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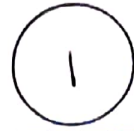
BRANCH :

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MAX. 10 MARKS



Unit - 2

*

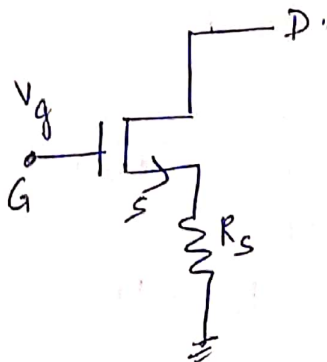
We don't use single stage amplifiers practically. we always use multi-stage amplifiers. Single stage amplifiers don't give the required gain. Hence to obtain the gain we require we use multi stage amplifiers wherein gain is $\uparrow$.

* There are different types of multi stage amplifiers

- 1) CS-CS - (to $\uparrow$ gain)
- 2) CS-CG - (to $\uparrow$ Bandwidth)
- 3) CS-CD - (for impedance matching).

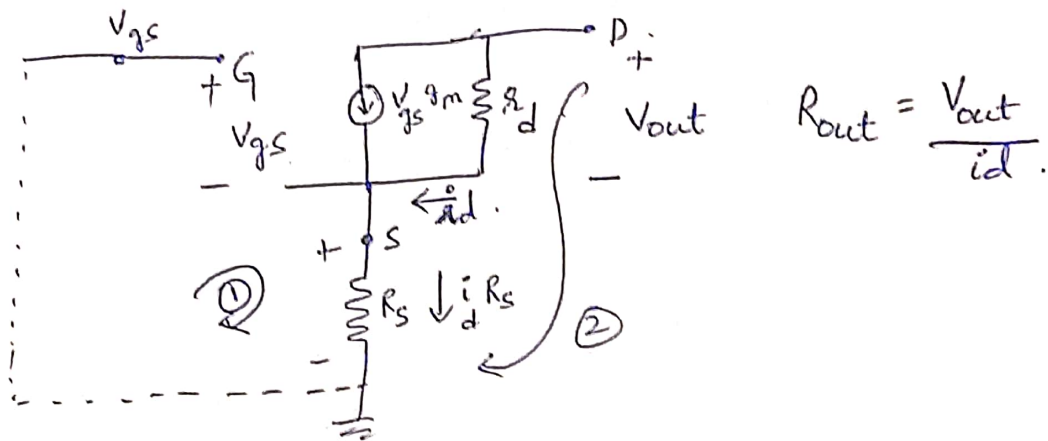
* Cascode stage :-

Due to channel length modulation the o/p impedance of single stage amplifier is limited. To $\uparrow$ the o/p impedance an additional resistor R_S is connected to source terminal of MOSFET.



$V_g \rightarrow$ i/p gate voltage.
 $V_G \rightarrow$ i/p biasing voltage.

Replace MOSFET with its small s/g equivalent model.



Apply KVL @ Loop ①

$$-V_{gs} = i_d R_s$$

Apply KVL @ Loop ②

$$V_{out} = (i_d - g_m V_{gs}) r_d + i_d R_s$$

$$\text{But } V_{gs} = -i_d R_s$$

$$V_{out} = i_d R_d - g_m (-i_d R_s) r_d + i_d R_s$$

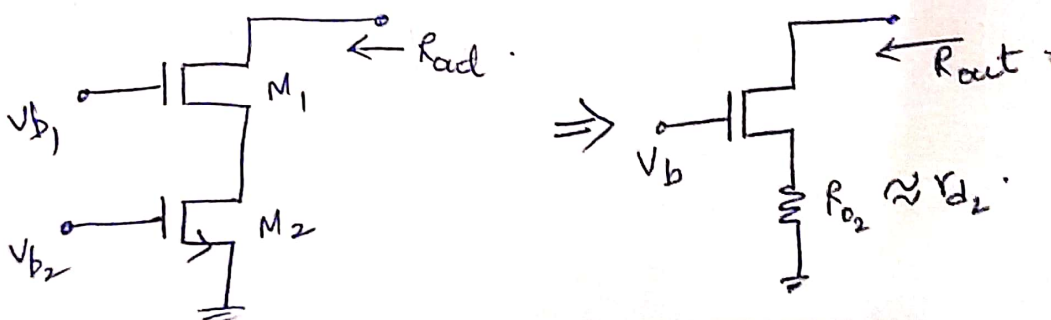
$$V_{out} = i_d [r_d + R_s + g_m R_s r_d]$$

$$\therefore R_{out} = \frac{V_{out}}{i_d} = [r_d + R_s + g_m R_s r_d]$$

This is called "degenerated stage" which is used to ↑ the o/p impedance of the current source.

MOS cascade :-

Two MOSFETS connected in cascade.





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R_S in degenerated stage is replaced with MOSFET.
Here R_{O2} = o/p impedance of M_2 in CS stage.

$$R_{O2} = R_{O2} \approx r_{d2}$$

$$\therefore R_{out} = r_{O2} + r_{d1} [1 + g_m r_{O2}]$$

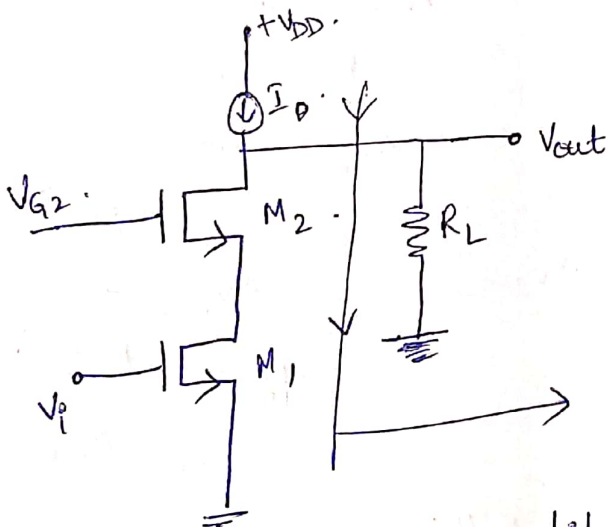
$$= r_{d2} + r_{d1} [1 + g_m r_{d2}]$$

$$\therefore R_{out} = r_{d2} + r_{d1} [1 + g_m r_{d2}]$$

$$\therefore R_{out} \approx g_m r_{d1} r_{d2} \quad g_m r_{d1} r_{d2} \gg r_{d1}$$

As $R_{out} \uparrow$ voltage gain also $\uparrow$.

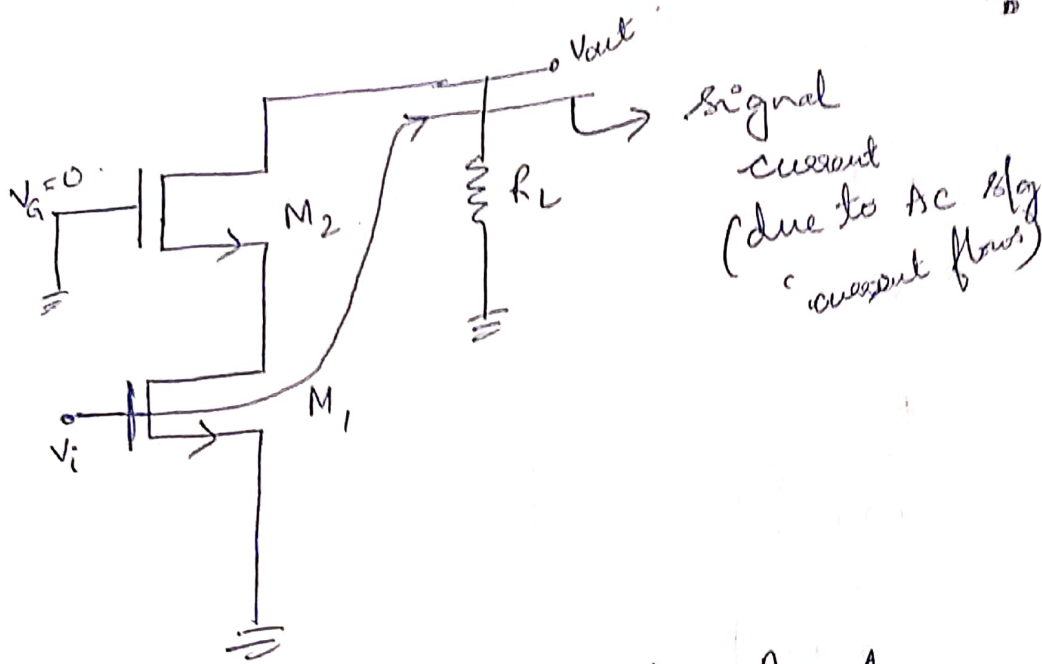
Analysis of cascode amplifier (CS-CG) :-



This is called biasing current.

