AEC lec 36 15/10/23

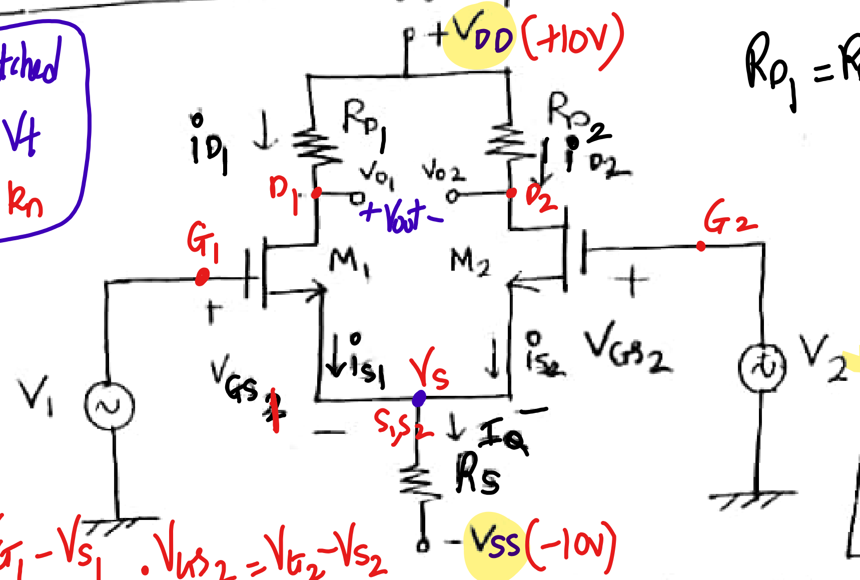
• Basic MOSFET Diffamp:- (DIBO)

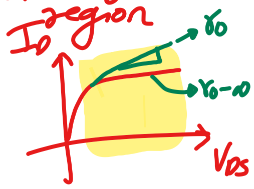
M_1, M_2 matched

$V_{tn_1} = V_{tn_2} = V_t$

$k_{n_1} = k_{n_2} = k_n$

$M_1 \,\&\, M_2 \rightarrow$ saturation region





$R_{D_1} = R_{D_2} = R_D$

$v_d = V_1 - V_2$

$v_{cm} = V_1 + V_2/2$

$V_{GS_1} - V_{GS_2} = V_{G_1} - V_{G_2} = V_1 - V_2$

$\boxed{I_Q = i_{S_1} + i_{S_2} = i_{D_1} + i_{D_2}}$

$$I_Q = i_{S_1} + i_{S_2}$$
$$I_Q = i_{D_1} + i_{D_2}$$

$V_{GS_1} = V_{G_1} - V_{S_1}$, $V_{GS_2} = V_{G_2} - V_{S_2}$

ckt ①: Basic MOSFET Diffamp (DIBO) configuration

- The transistor M_1 and M_2 are matched and we assume that both M_1 and M_2 are always biased in the saturation region.
- The basic MOSFET diff-amp use both positive and negative bias supply voltages, thereby eliminating the need for any coupling capacitors and voltage-divider biasing resistors at the gate terminals.
- The above circuit is called "direct-coupled" diffamp

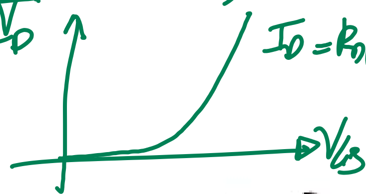
$$V_d = V_1 - V_2$$

The dc transfer characteristics of MOSFET Diffamp can be determined from the circuit ①.

- Neglecting the o/p resistances of M_1 and M_2 and assuming that the two transistors are matched, we can write,

$i_{D_1} \propto V_{GS_1}^2$; $i_{D_2} \propto V_{GS_2}^2$.

$\left(V_{tn_1} = V_{tn_2} = V_t \atop K_{n_1} = K_{n_2} = K_n \right)$



$$i_{D_1} = K_n\left(V_{GS_1} - V_{TN}\right)^2 \quad — ①$$

and $$i_{D_2} = K_n\left(V_{GS_2} - V_{TN}\right)^2 \quad — ②$$

Taking the square-roots of eqn ① & ② & subtracting ① & ②, we get

$$\sqrt{i_{D_1}} - \sqrt{i_{D_2}} = \sqrt{K_n}\left(V_{GS_1} - V_{GS_2}\right) = \sqrt{K_n}\, V_d \quad — ③$$

$V_d = V_{GS_1} - V_{GS_2}$

$V_d = V_{GS_1} - V_{GS_2} = V_1 - V_2$

↓ Differential-mode I/P voltage.

$V_d > 0 \rightarrow V_1 - V_2 > 0$
$V_1 > V_2$

∴ If $V_d > 0$, then $V_{GS_1} > V_{GS_2}$, which implies that $i_{D_1} > i_{D_2}$
$(V_1 > V_2)$

Since $i_{D_1} + i_{D_2} = I_Q \quad — ④$

$i_{D_2} = I_Q - i_{D_1}$

Eqn ③ becomes, (by squaring both sides)

$\sqrt{i_{D_1}} - \sqrt{i_{D_2}} = \sqrt{K_n}\, V_d \rightarrow$ Eq ③

$$\left(\sqrt{i_{D_1}} - \sqrt{I_Q - i_{D_1}}\right)^2 = K_n V_d^2 \quad — ⑤$$

ie $$\cancel{i_{D_1}} + \left(I_Q - \cancel{i_{D_1}}\right) - 2\sqrt{i_{D_1}}\sqrt{I_Q - i_{D_1}} = K_n V_d^2$$

$$\sqrt{i_{D_1}\left(I_Q - i_{D_1}\right)} = \frac{1}{2}\left(I_Q - K_n V_d^2\right) \quad — ⑥$$

Squaring ⑥, we get $$i_{D_1}^2 - I_Q\, i_{D_1} + \frac{1}{4}\left(I_Q - K_n V_d^2\right)^2 = 0 \quad — ⑦$$

