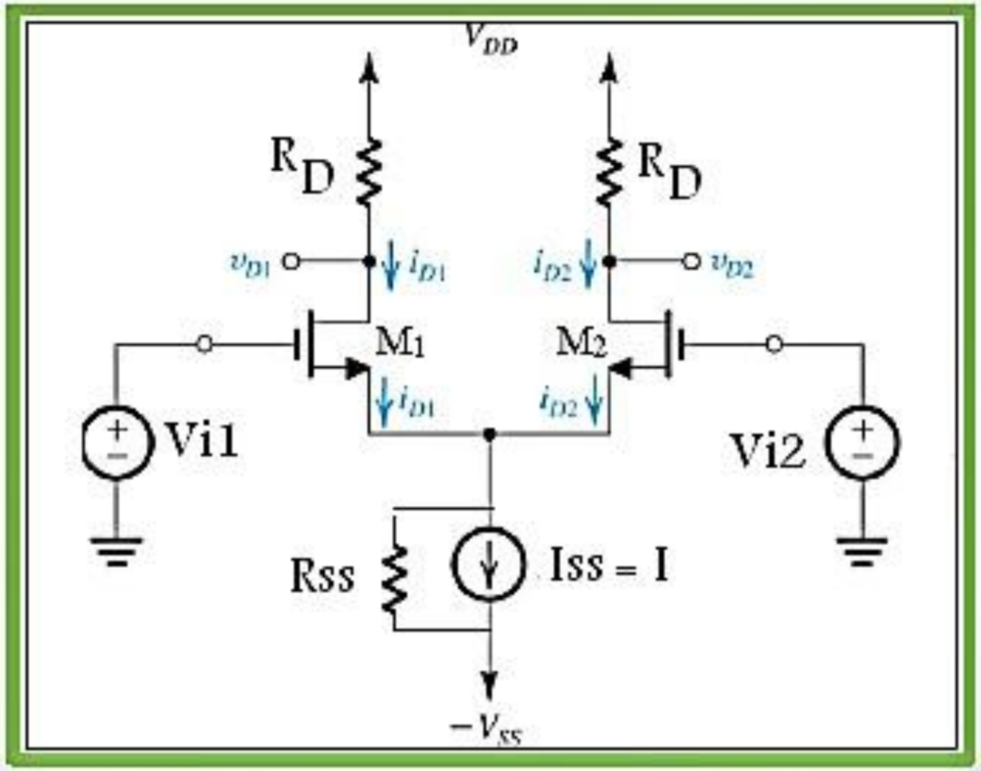
MOS Differential Amplifier/Pair

- Source Coupled Circuit:
  - Two matched MOS-FET **(Same K and V_T)**
  - Their Sources are connected together
  - The input signals are connected to the M's Gates
  - A Constant DC biasing Current 'I' is used to set the DC operating point.



$$i_{D1} + i_{D2} = \mathrm{I}$$

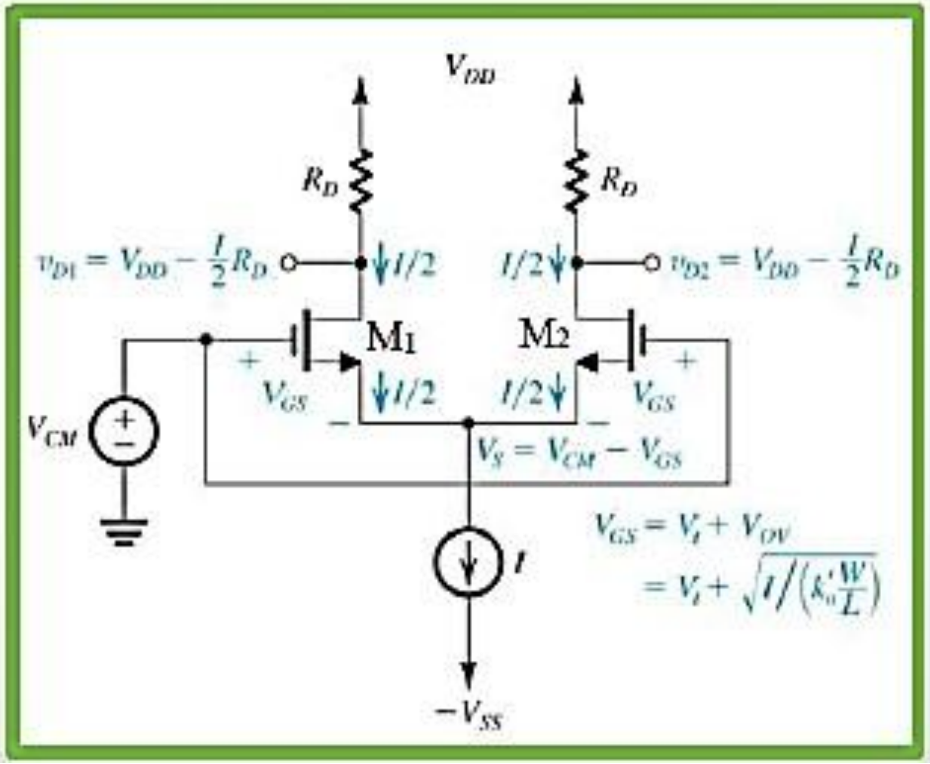
Source Coupled Circuit Large Signal Analysis (**Saturation Mode**)

- If Gate 1 and 2 are connected together (Common mode signal), then the two drain currents will be equal