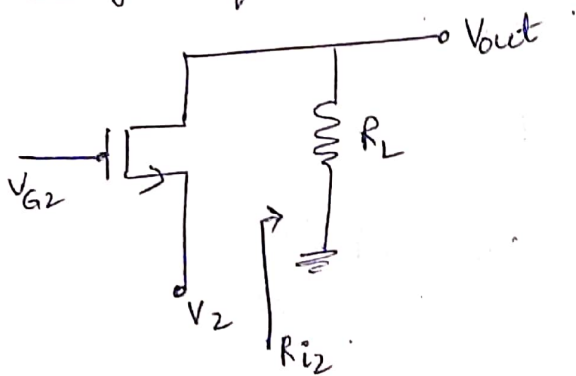
Cascode amplifier with current source.

AC equivalent ckt.
dc source connected to ground ($+V_{DD} = s.c$)
 $V_{G2} = 0$ $I_D = 0.c$)



W.K.T voltage gain $A_V = A_{V1} \cdot A_{V2}$

Analysis of CG amplifier



i/p resistance :-

$$R_{iG} = \frac{r_{d2} + R_L}{1 + g_{m2} r_{d2}} = \text{High}$$

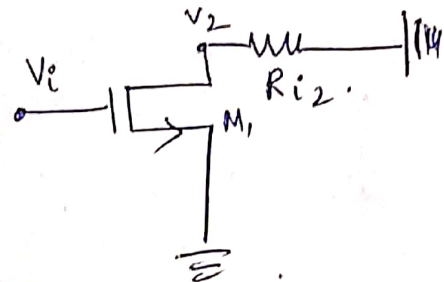
Voltage gain :-

$$A_V = A_{V1} \times A_{V2}$$

$$A_{V2} = g_{m1} [R_L \parallel r_{d2}]$$

$$A_{V2} = \frac{1 + g_{m2} r_{d2}}{r_{d2} + R_L} \cdot R_L \approx g_{m2} [R_L \parallel r_{d2}]$$

Analysis of CS amplifier



Voltage gain :-

$$A_{V1} = -g_{m1} [r_{d1} \parallel R_L]$$

$$R_{i2} = R_L$$

$$A_{V1} = -g_{m1} [r_{d1} \parallel R_{i2}]$$

$$R_{i2} \gg r_{d1}$$

$$\therefore A_{V1} \approx -g_{m1} \times r_{d1}$$

o/p resistance :-

$$R_{o1} = r_{d1}$$



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∴ overall gain is

$$A_V = A_{V1} \times A_{V2}$$

$$A_V = g_{m2} [R_L \parallel R_{d2}] \times [-g_{m1} (R_{d1} \parallel R_L)]$$

$$= g_{m2} (R_{d2}) \times (-g_{m1} (R_{d1}))$$

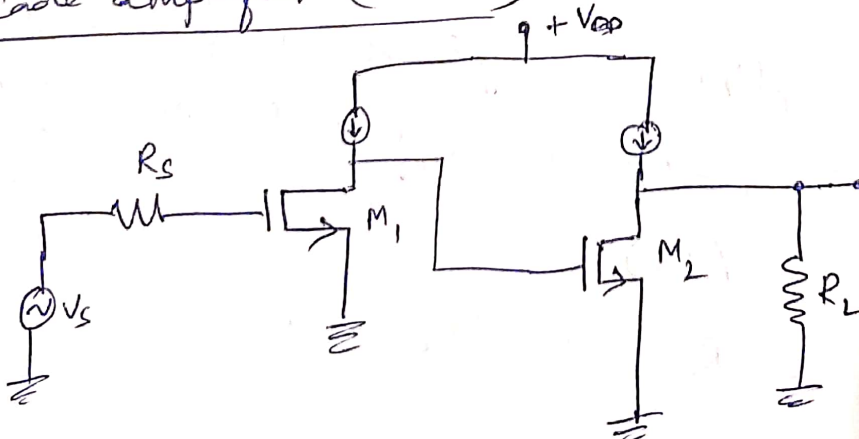
$$\text{If } R_L \rightarrow \infty$$

$$\therefore A_V \approx -g_{m1} g_{m2} R_{d1} R_{d2}$$

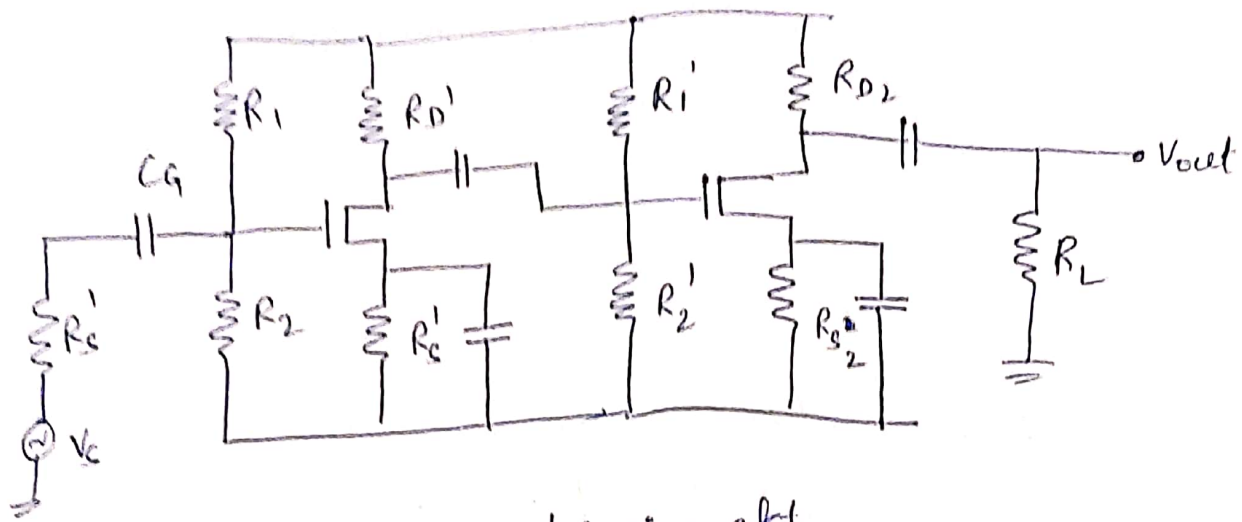
This is CS-CG cascode amplifier which is used to
↑ Bandwidth.

Pblms

Cascode amplifier (CS-CS) :-

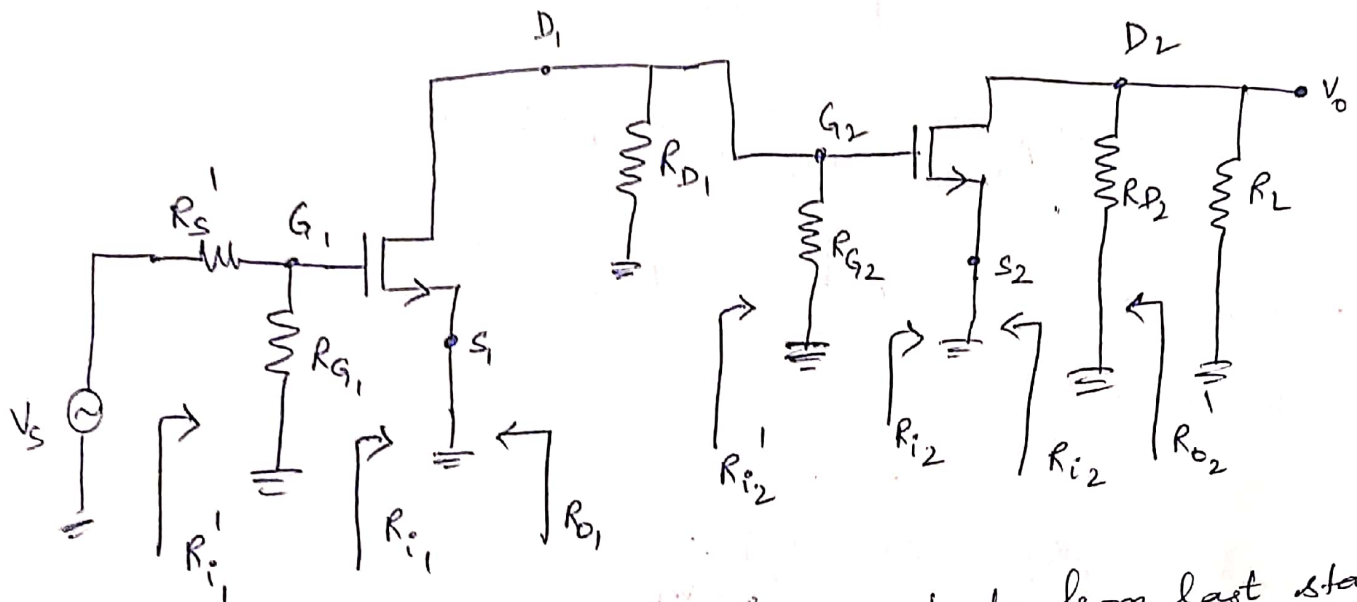


without biasing resistor



with biasing ckt

Analysis of cascode amplifier :-



In multi stage amplifiers analysis starts from last stage because i/p resistance of 2nd stage affects the load of 1st stage.