1.5mA 0.5mA 2mA
$i_{D_1} + i_{D_2} = I_Q$ $\quad V_d > 0$
$i_{D_1} > i_{D_2}$

Apply the quadratic formula & rearranging terms, we get (Note: $i_{D_1} > \frac{I_Q}{2}$ & $v_d > 0$)

$$\frac{-b \pm \sqrt{b^2-4ac}}{2a}$$

$$i_{D_1} = \frac{I_Q}{2} + \sqrt{\frac{K_n I_Q}{2}} \cdot v_d \sqrt{1 - \left(\frac{K_n}{2I_Q}\right) v_d^2} \quad \text{—(8)}$$

$\frac{i_{D_1}}{I_Q}$

Using eqn (4), similarly we find that

$$i_{D_2} = \frac{I_Q}{2} - \sqrt{\frac{K_n I_Q}{2}} \cdot v_d \sqrt{1 - \left(\frac{K_n}{2I_Q}\right) v_d^2} \quad \text{—(9)} \quad \frac{i_{D_2}}{I_Q}$$

- The normalized drain currents are,

$$\boxed{\begin{aligned} \frac{i_{D_1}}{I_Q} &= \frac{1}{2} + \sqrt{\frac{K_n}{2I_Q}} \cdot v_d \sqrt{1 - \left(\frac{K_n}{2I_Q}\right) v_d^2} \quad \text{—(10)} \\ \frac{i_{D_2}}{I_Q} &= \frac{1}{2} - \sqrt{\frac{K_n}{2I_Q}} \cdot v_d \sqrt{1 - \left(\frac{K_n}{2I_Q}\right) v_d^2} \quad \text{—(11)} \end{aligned}}$$

Eqn (10) and (11) describe the dc transfer characteristics for MOSFET Diffamp

$$v_d' = \frac{v_d}{\sqrt{2I_Q/K_n}}$$

$I_Q = i_{D_1} + i_{D_2}$

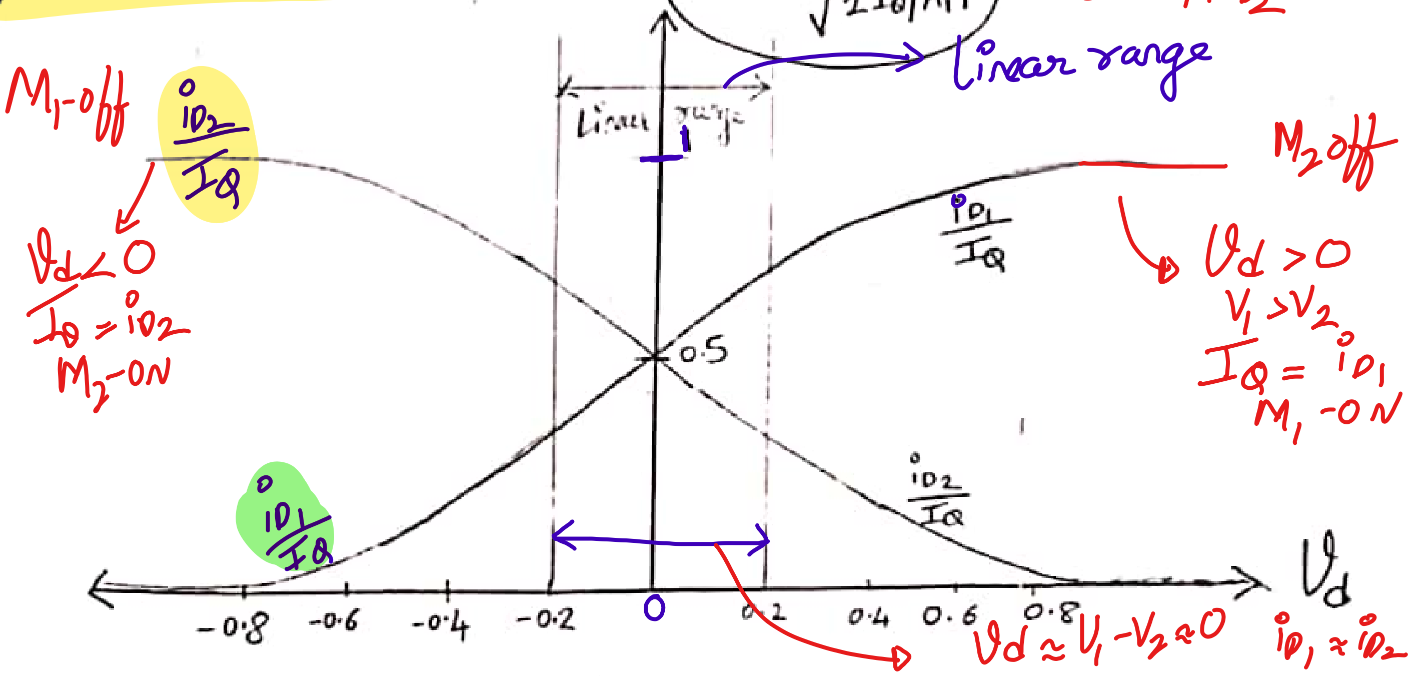


Fig 1.1: Normalized dc transfer characteristics of MOSFET diffamp.

AC analysis: → A_d, A_{cm}, CMRR (DIBO, DIVO, SIBO, SIVO)

DC analysis: same for all types of Diff

Observations:-

1. From eqn (10) and (11), and fig 1.1, at a specific differential I/P voltage, bias current I_Q is switched entirely to one transistor or the other.

This occurs when

$$\boxed{|V_d|_{max} = \sqrt{\frac{I_Q}{K_n}}} \quad - (12)$$

—x—

Why we go for MOSFET Diffamp?

The maximum differential I/P signal for the MOSFET diffamp is much larger than for BJT diffamp.

- The primary reason is that the gain of the MOSFET diffamp, as we will see, is much smaller than the gain of the BJT diffamp.
- Many diffamp's are constructed with MOSFET's, since it provides high I/P impedances, which helps amplifiers avoid loading of source (which are instrumental in circuits like opamp's, instrumentation amplifiers).