$$v_{GS1} = v_{GS2} = v_{CM}$$

$$i_{D1} = i_{D2} = \frac{I}{2}$$

$$v_{D1} = v_{D2} = V_{DD} - \frac{I}{2} R_D$$

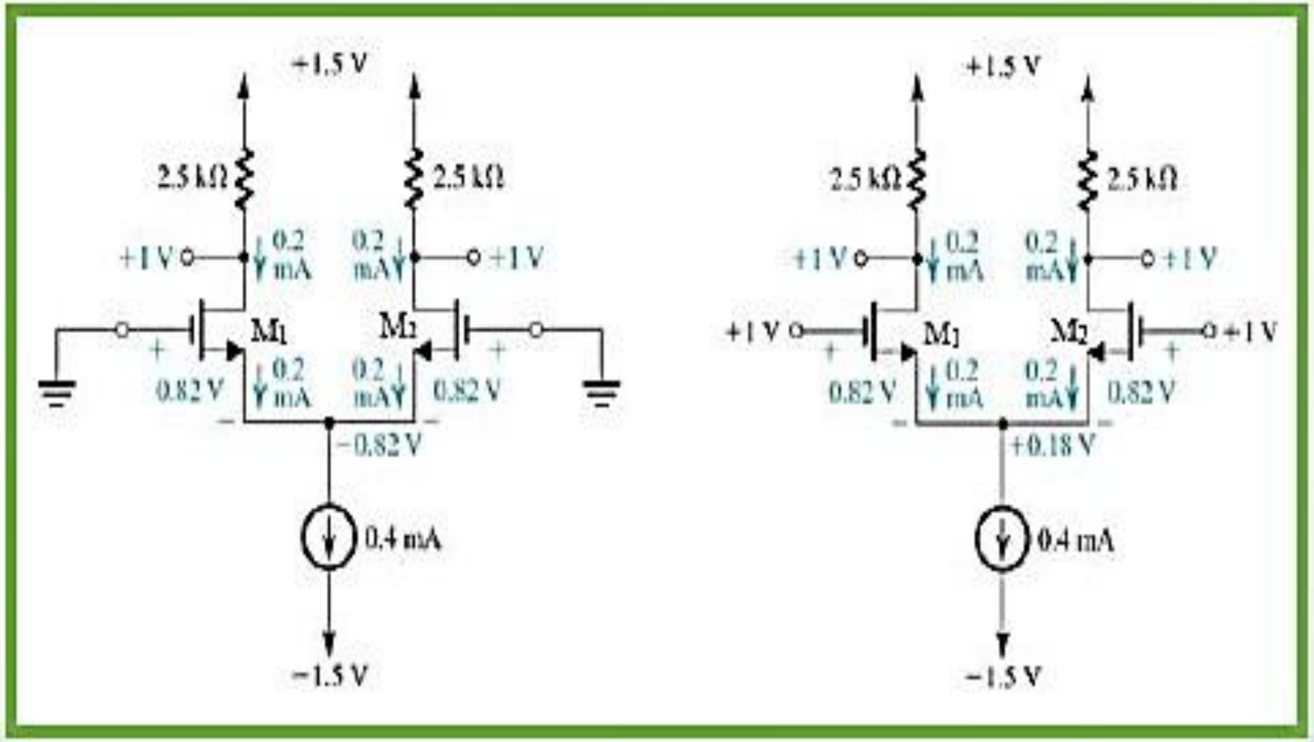


Differential Amplifier Large Signal Analysis (Cont.):

- Changing the value of the common mode signal <u>will not</u> change the transistors currents

$$v_{GS1} = v_{GS2} = v_{CM}$$

$$v_{D1} = v_{D2} = V_{DD} - \frac{I}{2} R_D$$



The DA rejects the common mode Signal

MOS Differential Amplifier/Pair

- Source Coupled Circuit Large Signal Analysis:
  - If Gate 1 and 2 are not connected together (**Differential signal**), then the two drain currents **won't be equal**