Analysis of 2nd stage (CS) :-

$$A_{i2} = \infty \quad R_{i2} = \infty \quad R_{i2}' = R_{G2} \parallel R_{i2} \approx R_{G2}$$

$$R_{O2} = R_{D2} ; R_{O2}' = r_{D2} \parallel R_{D2} (R_L \parallel R_{D2}).$$

↳ If R_L is not considered.

If R_L is included.

$$R_{O2}' = r_{D2} \parallel R_L \parallel R_{D2}.$$



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$$A_V = -g_{m2} [r_{d2} \parallel R_{D2} \parallel R_L]$$

Analysis of 1st stage.

$$R_{L1} = \text{Load to 1st stage} = R_{i2}$$

$$A_{i1} = \infty \quad R_{i1} = \infty \quad R_{i1}' = R_{G1} \parallel R_{i1} \approx R_{G1}$$

$$R_{o1} = r_{d1} \quad R_{o1}' = r_{d1} \parallel R_{D1}$$

$$A_{V1} = -g_{m1} [r_{d1} \parallel R_{D1} \parallel R_{i2}']$$

Overall analysis of multistage amplifier.

- 1) $R_i = R_{i1} = \infty \rightarrow$ overall input impedance
- 2) $R_i' = R_{i1}' = R_{G1} \Rightarrow$ overall effective input impedance
- 3) $R_o = R_{o2} = r_{d2} \rightarrow$ overall effective o/p impedance
- 4) $A_V = A_{V1} \cdot A_{V2}$
- 5) $A_i = A_{i1} \times A_{i2} \times [\text{Ratio of some resistance}]$

$$A_i = \infty$$

Impedance Matching :-



$A_V =$ Voltage gain.

$$A_V = -g_m R_D \quad R_D \gg R_o$$

* These 2 amplifiers are cascaded. Then 2nd stage i/p impedance acts as load to 1st stage.

$$A_{V_1} \approx -g_m [R_{O_1} \parallel R_{i_2}']$$

$$\therefore \boxed{A_{V_1} < A_{V_2}}$$

→ Because i/p resistance of 2nd stage affected the load of 1st stage.

→ Hence voltage gain of 1st stage is reduced when compared with 2nd stage.

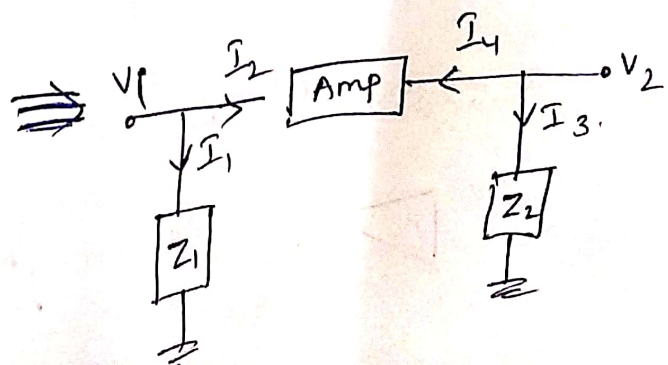
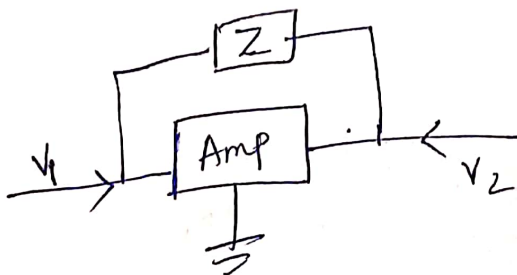
→ Due to high i/p resistance of 2nd stage amplifier the load of 1st stage is affected which is called as loading effect.

* To overcome loading effect.

$$\text{if } R_{i_2}' \gg R_{O_1} ; R_{i_2} \gg R_{O_1}.$$

* To match the impedance, we need to place an additional resistance b/w the 2 stages. Such a ckt is called impedance matching ckt.

Miller's theorem :-





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Since feedback is present we can split and place it equal to i/p & o/p i.e same resistor is split into two equal parts. One part is at i/p & other part is at o/p. This is called "Miller effect".

$$\therefore Z_1 = \frac{Z}{1-A_V} ; Z_2 = \frac{Z}{1-\frac{1}{A_V}} \quad \text{where } A_V = \frac{V_2}{V_1}$$

↓
Voltage gain.

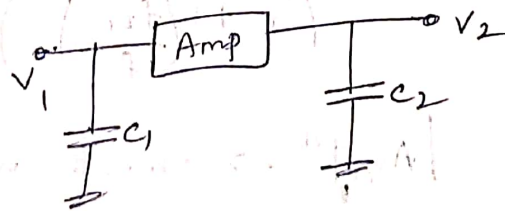
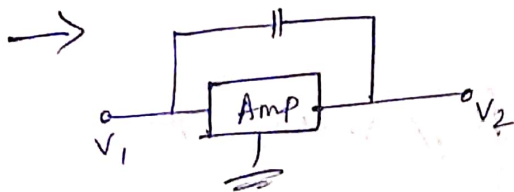
Analysis is same as BJT analysis & values of Z_1 & Z_2 are same as BJT.

→ For inductor.

$$L_1 = \frac{L}{1-A_V} , L_2 = \frac{L}{1-\frac{1}{A_V}}$$

For resistor Miller theorem is

$$R_1 = \frac{R}{1-A_V} ; R_2 = \frac{R}{1-\frac{1}{A_V}}$$



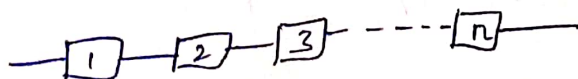
$$\therefore C_1 = C(1-A_V)$$

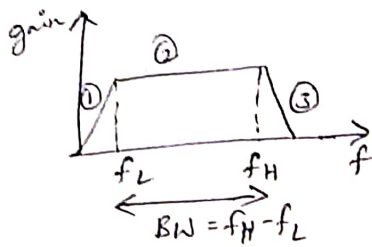
$$C_2 = C\left(1-\frac{1}{A_V}\right).$$

→ Effect of cascading on cut off frequencies :-

① Effect on lower cut-off frequency :-

Let us consider n -identical stages are cascaded.





where f_L is lower cut off freq/. ~~for individual amplifier~~

$$|A_{V_L}| = \frac{|A_{V_{m_1}}|}{\sqrt{1 + \left(\frac{f_{L_1}}{f}\right)^2}} \quad \text{where } f_{L_1} \rightarrow \text{lower cut off freq/... for each stage.}$$

$\therefore$ If 'n' such amplifiers are cascaded,

then

$$|A_{V_L}| = |A_{V_{L_1}}| \times |A_{V_L}| \times \dots \times |A_{V_{L_1}}| \times n \text{ times}$$

$$= |A_{V_{L_1}}|^n$$

$\therefore a \times a \times a \dots n \text{ times} = a^n$

$$= \frac{|A_{V_{m_1}}|^n}{\left(\sqrt{1 + \left(\frac{f_{L_1}}{f}\right)^2}\right)^n} \rightarrow \textcircled{1}$$

where $|A_{V_{m_1}}|^n \Rightarrow$ overall mid freq/. voltage gain.

$$|A_{V_{m_1}}|^n = A_{V_m}$$

$$\textcircled{1} \Rightarrow |A_{V_L}| = \frac{|A_{V_m}|}{\left(\sqrt{1 + \left(\frac{f_L}{f}\right)^2}\right)^n}$$

where f_L - overall lower cut off freq/.

$f \rightarrow$ applied freq/.



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If $f_L = f$ then.

$$|A_{v_L}| = \frac{A_{v_m}}{\left(1 + \left(\frac{f_{L1}}{f}\right)^2\right)^{n/2}} = \frac{|A_{v_m}|}{\sqrt{2}}$$

$$\therefore |A_{v_L}| = \frac{|A_{v_m}|}{\left(1 + \left(\frac{f_{L1}}{f_L}\right)^2\right)^n} = \frac{|A_{v_m}|}{2}$$

$\therefore$ Overall lower cut off frequency.

$$2 = \left[1 + \left(\frac{f_{L1}}{f_L}\right)^2\right]^n$$

Take exponential $\frac{1}{n}$ on b. sides.

$$2^{1/n} = \left[1 + \left(\frac{f_{L1}}{f_L}\right)^2\right]^{n/2} = \left[1 + \left(\frac{f_{L1}}{f_L}\right)^2\right]$$

$$\left(\frac{f_{L1}}{f_L}\right)^2 = 2^{1/n} - 1$$

$$\frac{f_{L1}}{f_L} = \sqrt{2^{1/n} - 1}$$

$$\therefore \boxed{f_L = \frac{f_{L1}}{\sqrt{2^{1/n} - 1}}}$$

for $n \geq 2$; then $f_L > f_{L1}$

$\rightarrow$ If 'n' no of stages $\uparrow$ the lower cut off freq. also

increases.