∴ A MOSFET diffamp cannot provide high gain but it avoid loading of source.

Also, MOSFETs can be easily fabricated in IC form.

DC Analysis and derivation of Ad for MOSFET DIBO Diffamp

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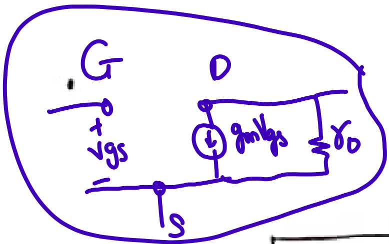
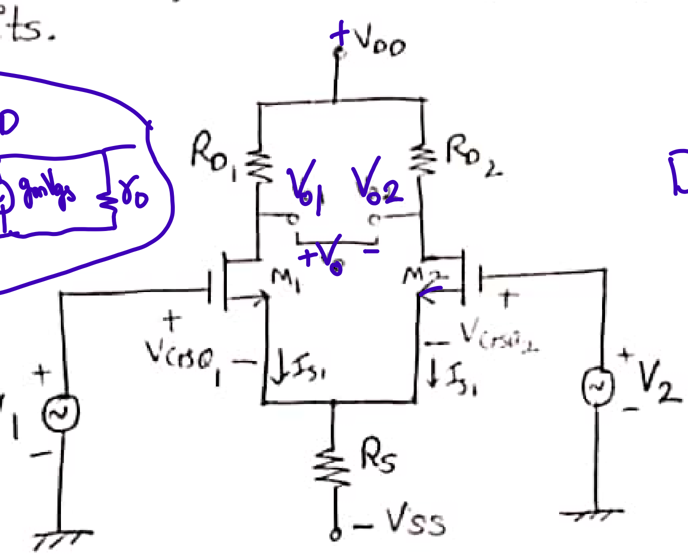
* Small-signal Analysis for MOSFET Diffamp:- 44.

. We can determine the basic relationships for Ad, Acm and CMRR from an analysis of small-signal equivalent circuits.

$\boxed{A_d, A_{cm} \text{ \& CMRR}}$

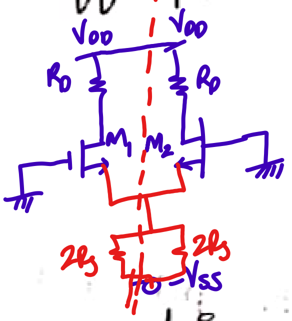




DIBO diffamplr $R_{D1} = R_{D2} = R_D$

M_1, M_2 match

ckt (2.1): A DIBO MOSFET Diffamp.



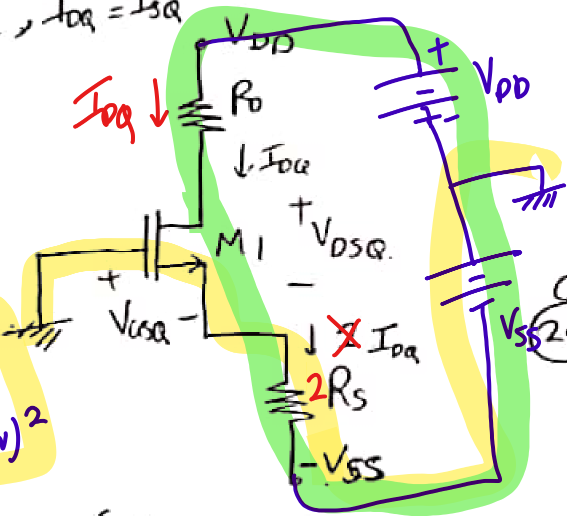
For DC Analysis:-

- Remove all AC signal sources ($V_1 = V_2 = 0$)
- Since both sections including M_1 & M_2 are symmetric, consider only half-ckt

$R_{D1} = R_{D2}$, $V_{TN1} = V_{TN2}$, $I_{DQ} = I_{SQ}$

$I_G = 0$ (becoz of SiO_2 layer)

Qpt: (V_{GSQ}, I_{DQ}) (V_{DSQ}, I_{DQ})



ckt (2.2): DC equivalent half-ckt

KVL to G-S loop

$-V_{GSQ} - 2R_S I_{DQ} + V_{SS} = 0$

$$\boxed{\begin{aligned} V_{GSQ} &= V_{SS} - 2R_S I_{DQ} \\ I_{DQ} &= k_n (V_{GSQ} - V_{TN})^2 \end{aligned}}$$

for KVL to D-S loop,

$V_{DD} - I_D R_D - V_{DSQ} - I_D \times 2R_S + V_{SS} = 0$

$$\boxed{V_{DSQ} = (V_{DD} + V_{SS}) - I_D (R_D + 2R_S)}$$

• Find Q-point $\equiv (V_{DSQ}, I_{DQ})$ using the equation's,

$V_{GSQ} = V_{SS} - 2 I_{DQ} R_S$ (KVL to G-S loop)

$I_{DQ} = K_n (V_{GSQ} - V_{Tn})^2$; $V_{DSQ} = (V_{DD} + V_{SS}) - 2 I_{DQ} R_S - I_{DQ} R_D$

From (2.2).