$v_{GS1} - v_{GS2} = v_{ID}$

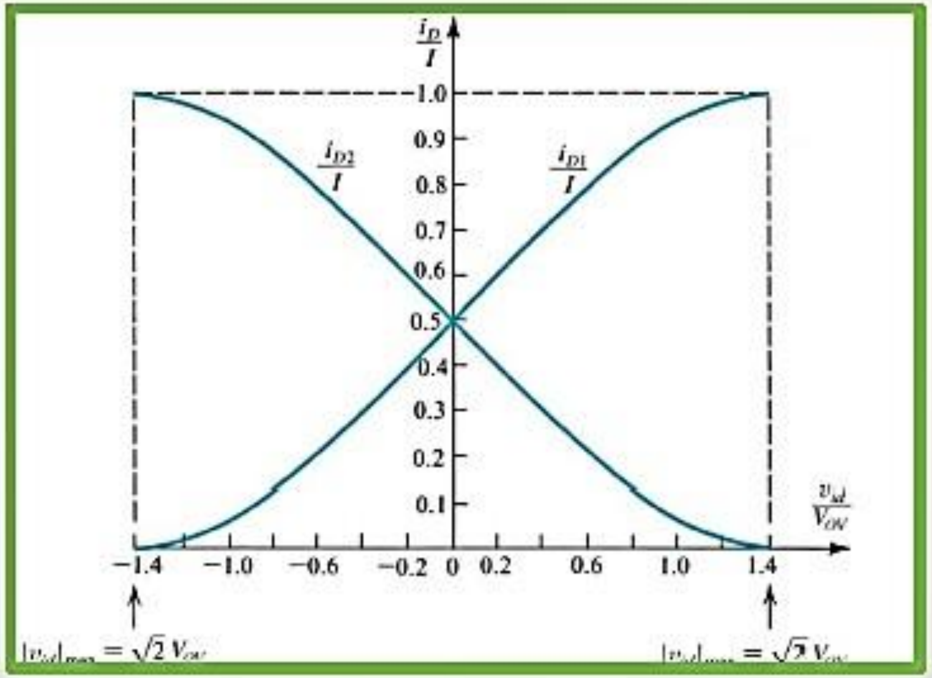
$i_{D1} \neq i_{D2}$

If v_{ID}>>0 such that M1 is Linear and M2 is Off

$i_{D1} = \mathrm{I} \;\&\; i_{D2} = 0$

If v_{ID}<<0 such that M1 is OFF and M2 is Linear

$i_{D1} = 0 \;\&\; i_{D2} = \mathrm{I}$



The DA responds to any change in the Differential mode Signal

MOS Differential Amplifier/Pair

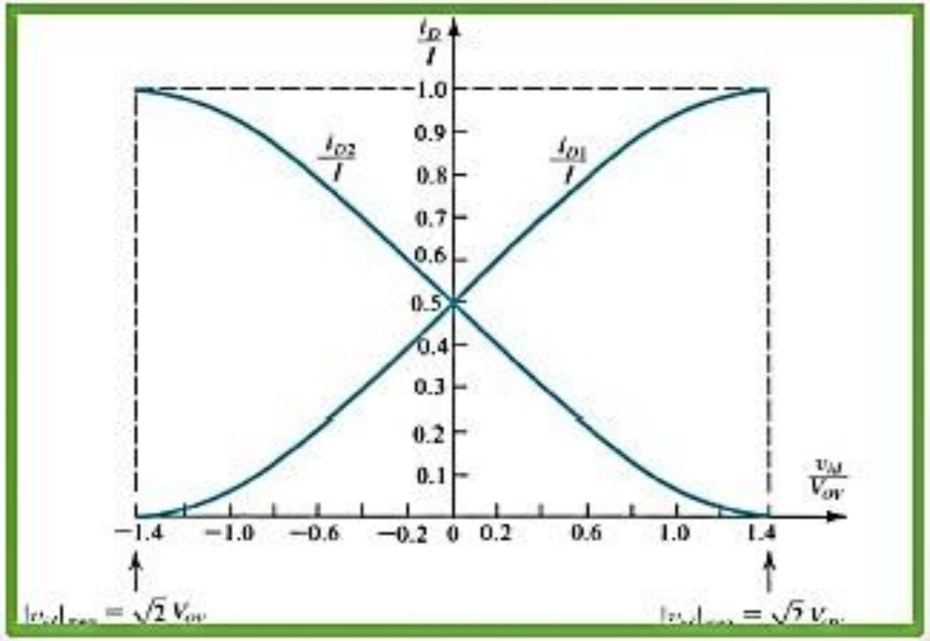
- Source Coupled Circuit Large Signal Analysis:
  - M1 and M2 are Saturated and matched

$$i_{D1} = \frac{K}{2}(v_{GS1} - V_t)^2 \qquad i_{D2} = \frac{K}{2}(v_{GS2} - V_t)^2$$

$$i_{D1} + i_{D2} = I$$

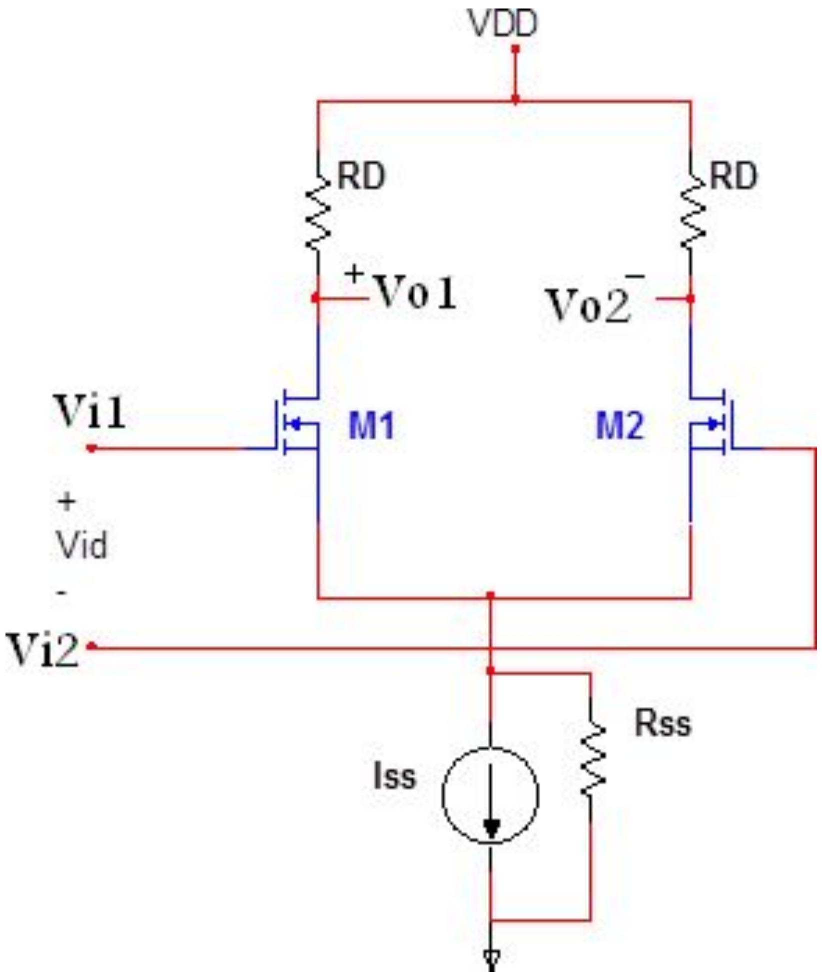
$$\sqrt{i_{D1}} = \sqrt{\frac{K}{2}}(v_{GS1} - V_t) \qquad \sqrt{i_{D2}} = \sqrt{\frac{K}{2}}(v_{GS2} - V_t)$$