Pblm
* If $n=4$ [all stage are identical amplifiers which are cascaded & $f_L = 2k$. then find f_L .

Sol:-

$$f_{L1} = 2k.$$

$$f_L = \frac{f_{L1}}{\sqrt{2^n - 1}}$$

$$= \frac{2k}{\sqrt{2^4 - 1}}$$

$$n=4 \rightarrow f_L = 4.59 \text{ kHz for 4 stage}$$

$$n=10 \rightarrow f_L = 7.46 \text{ kHz for 10 stage}$$

$$n=20 \rightarrow f_L = ?$$

* If n value $\uparrow$ then f_L also $\uparrow$.

② Effect on upper cut off frequency :-

Higher freq/. voltage gain.

$$|A_{vH1}| = \frac{|A_{vm1}|}{\sqrt{1 + \left(\frac{f_H}{f_{H1}}\right)^2}}$$

Due to internal capacitors, gain decreases at high frequency.

$$|A_{vH}| = |A_{vH1}|^n$$



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$$|A_{vH}| = \frac{|A_{vm}|^n}{\left(1 + \left(\frac{f}{f_{H1}}\right)^2\right)^{n/2}} = \frac{|A_{vm}|}{\left(1 + \left(\frac{f}{f_{H1}}\right)^2\right)^{n/2}}$$

If $f_H = f_{H1}$ then

$$|A_{vH}| = \frac{|A_{vm}|}{\sqrt{2}} \rightarrow \text{for single stage.}$$

$f_H \rightarrow$ overall higher cut off freq.

Then,

$$\frac{|A_{vm}|}{\left(1 + \left(\frac{f_H}{f_{H1}}\right)^2\right)^{n/2}} = \frac{|A_{vm}|}{(2)^{1/2}}$$

$$2 = \left(1 + \left(\frac{f_H}{f_{H1}}\right)^2\right)^n$$

Take $\frac{1}{n}$ on b. sides.

$$2^{1/n} = \left(1 + \left(\frac{f_H}{f_{H1}}\right)^2\right)^{n \times \frac{1}{n}}$$

$$2^{1/n} = 1 + \left(\frac{f_H}{f_{H1}}\right)^2$$

$$\left(\frac{f_H}{f_{H1}}\right)^2 = 2^{1/n} - 1$$

$$\frac{f_H}{f_{H1}} = \sqrt{2^{1/n} - 1}$$

$$\boxed{f_H = f_{H1} \sqrt{2^{1/n} - 1}} \rightarrow \text{overall higher-cut off freq.}$$

Pblm.

* If $n=4$, $f_{H1} = 10 \text{ kHz}$.

Sol:- $f_H = 10,000 \times \sqrt{2^{1/4} - 1}$

$f_H = 4.3 \text{ kHz}$ for $n=4$ stage.

$f_H = ?$ for $n=10$ stage.

* If 'n' number of stages are cascaded, higher cut off freq. decreases. & lower cut off freq. increases.

then B.W. also ↓.

$$BW = \downarrow f_H - f_L \uparrow = \downarrow \text{sec.}$$

$$\therefore \boxed{BW \approx f_H \sqrt{2^{1/n} - 1}}$$

→ The transfer function has poles, at $f_1, f_2, f_3, \dots, f_n$ etc

then

$$\frac{1}{f_H} \approx 1.1 \left[\sqrt{\frac{1}{f_1^2} + \frac{1}{f_2^2} + \frac{1}{f_3^2} + \dots + \frac{1}{f_n^2}} \right]$$

Similarly,

$$f_L \approx \sqrt{f_{L1}^2 + f_{L2}^2 + f_{L3}^2 + \dots + f_{Ln}^2}$$



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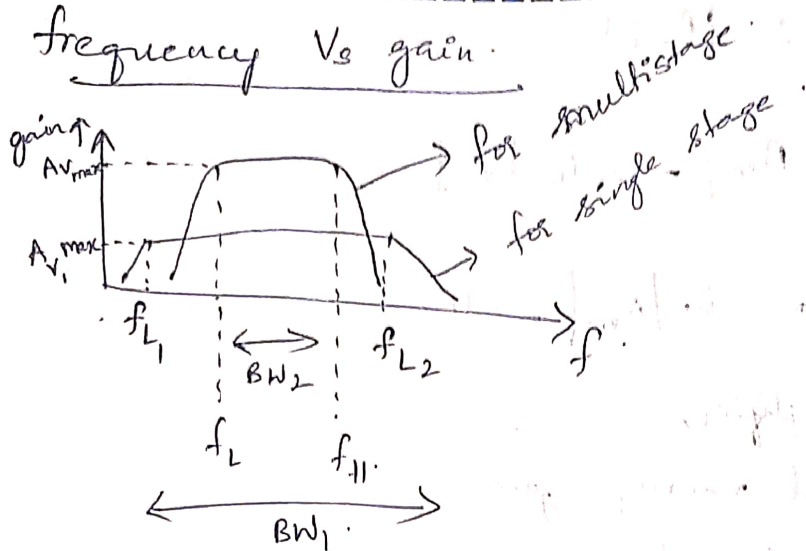
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frequency Vs gain.

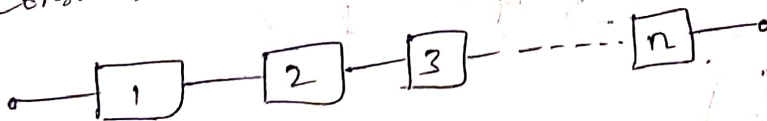


$$f_H = f_{H1} \sqrt{2^{1/n} - 1}$$

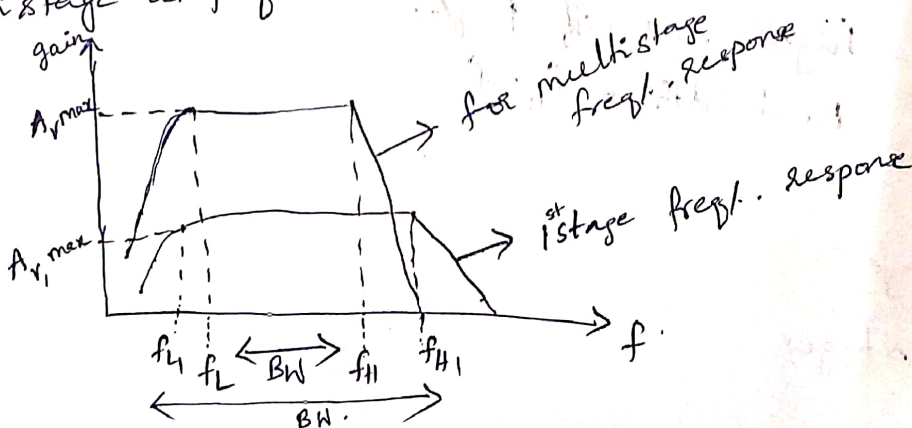
$$f_L = \frac{f_{L1}}{\sqrt{2^{1/n} - 1}}$$

Frequency response of Multistage Amplifier :-

Consider 'n' number of stages.



All stages are identical, then frequency response of multistage amplifier is



At $f = f_L$.

$$\frac{A_{vm}}{\sqrt{2}} = A_{vL}$$

Apply log on b.sides

$$20 \log \left(\frac{A_{vm}}{\sqrt{2}} \right) = 20 \log (|A_{vL}|)$$

$$20 \log |A_{vL}| = 20 \log |A_{vm}| - 20 \log |\sqrt{2}|$$

$$\therefore \boxed{20 \log |A_{vL}| = 20 \log |A_{vm}| - 3 \text{ dB}}$$

For single stage amplifier,

A_{vm} - Mid band voltage gain

A_{vL} - gain @ low freq/.

$$\boxed{|A_{vL}| = \frac{|A_{vm}|}{\sqrt{1 + \left(\frac{f_L}{f}\right)^2}}} \rightarrow \text{gain @ low freq/..}$$

$$\boxed{|A_{vH}| = \frac{|A_{vm}|}{\sqrt{1 + \left(\frac{f}{f_H}\right)^2}}} \rightarrow \text{gain @ high freq/..}$$

Where f_L - lower cut-off freq/.

f_H - higher cut-off freq/.