· Applying KVL to Gate-source loop, we get

$$-V_{GSQ} - 2I_{DQ}R_S + V_{SS} = 0$$

$$\therefore \boxed{V_{GSQ} = V_{SS} - 2I_{DQ}R_S} \quad -(1)$$

Then, $I_{DQ} = K_n (V_{GSQ} - V_{Tn})^2 \quad -(2)$ --> Drain current eq^n for E-MOSFET (n-channel)

From (1) & (2), we can find values of I_{DQ} & V_{GSQ}

Applying KVL to drain-source loop,

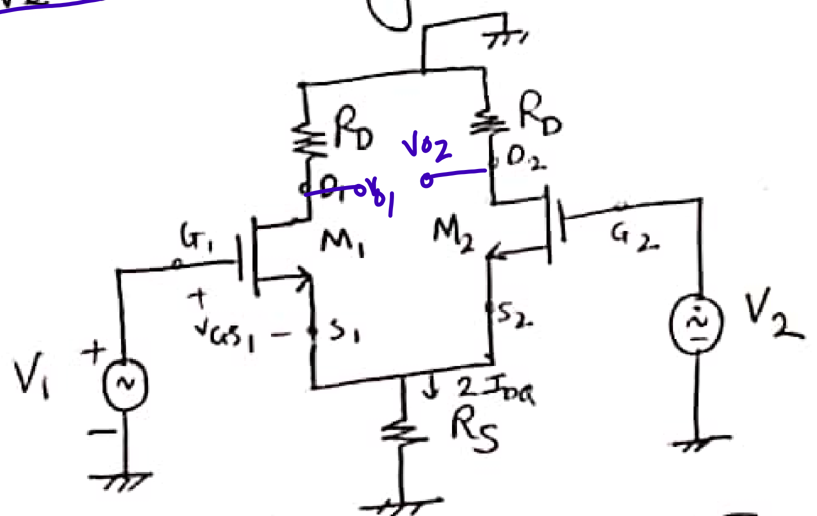
$$V_{DD} - I_{DQ}R_D - V_{DSQ} - 2I_{DQ}R_S + V_{SS} = 0$$

$$V_{DSQ} = (V_{DD} + V_{SS}) - 2I_{DQ}R_S - I_{DQ}R_D$$

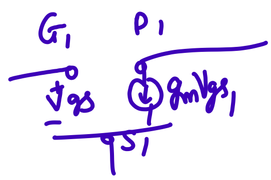
$$\therefore \boxed{V_{DSQ} = (V_{DD} + V_{SS}) - I_{DQ}(R_D + 2R_S)} \quad -(3)$$

AC analysis:-

· Remove all DC signal sources ($V_{DD} = -V_{SS} = 0$)



M_1 & M_2 with its small sig model



ckt 2.3: AC equivalent of ckt (2.1).

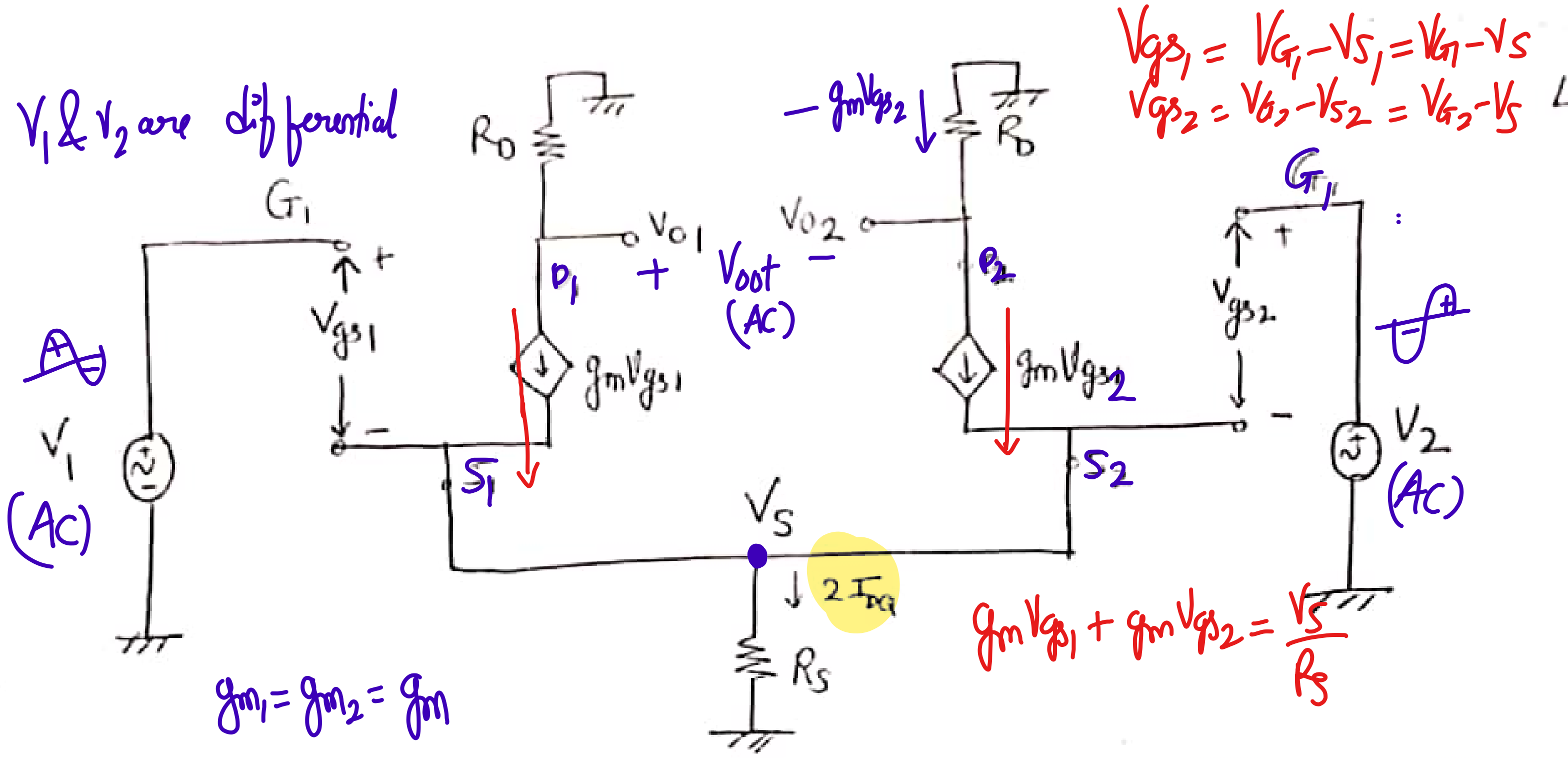


fig 2.4: Small-signal equivalent circuit for MOSFET DIBO Diffamp. with differential-mode I/P's

- Note, the two transistor's are biased at the same Q-point current & hence $g_{m_1} = g_{m_2} = g_m$.