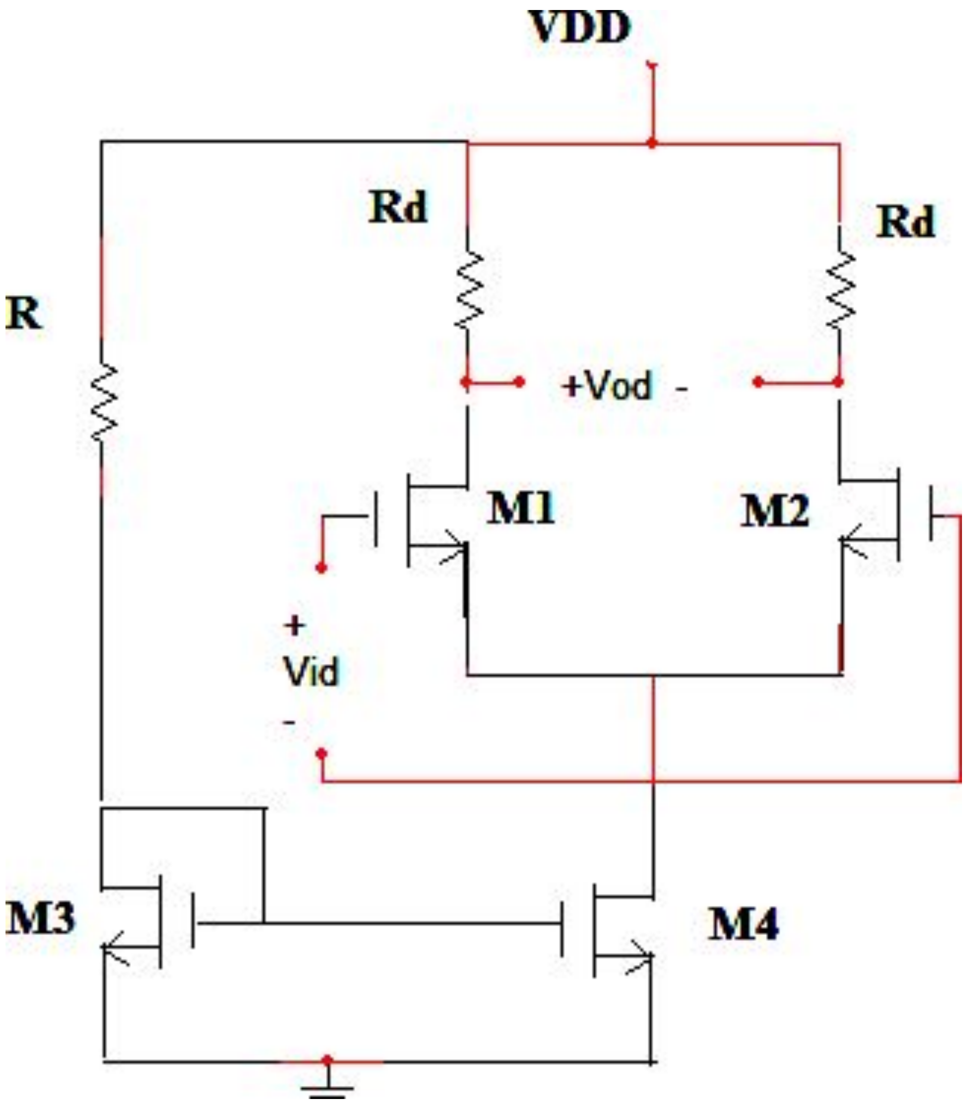
$$\sqrt{i_{D1}} - \sqrt{i_{D2}} = \sqrt{\frac{K}{2}}\, v_{ID} \qquad 2\sqrt{i_{D1} i_{D2}} = I - \frac{K}{2} v_{ID}^2$$



$$i_{D1} = \frac{I}{2} + \sqrt{KI}\left(\frac{v_{ID}}{2}\right)\sqrt{1 - \frac{\left(\frac{v_{ID}}{2}\right)^2}{I/K}} \qquad i_{D2} = \frac{I}{2} - \sqrt{KI}\left(\frac{v_{ID}}{2}\right)\sqrt{1 - \frac{\left(\frac{v_{ID}}{2}\right)^2}{I/K}}$$

Summary of MOSFET Differential Amplifier Analysis





Example(1)

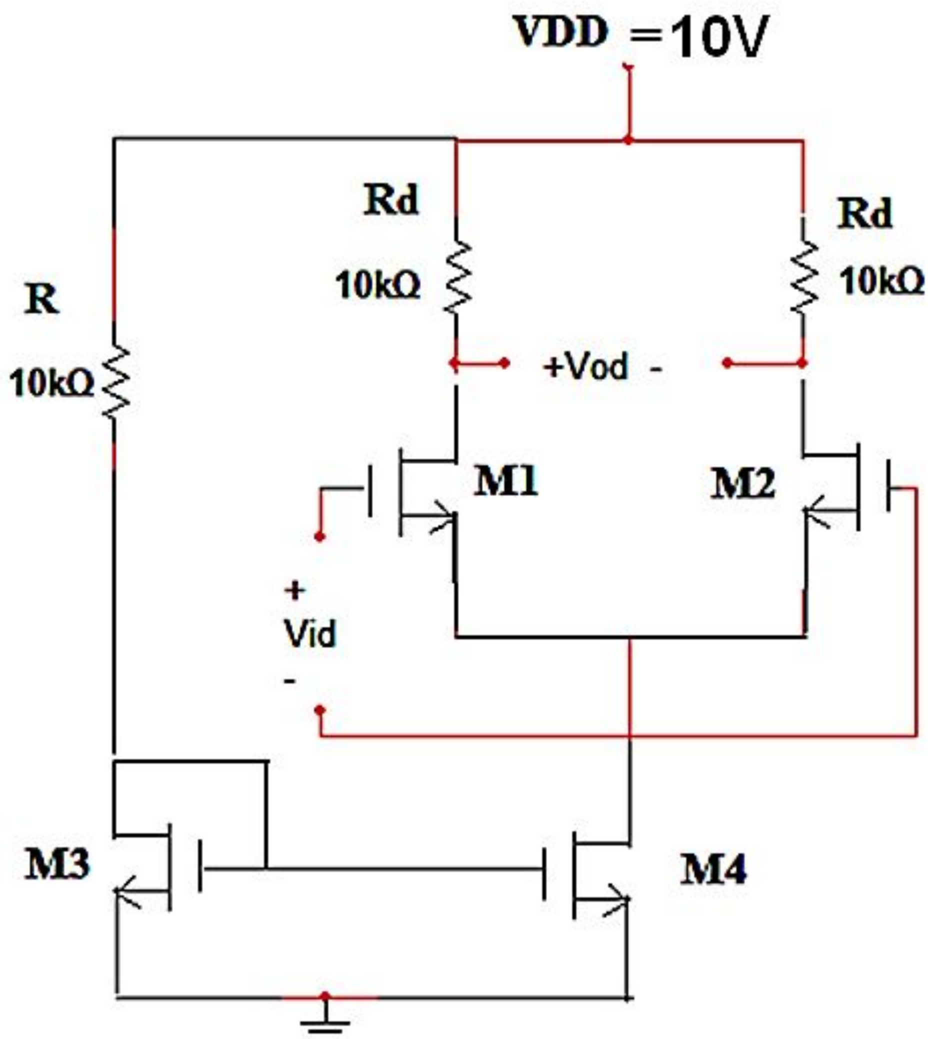
Analyze the MOS-differential amplifier circuit shown in Figure if M1 and M2 are matched with $K = 2mA/V^2$, $V_T = 1V$ and r_{ds} is neglected.M3 and M4 are matched with $K = 1mA/V^2$, $V_T = 1V$ and $r_{ds} = 100K\ \Omega$. Calculate:

(a) ALL DC Drain currents.