BW - Bandwidth = $f_H - f_L$

For multi stage:

n - No of stages



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f_L^* — Lower cut off freq. for 'n' stage

f_H^* — upper cut off freq. " " " "

BW — Bandwidth for 'n' stages.

If all stages are identical, then

$$f_L^* = \frac{f_L}{\sqrt{2^{1/n} - 1}}$$

$$f_H^* = f_H \sqrt{2^{1/n} - 1}$$

→ For interchanging 'n' stages.

For non-interchanging 'n' stages:

$$f_L^* = 1.1 \sqrt{f_{L1}^2 + f_{L2}^2 + \dots + f_{Ln}^2}$$

$$\frac{1}{f_H^*} = 1.1 \sqrt{\frac{1}{f_{H1}^2} + \frac{1}{f_{H2}^2} + \frac{1}{f_{H3}^2} + \dots + \frac{1}{f_{Hn}^2}}$$

Problems:-

→ Calculation of f_L & f_H :-

f_L — Lower cut off freq.

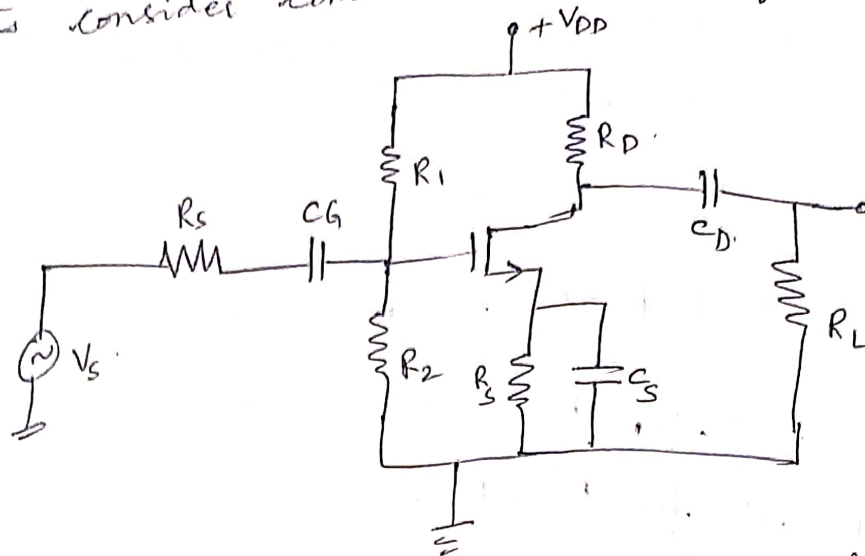
f_H — higher cut off freq.

C_S → Bypass capacitor

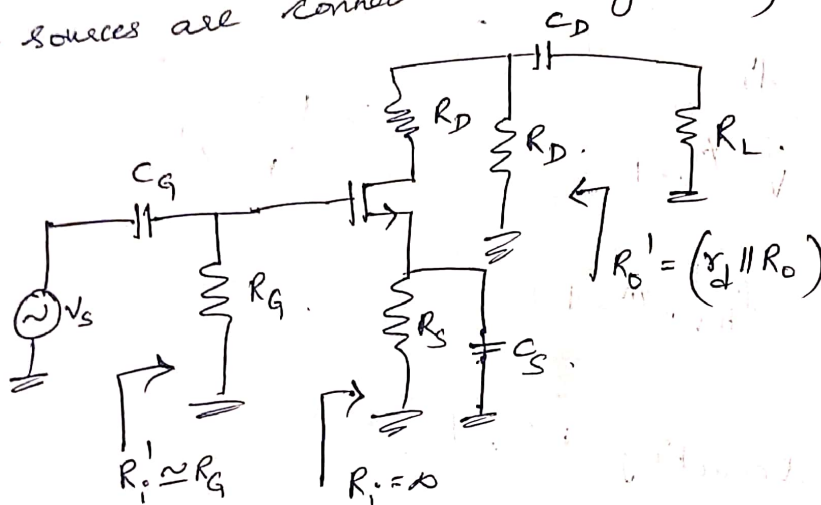
C_D, C_G → coupling capacitor

f_H & f_L value in common source are affected by external capacitors C_S, C_G & C_D .

Let's consider common source amplifier ckt.



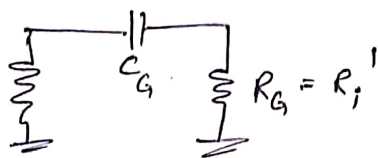
Equivalent ckt for the above ckt is drawn.
(DC sources are connected to ground)



Case (i) :-

W.r. to C_G :-

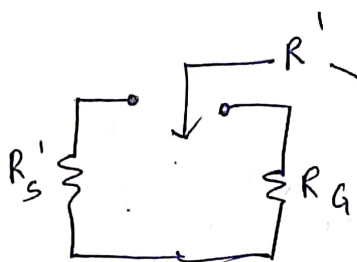
Taking all sources to zero



Lower cut off freq.:

$$f_{LG} = \frac{1}{2\pi R' C_G} \text{ w.r. to } C_G$$

$$X_C = \frac{1}{2\pi f C}$$



Thevenin's equivalent ckt w.r. to C_G

$$\therefore R' = R_s' + R_G$$



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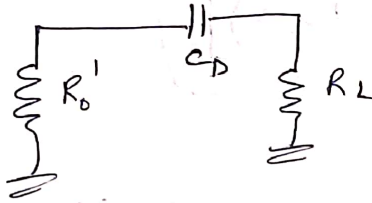
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$$f_{LG} = \frac{1}{2\pi [R_s' + R_g] C_g}$$

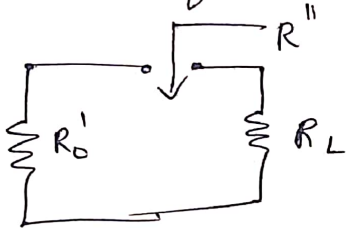
Case (ii) W.r.t C_D :-



$f_{LD} \rightarrow$ Lower cut off freq. W.r.t C_D

$$f_{LD} = \frac{1}{2\pi R'' C_D}$$

Theremin's equivalent ckt

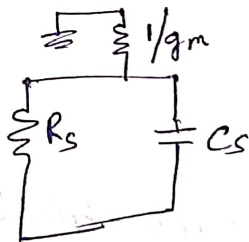


$$R'' = R_L + R_o'$$

$$R_L = (Y_D \parallel R_o)$$

Case (iii) W.r.t C_S :-

Due to MOSFET we have some transconductances.



$f_{LS} \rightarrow$ Lower cut off freq. W.r.t C_S

$$f_{LS} = \frac{1}{2\pi R''' C_S}$$

$R''' \rightarrow$ Theremin's equivalent capacitor



$$R''' = R_s \parallel \frac{1}{g_m}$$

∴ The overall lower frequency.

$$\therefore f_L = f_{LG} + f_{LD} + f_{LS}$$

→ Higher cut-off frequency (f_H) :-

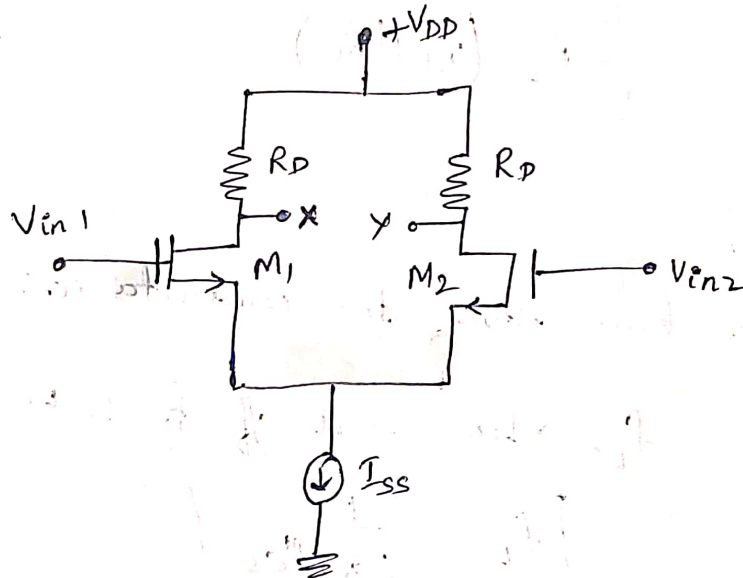
f_H depends on transistor (or) MOSFET parameter like junction capacitance.

$$\therefore f_H = \frac{1}{2\pi R_s' [C_{gs} + C_{gd} (1 - g_m R_{out})]}$$

→ Differential Amplifier :-

It amplifies the difference btw 2 i/p s/g & rejects the common in two s/g.