For differential mode of operation:, both I/p's are equal in magnitude's but opposite in phase with each other. ie $V_1 = -V_2$

Writing KCL equation's at node V_S, we have

$$g_m V_{gs_1} + g_m V_{gs_2} = \frac{V_S}{R_S} \quad \text{— (1)}$$

$$g_m [V_{gs_1} + V_{gs_2}] = \frac{V_S}{R_S}$$

Now, $V_{gs_1} = V_1 - V_S$ and $V_{gs_2} = V_2 - V_S$ (From fig 2.4) → (2)

$$\therefore g_m [V_1 - V_S + V_2 - V_S] = \frac{V_S}{R_S}$$

$$\text{ie} \quad g_m [V_1 + V_2 - 2V_S] = \frac{V_S}{R_S}$$

ie $g_m(V_1+V_2) = \left(2g_m + \frac{1}{R_S}\right)V_S$

ie $\boxed{V_S = \dfrac{V_1+V_2}{2+\dfrac{1}{g_m R_S}}}$ — (3)

Now, since it's an DIBO Diffam,

$V_o = V_{o2} - V_{o1} = V_{out}$

⇨ From fig (2.4), $V_{o2} = -(g_m V_{gs2})R_D$

$V_{o2} = -g_m R_D (V_2 - V_S)$ — (4)

Also, $V_{o1} = -(g_m V_{gs1})R_D$

$V_{o1} = -g_m R_D (V_1 - V_S)$ — (5)

∴ $V_o = V_{o2} - V_{o1}$

$= -g_m R_D \left[(V_2 - \cancel{V_S}) - (V_1 - \cancel{V_S})\right]$

$\boxed{V_o = g_m R_D (V_1 - V_2)}$ — (6)

Now, $V_d = V_1 - V_2$ → differential mode I/P signal.

$V_d = V_1 - V_2$

ie $A_d = \dfrac{V_o}{V_d}$

$A_d = \dfrac{V_o}{V_d}$

$\boxed{A_{d_{DIBO}} = g_m R_D}$

$\boxed{A_d = g_m R_D}$ — (A)

DIBO

→ For DIBO MOSFET diffamp

Derivation of Acm for MOSFET Diffamp

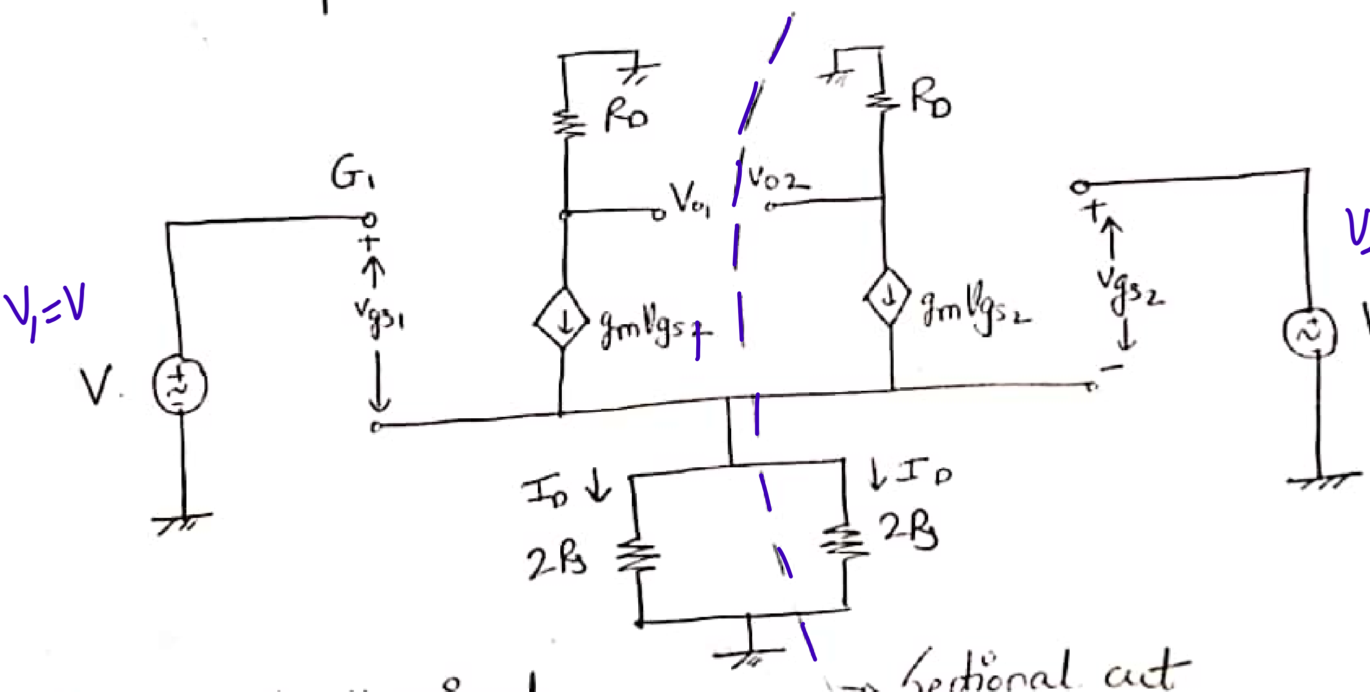
$V_1 = V_2 = V$

- For common-mode of operation (Find expression for Acm)

Acm DIBO

We select both I/P's to be equal in magnitude and phase i.e $V_1 = V_2 = V$, This make the AC equivalent ckt exactly mirror image's.