(b) The differential mode gain (Adm(

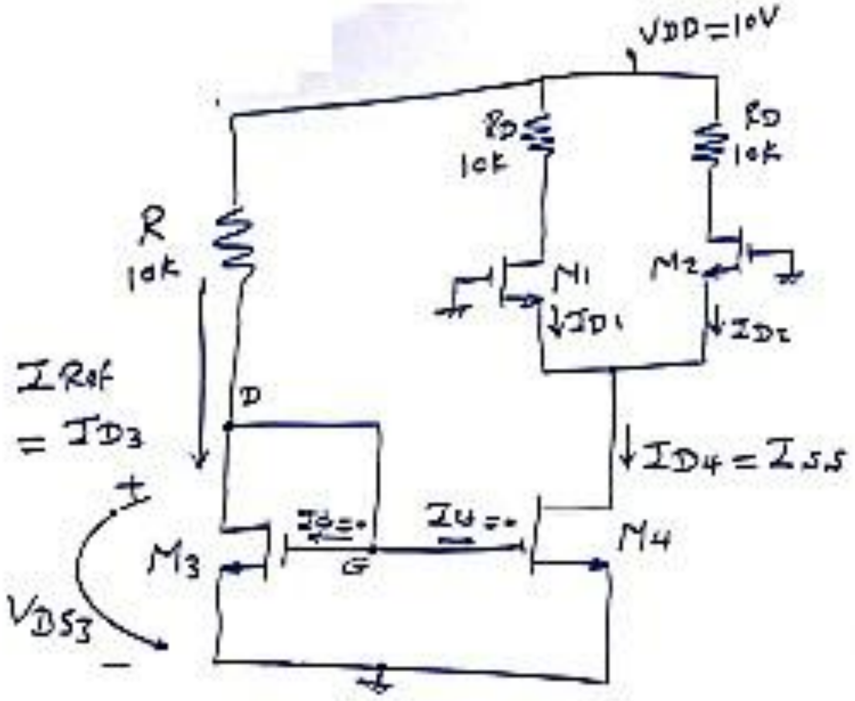
(c) The common mode gain (Ac.

(d) The CMRR in dB.



Solution:

(a) DC Analysis



Condition for saturation

$V_{DS} > V_{GS} - V_T$

$V_{GS} = V_G - V_S$

$V_{DS} = V_D - V_S$

For M3

$V_{GS_3} = V_{DS_3}$

$\therefore$ M3 is saturation

K.V.L $\quad 10 = 10\, I_{D3} + V_{DS_3}$

$10 = 10\, I_{D3} + V_{GS_3}$

$$I_{D3} = \frac{10 - V_{GS_3}}{10}$$

$$\boxed{I_{D3} = 1 - 0.1\, V_{GS_3}} \quad (1)$$

We have $\quad I_{D_3} = \frac{K}{2}(V_{GS_3} - V_T)^2$

$$1 - 0.1\, V_{GS_3} = \frac{1}{2}(V_{GS_3} - 1)^2$$

$$2 - 0.2\, V_{GS_3} = V_{GS_3}^2 - 2V_{GS_3} + 1$$

$$\boxed{V_{GS3}^2 - 1.8V_{GS3} - 1 = 0}$$

solving

$$V_{GS3} = \begin{cases} 2.2454V & \text{ok} > V_T \\ -0.443V & \text{Rejected} < V_T \end{cases}$$

$$V_{GS3} = 2.2454V$$

sub. into ①

$$I_{D3} = 0.7755\,mA$$

$\because V_{GS4} = V_{GS3}$

$\therefore I_{D4} = I_{D3}$

$$\therefore \boxed{I_{D4} = I_{SS} = 0.7755\,mA}$$

$\because V_{GS1} = V_{GS2}$

$\therefore I_{D1} = I_{D2} = \frac{I_{SS}}{2}$

$$I_{D1} = I_{D2} = 0.3877\,mA$$

$* \; g_m = \sqrt{2K I_D}$

$$g_{m1} = g_{m2} = g_m = \sqrt{2 \times 2 \times 0.3877}$$

$$g_m = 1.2454\,m\mho = 1.2454\,mA/V$$

$* \; r_{ds1} = r_{ds2} = \frac{V_{A1}}{I_{D1}} = \frac{\infty}{I_{D1}} = \infty$

$* \; R_{SS} = r_{ds4} = \frac{V_{A4}}{I_{D4}} = \frac{100V}{0.7755\,mA} = 128.95\,k\Omega$

(b) AC Anaysis

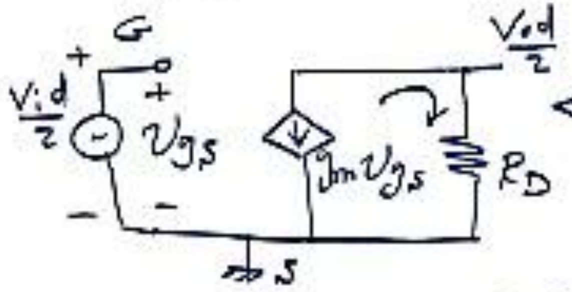
$$v_{i1} = V_{ic} + \frac{V_{id}}{2}$$

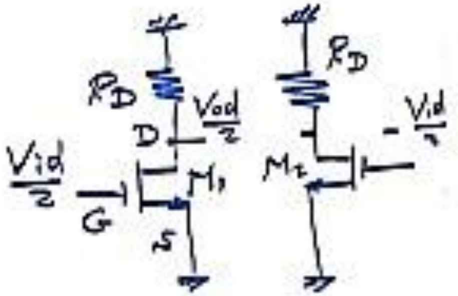
$$v_{i2} = V_{ic} - \frac{V_{id}}{2}$$

(2) Differential Mode gain (A_{dM})

$v_{i1} = \frac{V_{id}}{2}$, $v_{i2} = -\frac{v_{id}}{2}$ $\therefore V_S = 0$

Using half-Circuit





$$A_{dM} = \frac{V_{od}/2}{V_{id}/2} = \frac{-g_m V_{gs} \cdot R_D}{V_{gs}}$$

Gain of Signal

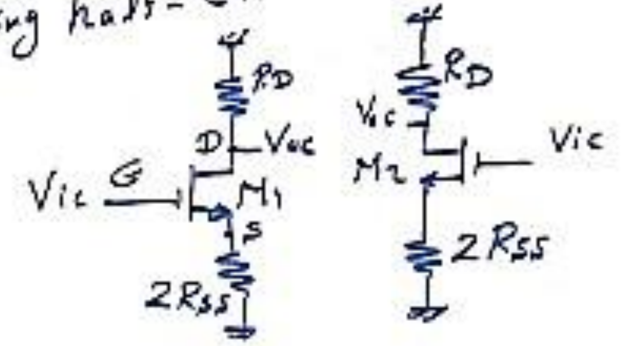
$$\therefore A_{dM} = -g_m R_D = -1.2454 \times 10 = -12.454$$