Ckt :-



Let us assume both M_1 & M_2 are symmetrical devices

* Drain voltages (x and y) are calculated by keeping

M_1 and M_2 are in saturated region.

→ Both inputs V_{in1} and V_{in2} are both joined together and it is called common mode voltage (V_{cm}).



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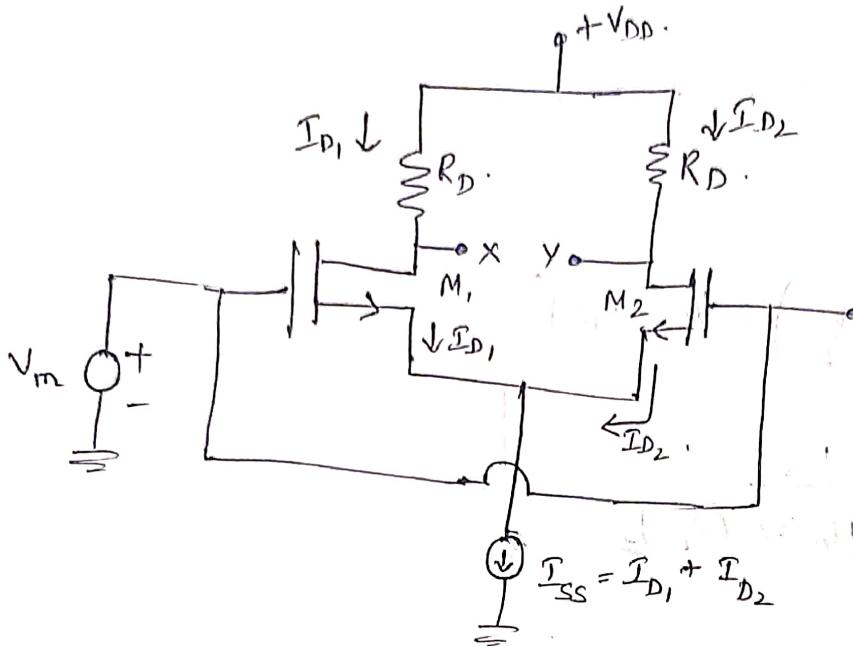
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Let us take $I_{D1} = I_{D2} = I_D$.

Gate voltage $V_G = V_{cm}$

Drain voltage $V_D = V_{DD} - \frac{I_{SS}}{2} R_D$.

$$I_{D1} + I_{D2} = I_{SS}$$

$$2 I_D = I_{SS}$$

$$I_D = \frac{I_{SS}}{2}$$

Source voltage $V_S = V_{cm} - V_{GS}$

Both M_1 & M_2 are symmetrical & same i/p is applied.

$$\therefore I_{D1} = I_{D2}$$

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

$$\therefore V_{D1} = V_{D2} = V_X = V_Y = V_{DD} - I_D R_D$$

$$\therefore \boxed{V_x = V_y = V_{DD} - \frac{I_{SS}}{2} R_D}$$

Let us assume $\lambda = 0$

$$I_{D1} = I_{D2} = I_D = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L} [V_{GS} - V_{th}]^2$$

We know that

$$V_{GS} - V_{th} = \text{overdrive voltage}$$

$$I_D = \frac{I_{SS}}{2}$$

$$\frac{I_{SS}}{2} = \frac{\mu_n C_{ox}}{2} \left(\frac{W}{L} \right) (V_{GS} - V_{th})^2$$

$$\boxed{V_{GS} - V_{th} = \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \left(\frac{W}{L} \right)}}$$

We know that

$$V_{DS} > V_{GS} - V_{th} \quad \left[\text{for MOSFET to operate in enhancement mode} \right]$$

$$V_D - V_S > V_G - V_S - V_{th}$$

$$\therefore V_D > V_G - V_{th}$$

$$\boxed{V_{DD} - \frac{I_{SS}}{2} R_D > V_{CM} - V_{th}} \quad \left(\because V_D = V_{DD} - \frac{I_{SS}}{2} R_D \right)$$

This condition is called biasing condition.

* Due to this condition, we cannot change the common mode input current and operate only with difference of two i/p s/o. $\therefore I_{D1} = I_{D2} = \frac{I_{SS}}{2}$

* If the condition is satisfied, then the circuit rejects the common mode variation (V_{CM}) & V_{CM} cannot be changed.

* This equation is useful for "calculating R_D value".



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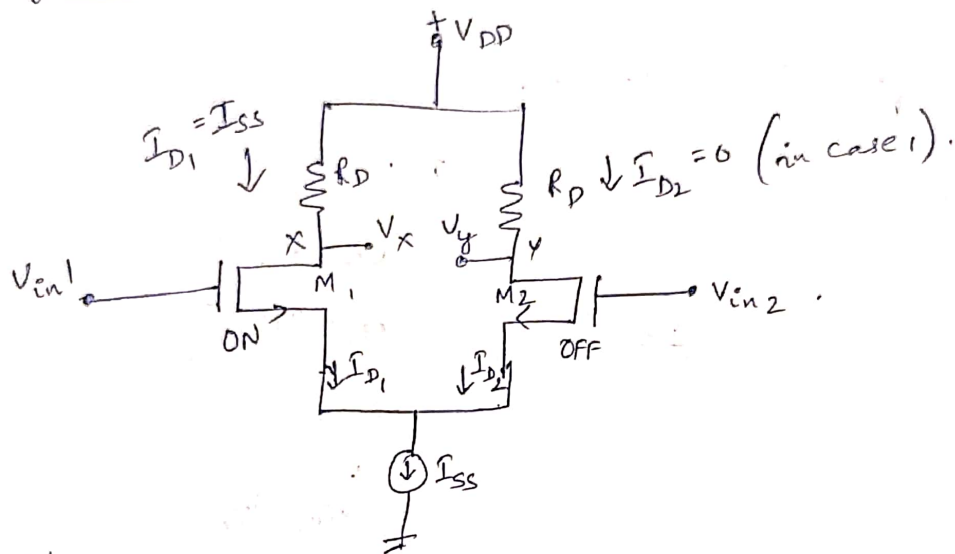
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Transfer characteristics ($V_{id} = V_{G_1} - V_{G_2} > 0$).

where V_{id} = difference i/p = $V_{G_1} - V_{G_2}$.

* Differential i/p (V_{id}) is always greater than zero.

Ckt diagram :-



Case (1) :-

Let V_{in1} is well above V_{in2}

Then M_1 is ON & M_2 is OFF.

$$\therefore V_x = V_{DD} - I_{D1} R_D$$

$$\therefore \boxed{V_x = V_{DD} - I_{SS} R_D}$$

$$\begin{aligned} \therefore I_{D1} + I_{D2} &= I_{SS} \\ I_{D1} + 0 &= I_{SS} \Rightarrow I_{D1} = I_{SS} \end{aligned}$$

$$V_y = V_{DD} - I_{D2} R_D \quad (\because I_{D2} = 0)$$

$$\therefore \boxed{V_y = V_{DD}}$$

Case (2) :-

If V_{in2} is well above V_{in1}

then M_1 is OFF & M_2 is ON

$$\frac{I}{D_1} = 0, \frac{I}{D_2} = I_{SS}$$

$$\therefore V_X = V_{DD} - \frac{I}{D_1} R_D$$

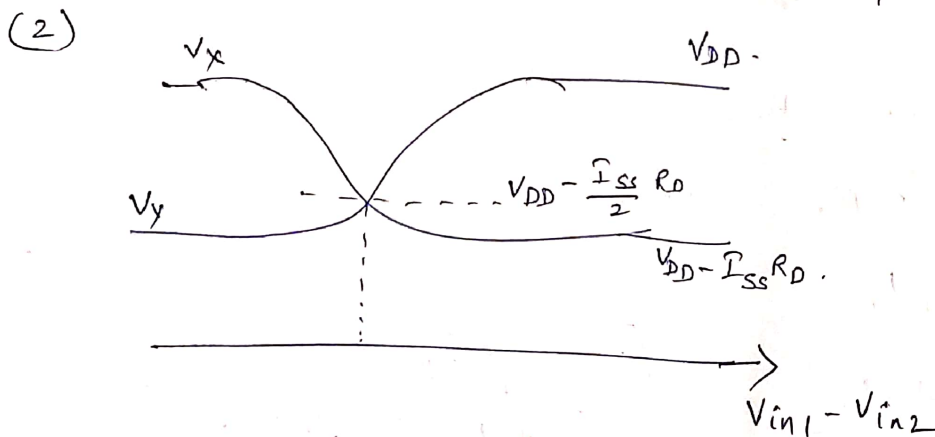
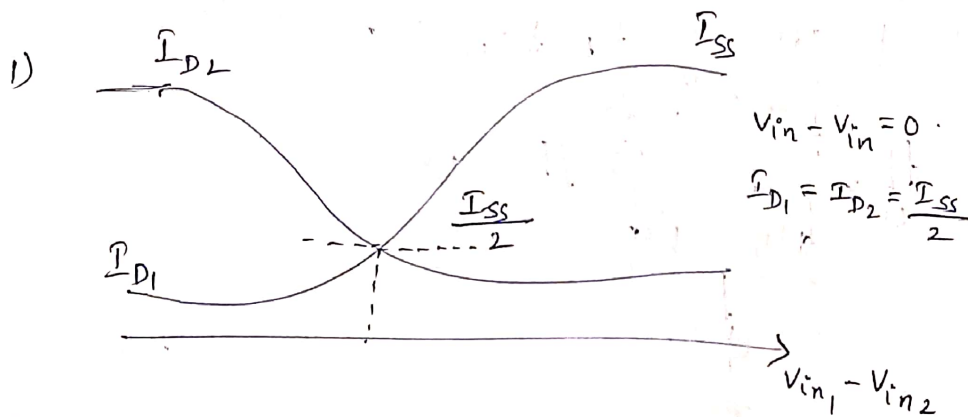
$$\boxed{V_X = V_{DD}}$$