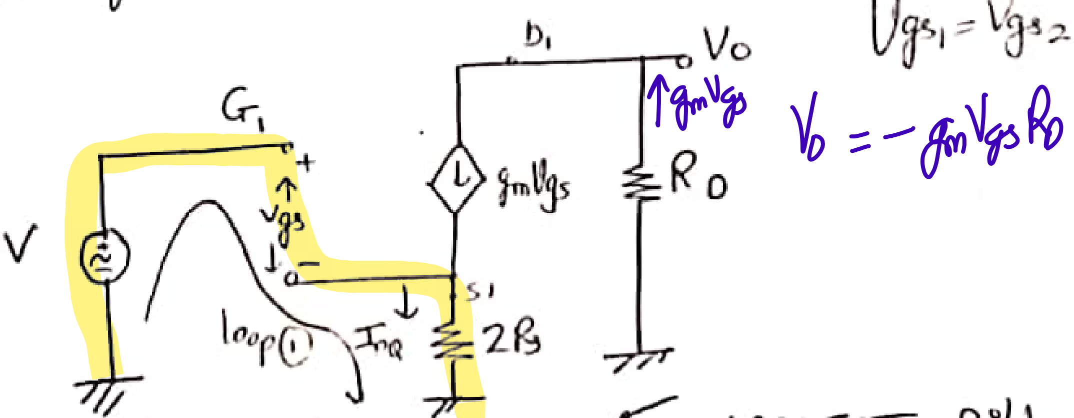
Since both section's including M_1 & M_2 are symmetrical we analysis one half of the section.



ckt 2.5: Small-signal equivalent mode for MOSFET DIBO Diffamp in Common-mode operation.

$V_{gs1} = V_{gs2}$

$V_0 = -g_m V_{gs} R_D$



ckt 2.6: Half-ckt for deriving Acm for MOSFET Diffamp (DIBO)

From ckt 2.6,

$$V_o = -I_o R_D$$

$$\boxed{V_o = -g_m V_{gs} R_D} \quad -(i)$$

Apply KVL to loop ①, we get

$$V - V_{gs} - 2 I_o R_S = 0$$

$$V = V_{gs} + 2 g_m V_{gs} R_S \qquad (I_o = g_m V_{gs})$$

$$\text{ie } V = V_{gs}\left[1 + 2 g_m R_S\right] \quad -(ii)$$

$$V_{cm} = \frac{V_1 + V_2}{2} = \frac{V+V}{2} = V$$

$$\text{Now, } A_{cm} = \frac{V_o}{V_{cm}} = \frac{V_o}{V}$$

$$\text{ie } A_{cm} = \frac{-g_m \cancel{V_{gs}} R_D}{\cancel{V_{gs}}\left[1 + 2 g_m R_S\right]}$$

$$\boxed{A_{cm_{DIBO}} = \frac{-g_m R_D}{(1 + 2 g_m R_S)}} \quad -(B)$$

--- For DIBO Diff amp (MOSFET)

If we neglect 1, ie $1 + 2g_m R_S \approx 2 g_m R_S$

$$|A_{cm}|_{DIBO} = \left|\frac{R_D}{2R_S}\right|$$

$$\text{ie } A_{cm} = -\frac{g_m R_D}{2 g_m R_S}$$

$$\boxed{A_{cm} = \left|\frac{R_D}{2 R_S}\right|} \quad -(b1)$$

$$CMRR\Big|_{DIBO} = \left|\frac{A_d}{A_{cm}}\right|$$

$$A_d\Big|_{DIBO} = g_m R_D$$

$$A_{cm}\Big|_{DIBO} = \left|\frac{R_D}{2R_s}\right|$$

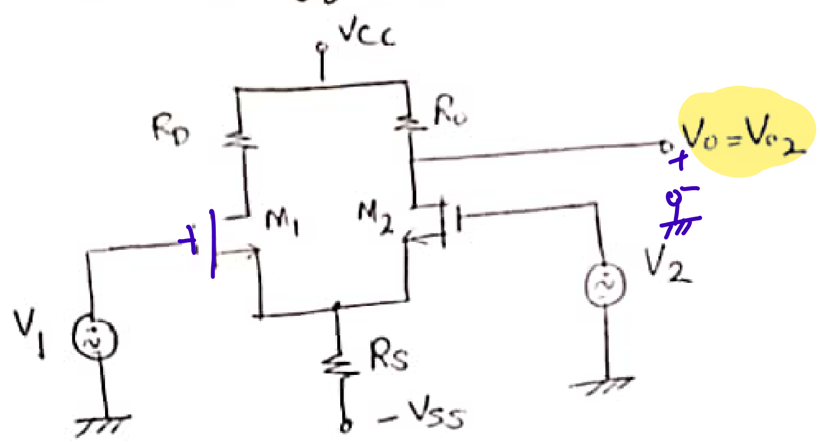
$$\therefore \quad CMRR\Big|_{DIBO} = \left|\frac{g_m \cancel{R_D}(2R_s)}{\cancel{R_D}}\right|$$

$$\boxed{CMRR\Big|_{DIBO} = |2g_m R_s|} \quad \text{— (C)}$$

$$CMRR_{in\,dB} = 20\log_{10}|2g_m R_s| = 20\log_{10}|2g_m R_s|$$

Thus, to ↑se the value of CMRR, we have to ↑se the value of source resistance.