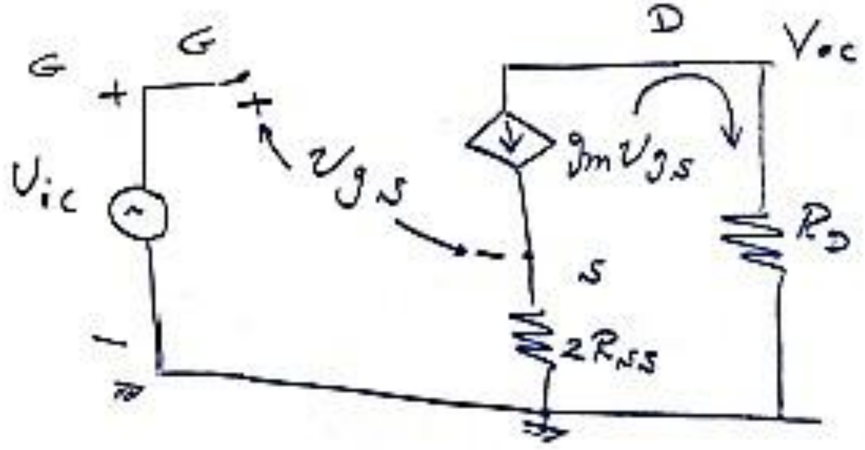
(3) Common Mode gain (A_{cM})

$v_{i1} = V_{ic}$, $v_{i2} = V_{ic}$

$V_S \neq 0$

Using half-Circuit Concept





$$A_{CM} = \frac{V_{oc}}{V_{ic}}$$

$$A_{CM} = \frac{-g_m V_{gs} R_D}{V_{gs} + g_m V_{gs}\, 2R_{SS}}$$

$$A_{CM} = \frac{-g_m R_D \cancel{V_{gs}}}{[1 + 2 g_m R_{SS}]\cancel{V_{gs}}}$$

$$A_{CM} = \frac{-g_m R_D}{1 + 2 g_m R_{SS}}$$

$$A_{CM} = \frac{-1.2454 \times 10}{1 + 2 \times 1.2454 \times 120.45}$$

$$A_{CM} = -0.0386544$$

Gain of noise

4 Common Mode Rejection Ratio

$$CMRR = \left| \frac{A_{dM}}{A_{CM}} \right|$$

$$CMRR = \frac{12.454}{0.0386544}$$

$$CMRR = 322.2$$

$$CMRR(dB) = 20 \log 322.2$$

$$CMRR(dB) = 50.2\ dB$$

Example(2)

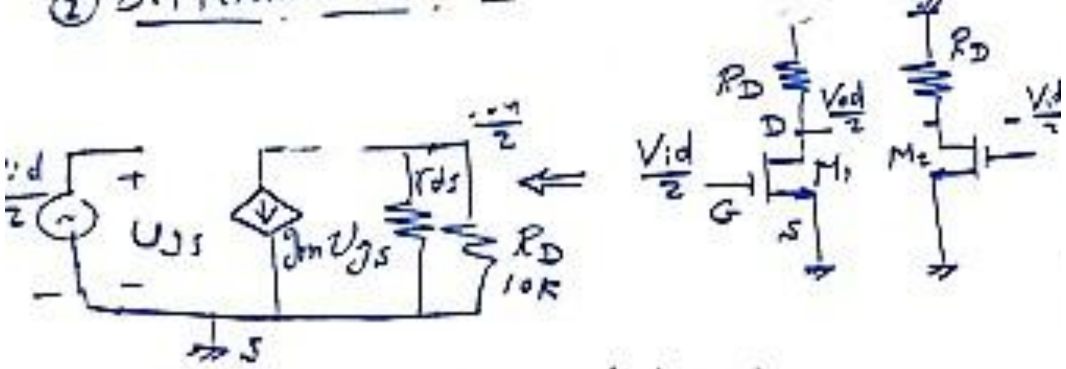
Repeat the last example if $V_{A1} = V_{A2} = 100V$ (rds of M1 and M2 are not neglected)

.Solution:(1) DC Drain currents will not changed

$$* \; r_{ds1} = r_{ds2} = \frac{V_{A1}}{I_{D1}} = \frac{100V}{0.3877} = 257.93K$$

$$r_{ds1} = r_{ds2} = r_{ds} = 257.93k\Omega$$

② Differential Mode gain



$$A_{dM} = \frac{V_{od}/2}{V_{id}/2} = \frac{-g_m V_{gs}(r_{ds} \| R_D)}{V_{gs}}$$

Gain of Signal

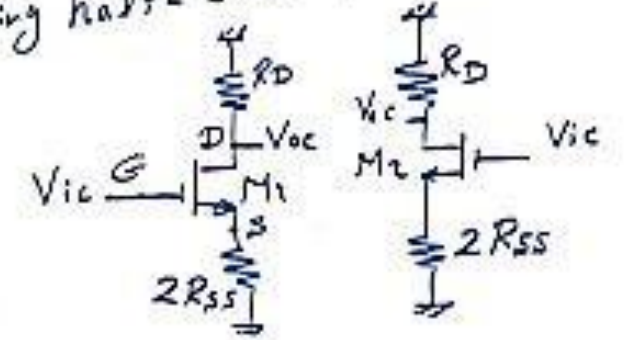
$$\therefore A_{dM} = -9.63 \times 1.2454 = -11.989 \simeq -12$$