$$V_Y = V_{DD} - I_{D2} R_D$$

$$\boxed{V_Y = V_{DD} - I_{SS} R_D}$$

The differential amplifier responds for differential i/p & rejects the common i/p.

→ Plot transfer characteristics:-





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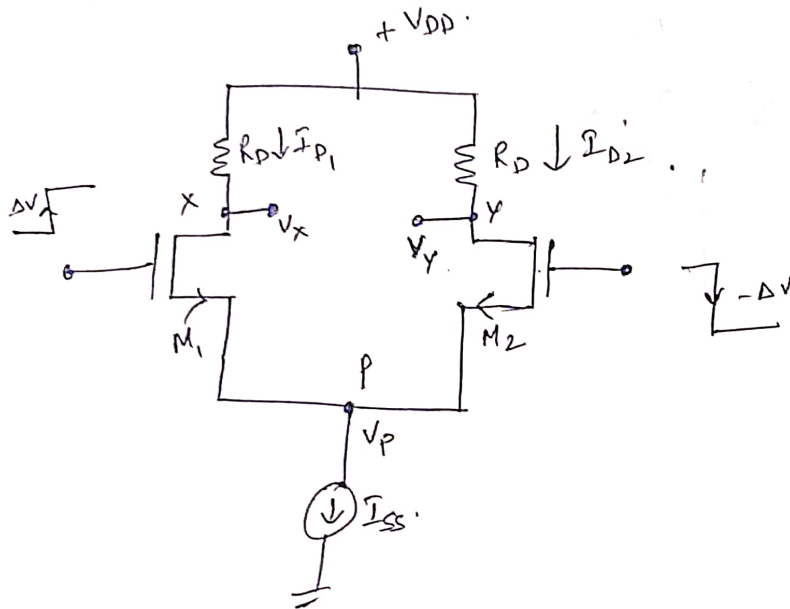
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MOSFET differential amplifier with resistive load :-

If resistor connected near drain its called resistive load.

If current mirror is connected at drain its called active load.

* Applying i/p:-



Here V_p is constant.

$$\therefore \Delta I_{D1} = g_m \Delta V \quad \text{w.r.t step s/g.}$$

$$\Delta I_{D2} = -g_m \Delta V$$

We know $V_x = V_{DD} - I_{D1} R_D$ ($\because V_{DD}$ is constant)

$$\Delta V_x = 0 - \Delta I_{D1} R_D \quad \Delta V_{DD} = 0$$

$$\Delta V_y = -\Delta I_{D2} R_D$$

Substitute ΔI_{D1} & ΔI_{D2} in ΔV_x & ΔV_y , we get

$$\therefore \Delta V_x = -g_m \Delta V_{R_D}$$

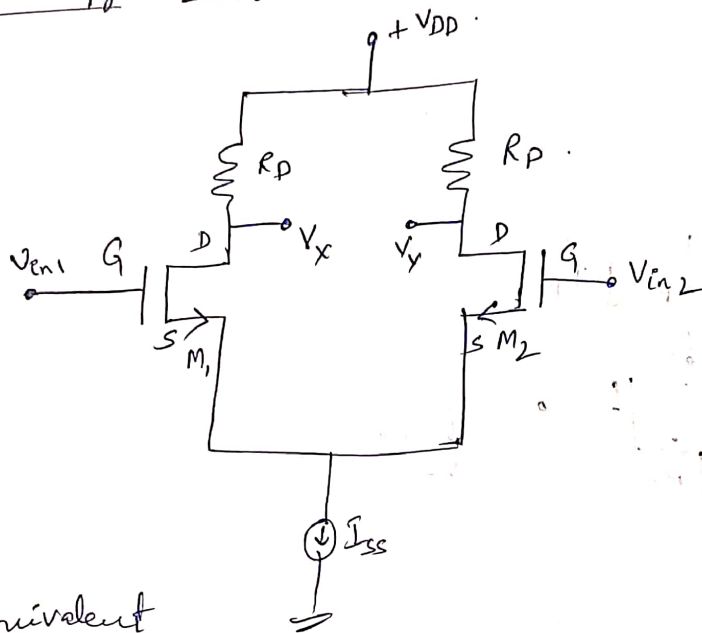
$$\Delta V_y = -[-g_m \Delta V_{R_D}] = g_m \Delta V_{R_D}$$

$$\text{change in o/p voltage} = \Delta V_D = \Delta V_x - \Delta V_y$$

$$= -g_m \Delta V_{R_D} - g_m \Delta V_{R_D}$$

$$\Delta V_D = \Delta V_x - \Delta V_y = -2g_m \Delta V_{R_D}$$

V.O.V. Imp
Small s/g analysis / Calculation of differential gain :-



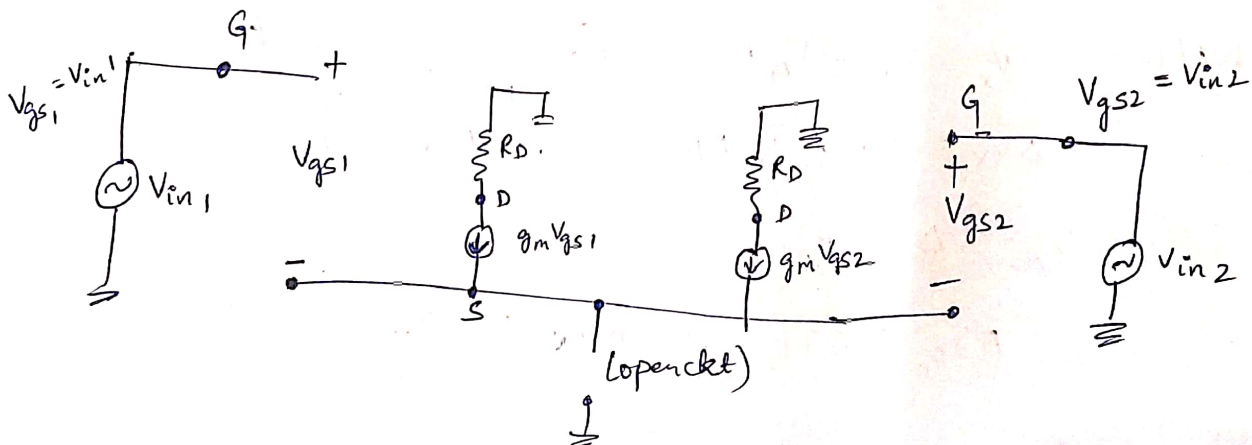
AC equivalent

$V_{DD} = \text{ground}$

$I_{SS} = \text{open ckt}$

$r_d \rightarrow$ internal resistance very high when $\lambda = 0$. but ideally it is ∞ .

$\therefore r_d$ is not considered when $\lambda = 0$





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o/p voltage $V_{out} = V_x - V_y$

$$= -g_m V_{gs1} R_D - (-g_m V_{gs2} R_D)$$

$$= -g_m V_{gs1} R_D + g_m V_{gs2} R_D$$

$$V_{out} = -g_m R_D (V_{gs1} - V_{gs2})$$

Differential mode gain $A_D = \frac{V_o}{V_{id}}$ ($\because V_{id} = \text{differential i/p}$
 $= V_{in1} - V_{in2}$)

$$\therefore A_{DM} = \frac{V_{out}}{V_{in1} - V_{in2}} = \frac{V_{out}}{V_{id}}$$

$$= \frac{-g_m R_D (V_{gs1} - V_{gs2})}{(V_{gs1} - V_{gs2})} \quad \begin{matrix} \therefore V_{in1} = V_{gs1} \\ V_{in2} = V_{gs2} \end{matrix}$$

$$A_{DM} = -g_m R_D$$

→ Range of i/p voltage within which transistor stay in saturation:-

$$1) V_{CM}(\max) = V_{th} + V_{DD} - \frac{I_{SS} R_D}{2}$$

$V_D = \text{Drain voltage}$

$$2) V_{CM}(\min) = -V_{SS} + V_{CS} + V_{th} + V_{OV}$$

min/. voltage required to keep transistor in saturation region.