MOSFET DIUO Diffamp:-



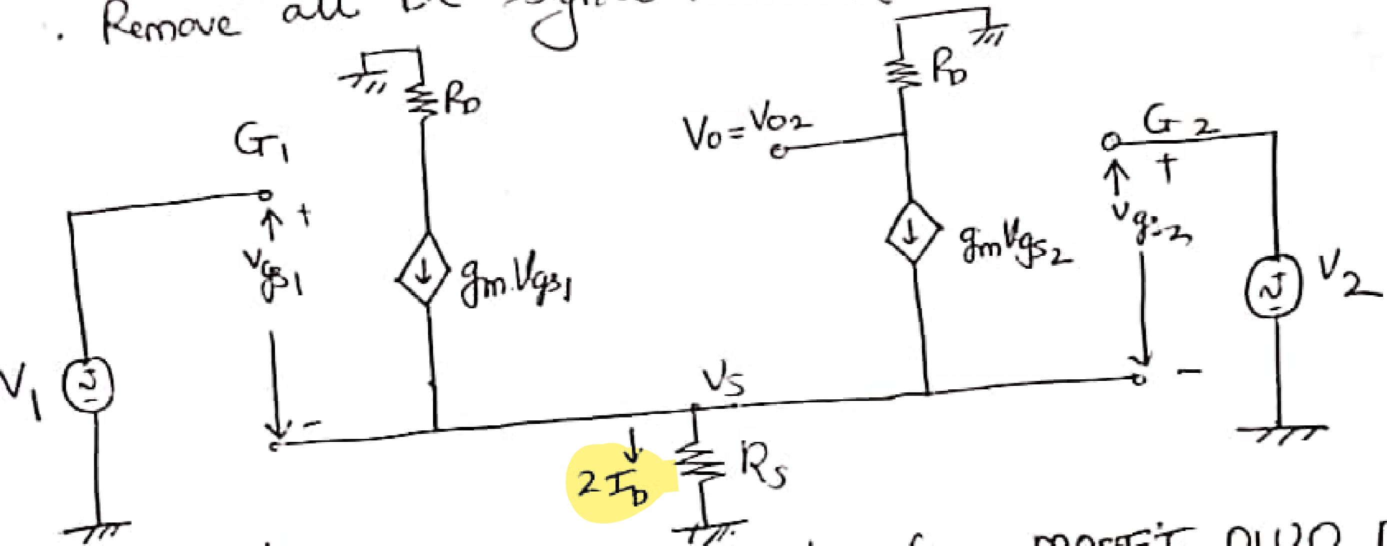
Vo or Vo2 is measured w.r.t gnd

ckt 4.1: Basic DIUO MOSFET Diffamp

$V_{o2} = -g_m V_{gs2} R_D$

AC Analysis:

. Remove all DC signal sources (ie $V_{DD} = -V_{SS} = 0$)



ckt 4.2: Small signal equivalent for MOSFET DIUO Diffamp

From ckt 4.2, $V_{gs1} = V_1 - V_s$, $V_{gs2} = V_2 - V_s$

At node V_s, applying KCL, we get

$$g_m V_{gs1} + g_m V_{gs2} = \frac{V_s}{R_s}$$

$$g_m [V_1 - V_s + V_2 - V_s] = \frac{V_s}{R_s}$$

$$g_m (V_1 + V_2) = \frac{V_s}{R_s} + 2V_s g_m$$

ie $$\boxed{V_S = \frac{V_1+V_2}{2+\frac{1}{g_m R_S}}} \quad — ①$$

For one-sided o/p at the drain of M_2, we have

$$V_o = V_{o_2} = -g_m V_{gs_2} R_D$$

$$V_o = -g_m R_D (V_2 - V_S) \quad — ②$$

Put ① in ② we get

$$V_o = -g_m R_D \left[V_2 - \left(\frac{V_1+V_2}{2+\frac{1}{g_m R_S}} \right) \right]$$

ie $$V_o = -g_m R_D \left[\frac{V_2\left(2+\frac{1}{g_m R_S}\right) - V_1 - V_2}{2+\frac{1}{g_m R_S}} \right]$$

ie $$V_o = -g_m R_D \left[\frac{V_2\left(1+\frac{1}{g_m R_S}\right) - V_1}{2+\frac{1}{g_m R_S}} \right] \quad — ③$$

Now, $V_d = V_1 - V_2$ and $V_{cm} = \frac{V_1+V_2}{2}$

$\therefore$ $V_1 = V_{cm} + \frac{V_d}{2}$ and $V_2 = V_{cm} - \frac{V_d}{2}$ — ④

(Refer pg 06)

Put 4 in 3, we get

$$V_o = -g_m R_D \left[\frac{\left(V_{cm} - \frac{V_d}{2}\right)\left(1 + \frac{1}{g_m R_s}\right) - \left(\cancel{V_{cm}} + \frac{V_d}{2}\right)}{2 + \frac{1}{g_m R_s}} \right]$$

$$\text{ie } V_o = -g_m R_D \left[\frac{V_{cm}\left(\frac{1}{g_m R_s}\right) - V_d\left(1 + \frac{1}{2 g_m R_s}\right)}{2 + \frac{1}{g_m R_s}} \right]$$

$$\therefore V_o = -g_m R_D \left[\frac{V_{cm} - V_d (g_m R_s)\left(1 + \frac{1}{2 g_m R_s}\right)}{2 g_m R_s + 1} \right]$$

$$\text{ie } V_o = \boxed{\frac{-g_m R_D}{1 + 2 g_m R_s}} V_{cm} + V_d \left(\frac{g_m R_D}{1 + 2 g_m R_s}\right)\left(\frac{1}{2} + g_m R_s\right)$$

$$V_o = \frac{-g_m R_D}{1 + 2 g_m R_D} V_{cm} + V_d \frac{g_m R_D}{\cancel{1 + 2 g_m R_s}} \cdot \frac{\cancel{1 + 2 g_m R_s}}{2}$$

$$\text{ie } V_o = \boxed{\left(\frac{g_m R_D}{2}\right)} V_d - \boxed{\left(\frac{g_m R_D}{1 + 2 g_m R_s}\right)} V_{cm} \quad — 5$$

Now, $V_o = A_d V_d + A_{cm} V_{cm} \quad — 6$

Comparing 5 and 6, we get

$$\boxed{\begin{aligned} A_d\Big|_{DIUO} &= \frac{g_m R_D}{2} \\ A_{cm}\Big|_{DIUO} &= -\frac{g_m R_D}{1+2g_m R_S} \end{aligned}}$$

→ Differential mode gain

→ Common-mode voltage gain — (C)