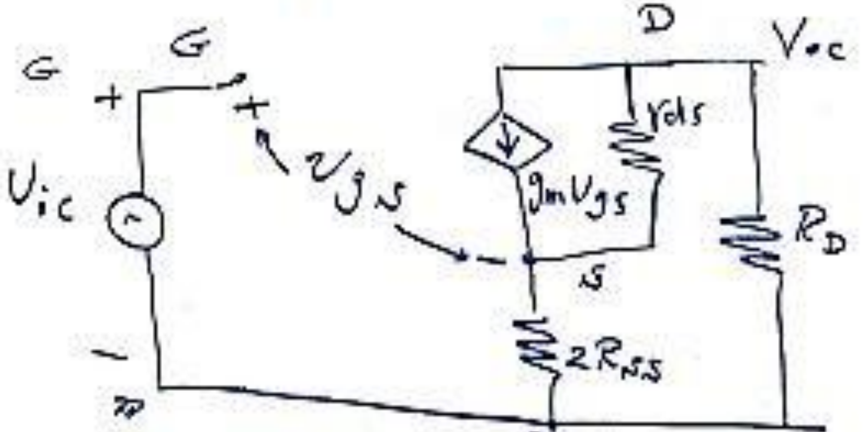
3 Common Mode gain (A_{CM})

$v_{i1} = v_{ic}$, $v_{i2} = v_{ic}$

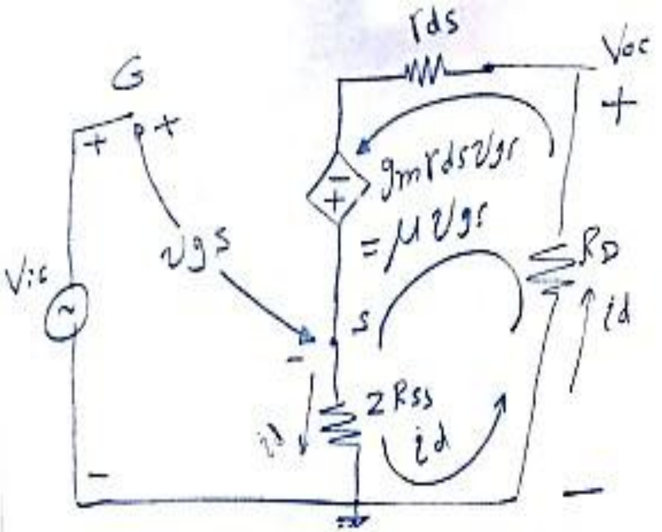
$v_S \neq 0$

Using half-circuit concept





Amplification factor $\mu = g_m r_{ds} = 321.23$



$$* \; i_d = \frac{\mu v_{gs}}{r_{ds} + R_D + 2R_{SS}} \quad (1)$$

$$* \; V_{oc} = -i_d R_D$$

$$V_{oc} = \frac{-\mu R_D V_{gs}}{r_{ds} + R_D + 2R_{SS}} \quad (2)$$

$$* \; V_{ic} = V_{gs} + i_d \, 2R_{SS}$$

$$= V_{gs} + \frac{2\mu R_{SS} V_{gs}}{r_{ds} + R_D + 2R_{SS}}$$

$$V_{ic} = \left[1 + \frac{2\mu R_{SS}}{r_{ds} + R_D + 2R_{SS}}\right] V_{gs}$$

$$V_{ic} = \frac{r_{ds} + R_D + 2R_{SS} + 2\mu R_{SS}}{r_{ds} + R_D + 2R_{SS}} V_{gs} \quad (3)$$

(2) ÷ (3) $$A_{CM} = \frac{V_{oc}}{V_{ic}} = \frac{-\mu R_D}{r_{ds} + R_D + (1+\mu) 2R_{SS}}$$

$A_{CM} = -0.03744$

4 $CMRR = \frac{12}{0.03744} = 320.5$

$CMRR(dB) = 20 \log 320.5 = 50.1 \, dB$

Example(3)

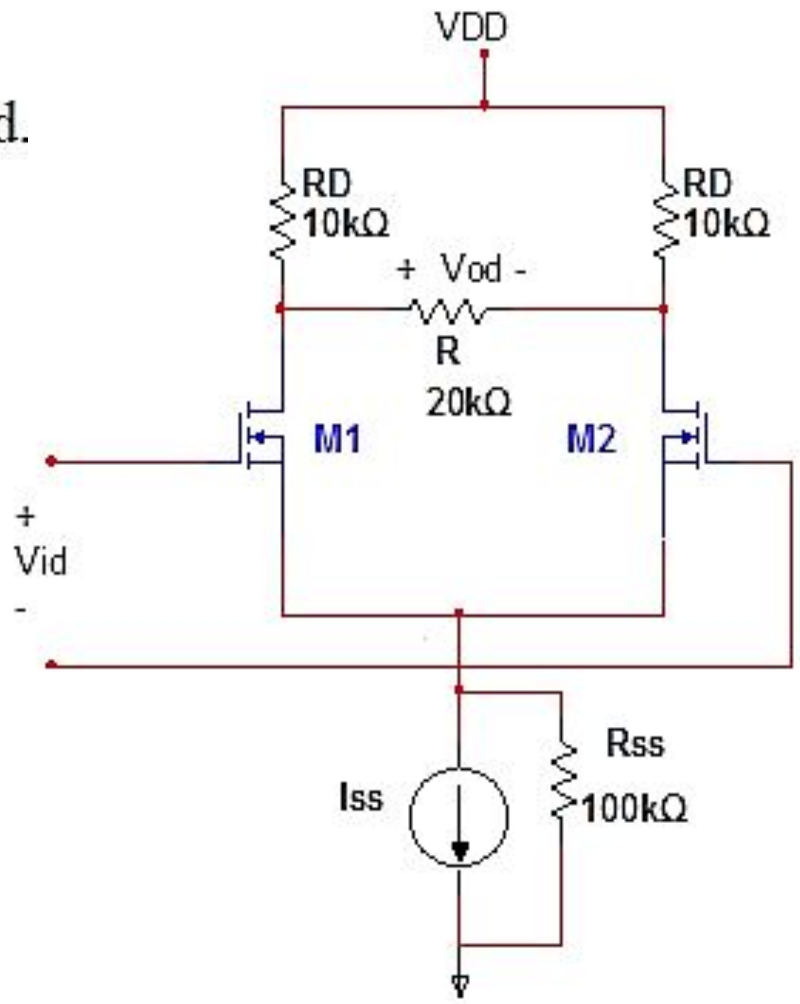
Analyze the MOS-differential amplifier circuit shown in Figure if M1 and M2 are matched with $g_m = 2mA/V$ and r_{ds} is neglected.

