\text{k}\Omega$

• DCbias

$$V_{O1(\text{DC})} = V_{DD} - \frac{I_{\text{BIAS}}}{2} R_D = +5V - \frac{250\mu\text{A}}{2} 20\text{k}\Omega = +2.5V$$

• Small signal: $g_m \approx 400\mu\text{A}/\text{V}$

$$g_{m1} R_D \approx (400\mu\text{A}/\text{V})(20\text{k}\Omega) = 8$$
Differential gain

\[ a_v(\text{diff}) = \frac{\{ \text{DIFFERENTIAL OUTPUT} \}}{\{ \text{DIFFERENTIAL INPUT} \}} \]

\[ a_v(\text{diff}) = \frac{V_{o1(dm)} - V_{o2(dm)}}{v_{dm}} \]

\[ a_v(\text{diff}) = \frac{-g_m R_D \frac{v_{dm}}{2} - g_m R_D \frac{v_{dm}}{2}}{v_{dm}} \]

\[ a_v(\text{diff}) = -g_m R_D \]

- Same as common source amplifier
- Still low for resistive load!
Drain Currents

\[ I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2} \]

\[ I_{D2} = \frac{I_{BIAS}}{2} - g_m \frac{v_{dm}}{2} \]
Drain Currents

\[ I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2} \]

\[ I_{D2} = \frac{I_{BIAS}}{2} - g_m \frac{v_{dm}}{2} \]
Mirror load

\[ I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2} \]

\[ I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2} \]

\[ I_{D2} = \frac{I_{BIAS}}{2} - g_m \frac{v_{dm}}{2} \]

DISAGREE!

\[ I_{D1} = \frac{I_{BIAS}}{2} + g_m \frac{v_{dm}}{2} \]