- **Differential and Common-mode I/P impedances:-**

- At low frequencies, the I/p impedances of a MOSFET is essentially infinite, which means that both the differential and common-mode I/p resistance of a MOSFET diffamp are infinite

ie $R_{icm} = \infty$

$R_{id} = \infty$

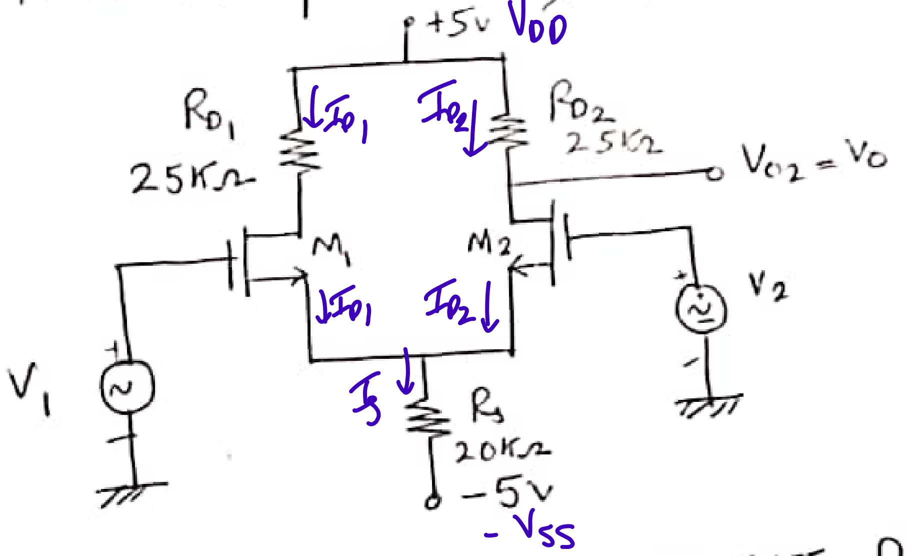
For MOSFET diffamp

Ex: Find a) I_S, I_{D_1}, I_{D_2} and V_{GS_1}, V_{GS_2} for $V_1 = V_2 = 0$

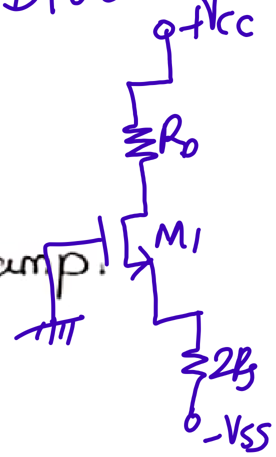
b) $A_d = \frac{V_{o2}}{V_d}$, $A_{cm} = \frac{V_{o2}}{V_{cm}}$

c) CMRR in dB

Given: Transistor parameters, $K_{n_1} = K_{n_2} = 50 \mu A/V^2$, $V_{TN_1} = V_{TN_2} = 1V$



DIVO



Sol^n:- Above ckt is a DIVO MOSFET Diff amp.

a) DC Analysis :-

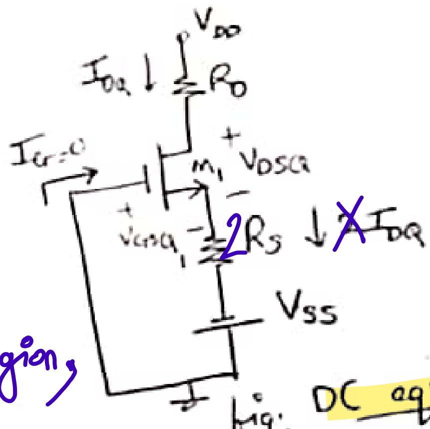


fig. DC equivalent half ckt
(∵ both sect^n are similar)

$$\boxed{V_{GSQ_1} = V_{SS} - 2 I_{DQ_1} R_S}$$

ie $V_{GSQ_1} = 5 - 2 I_{DQ_1} R_S$ — ①

→ Assuming M_1 is in saturation region,

Also, $I_{DQ_1} = K_{n_1} (V_{GSQ_1} - V_{TN_1})^2$

$I_{DQ_1} = 50 \times 10^{-6} (V_{GSQ_1} - 1)^2$ — ②

Put ② in ①,

From ① & ②,

$$V_{GSQ_1} = 5 - 2 \times 50 \times 10^{-6} \times R_S (V_{GSQ_1} - 1)^2$$

$$V_{GSQ_1} = 5 - 2 \times 50 \times 10^{-6} \times 20 \times 10^{3} (V_{GSQ_1} - 1)^2$$

$$V_{GSQ_1} = 5 - 2 (V_{GSQ_1}^2 - 2V_{GSQ_1} + 1)$$

$\therefore 2V_{GSQ_1}^2 - 3V_{GSQ_1} - 3 = 0$

ie $V_{GSQ_1} = 2.186\,V$ ✓ , $V_{GSQ_1} = -0.6861\,V$ ✗ (As $V_{GSQ_1} < V_{TN}$)

$\therefore I_{DQ_1} = K_{n1}(V_{GSQ_1} - V_{TN_1})^2$

$= 50\times10^{-6}(2.186-1)^2$

$\therefore \boxed{V_{GSQ_1} = V_{GSQ_2} = 2.186\,V}$

$\boxed{I_{DQ_1} = 70.33\,\mu A = I_{DQ_2}}$

$\therefore I_S = 2I_D = 140.65\,\mu A.$

$g_m = 2K_n(V_{GS} - V_{TN}) = 2\times50\times10^{-6}(2.186-1)$

$g_{m_1} = g_{m_2} = g_m = 0.118\ mA/V = 118.6\,\mu A/V.$

$A_d = \frac{V_{o2}}{V_d} = \frac{g_m R_D}{2} = 1.4825$

$A_{cm} = \left|\frac{g_m R_D}{1+2g_m R_S}\right| = \frac{V_{o2}}{V_{cm}}$

$= 0.515$

Ad >> 1

Acm << 1

$\therefore CMRR = \left|\frac{A_d}{A_{cm}}\right| = \left|\frac{1.4825}{0.515}\right| = 2.874$

$CMRR\ in\ dB = 20\log_{10}\left|\frac{A_d}{A_{cm}}\right| = 20\log_{10}(2.874)$

$CMRR = 9.17\ dB$

—x—