Calculate:

(a) The differential mode gain (A_{dm}).

(b) The common mode gain (A_{cm}).

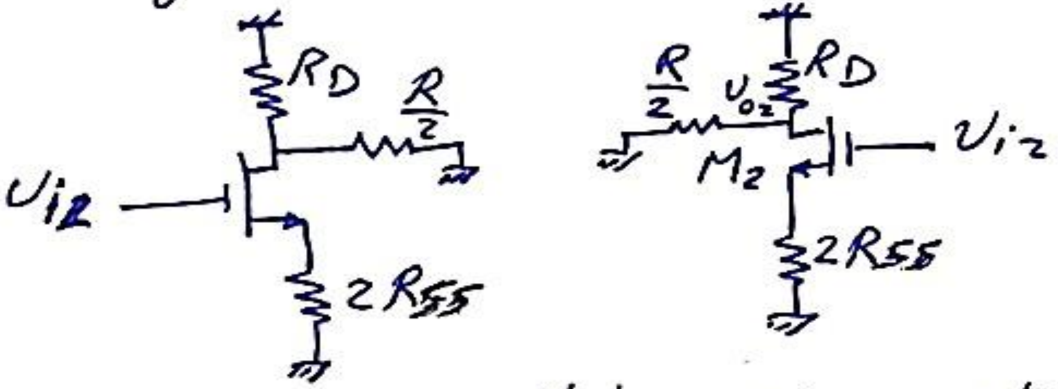
(c) The CMRR in dB.



Solution:

(a) The differential mode gain (A_{dm}).

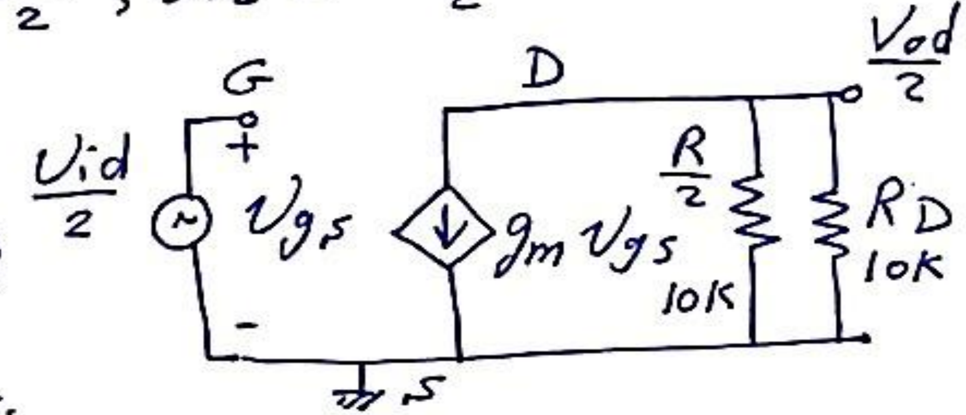
Using the half-Circuit Concept



$$v_{i1} = v_{ic} + \frac{v_{id}}{2} \quad , \quad v_{i2} = v_{ic} - \frac{v_{id}}{2}$$

* Differential Mode $v_{i1} = \frac{v_{id}}{2}$, $v_{i2} = -\frac{v_{id}}{2}$ ∴ $v_s = 0$

$$A_{dm} = \frac{v_{od}}{v_{id}} = \frac{v_{od}/2}{v_{id}/2}$$



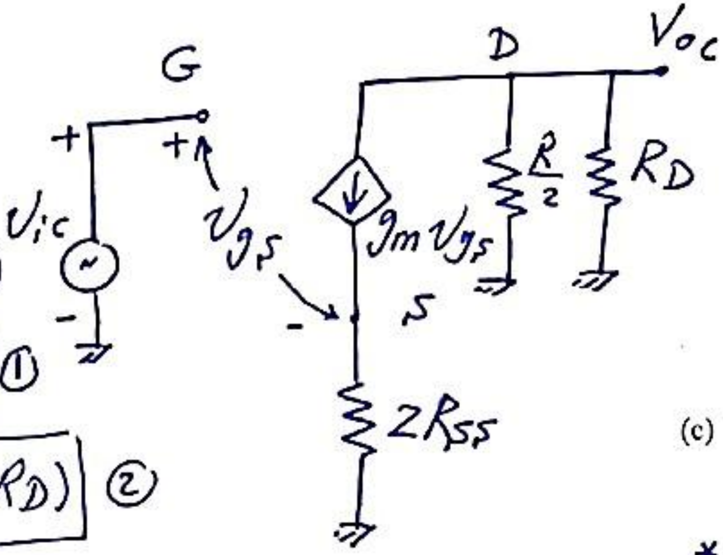
$$A_{dm} = \frac{-g_m v_{gs}(\frac{R}{2} \| R_D)}{v_{gs}}$$

$$\boxed{A_{dm} = -g_m(\frac{R}{2} \| R_D)}$$ # $A_{dm} = -2[10 \| 10] = -10$

(b) The common mode gain (A_{cm}).

$v_{i1} = v_{ic}$, $v_{i2} = v_{ic}$

$\therefore V_i \neq 0$



* $v_{ic} = v_{gs} + g_m v_{gs}(2R_{SS})$

$$\boxed{v_{ic} = [1 + 2g_m R_{SS}]\, v_{gs}} \quad ①$$

* $$\boxed{v_{oc} = -g_m v_{gs}\left(\frac{R}{2} \parallel R_D\right)} \quad ②$$

② ÷ ① $\rightarrow \therefore A_{cm} = \frac{v_{oc}}{v_{ic}}$

$$\boxed{A_{cm} = \frac{-g_m\left(\frac{R}{2} \parallel R_D\right)}{[1 + 2g_m R_{SS}]}} \quad \#$$

$$A_{cm} = \frac{-2\,[10 \parallel 10]}{1 + 2 \times 2 \times 100} = \frac{-10}{1+400}$$

$$\boxed{A_{cm} \cong -0.02494} \quad \#$$

(c) The CMRR in dB.

* $CMRR = \left|\frac{A_{dm}}{A_{cm}}\right| = \frac{10}{0.02494} \cong 401$

* $CMRR(dB) = 20 \log\left|\frac{A_{dm}}{A_{cm}}\right| = 20 \log 401$

$$\boxed{CMRR(dB) = 52.063\ dB} \quad \#$$