$V_{SS} \rightarrow$ Voltage across I_{SS}

$V_{th} \rightarrow$ threshold voltage

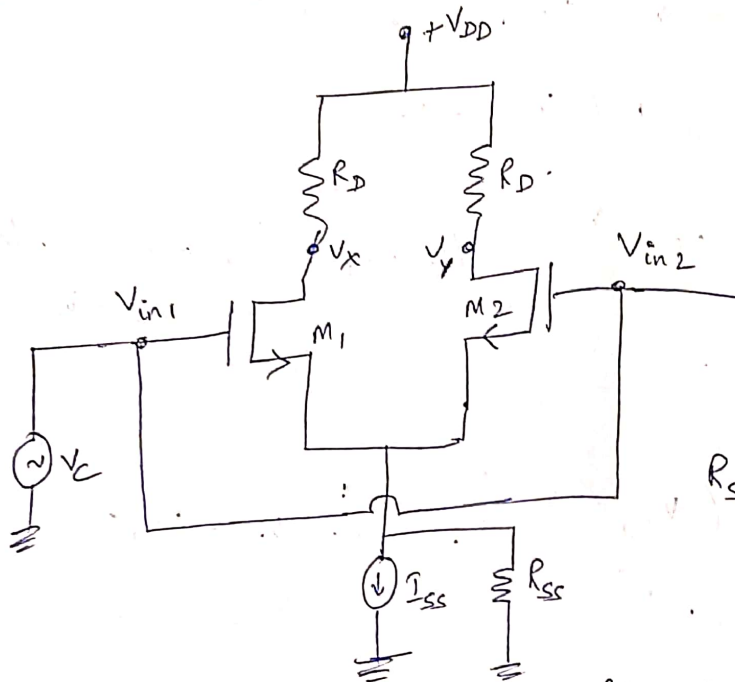
$$V_{ov} - \text{overdrive voltage} = V_{GS} - V_{th}$$

$$\Rightarrow V_{GS} = V_{ov} + V_{th}$$

$$V_{CM}(\min) = -V_{SS} + V_{CS} + V_{GS}$$

In this range transistor operates in saturation region.

* Common Mode gain and CMRR :-



R_{SS} = current source internal resistance

→ For common mode gain, both the inputs are same

$$V_{in1} = V_{in2} = V_C$$

$$\text{For } V_{in1} = V_{in2} \Rightarrow V_X = V_Y$$

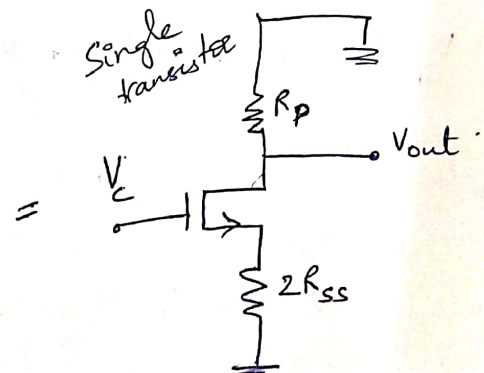
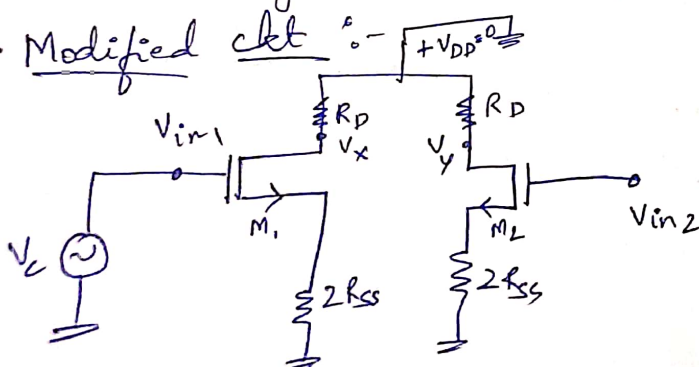
$$\therefore V_{out} = V_X - V_Y = 0$$

$$\boxed{\therefore V_{out} = 0}$$

→ The differential amplifier gives v_p voltage as zero when same v_{pp} is applied.

→ So, only single transistor is used to calculate the common mode gain.

→ Modified ckt :-





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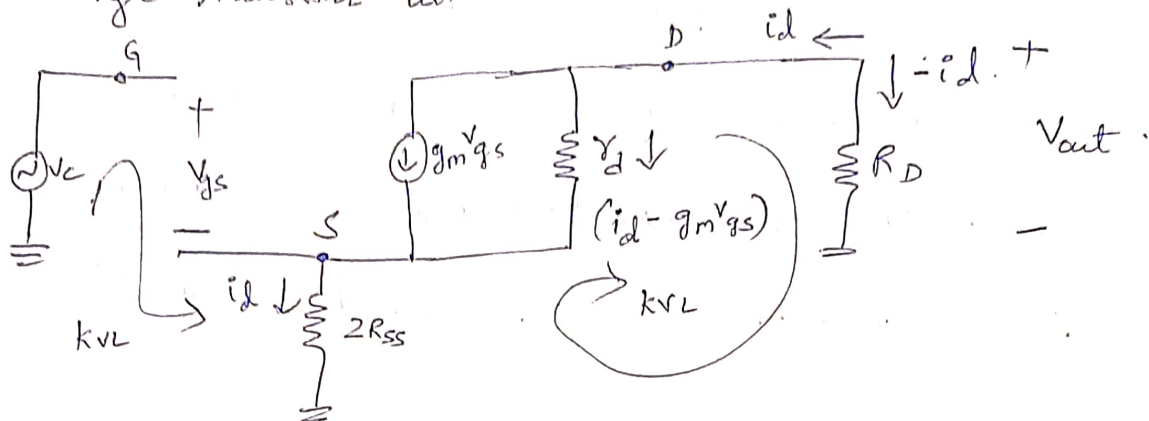
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Replace single transistor with small s/f model.



$$V_{out} = -i_d R_D$$

→ To find V_{out}

Apply KVL

$$-V_{out} + (i_d - g_m V_{gs}) r_d + i_d 2R_{ss} = 0$$

$$\therefore V_{out} = (i_d - g_m V_{gs}) r_d + i_d 2R_{ss} \rightarrow (1)$$

Apply KVL @ i/p loop

$$V_c = V_{gs} + i_d 2R_{ss}$$

$$V_{gs} = V_c - i_d 2R_{ss}$$

Substitute V_{gs} in eq (1)

$$V_{out} = i_d R_d - (V_c - i_d 2R_{ss}) r_d g_m + i_d 2R_{ss}$$

$$= i_d (R_d + 2R_{ss}) - g_m r_d (V_c - i_d 2R_{ss})$$

$$= i_d (R_d + 2R_{ss}) - g_m r_d V_c + i_d g_m r_d 2R_{ss}$$

$$\therefore V_{out} = i_d [R_d + 2R_{ss} + g_m r_d 2R_{ss}] - g_m r_d V_c$$

$$V_{out} + g_m r_d V_c = i_d [R_d + 2R_{ss} + g_m r_d 2R_{ss}]$$

$$\therefore i_d = \frac{V_{out} + g_m r_d V_c}{r_d + 2R_{SS} + g_m r_d 2R_{SS}}$$

but $V_{out} = -i_d R_D$

$$V_{out} = - \frac{(V_{out} + g_m r_d V_c) \cdot R_D}{r_d + 2R_{SS} + g_m r_d 2R_{SS}}$$

$$V_{out} [r_d + 2R_{SS} + g_m r_d 2R_{SS}] = -V_{out} R_D - g_m r_d V_c R_D$$

$$V_{out} [r_d + 2R_{SS} + g_m r_d 2R_{SS}] + V_{out} R_D = -g_m r_d V_c R_D$$

$$\therefore V_{out} [r_d + 2R_{SS} + g_m r_d 2R_{SS} + R_D] = -g_m r_d V_c R_D$$

Common Mode gain $A_{CM} = \frac{V_{out}}{V_c}$

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

$$r_d \gg (R_D + 2R_{SS})$$

$$\therefore A_{CM} \approx \frac{-g_m r_d R_D}{r_d + 2g_m r_d R_{SS}}$$

$$\Rightarrow CMRR = \frac{A_{DM}}{A_{CM}}$$

$$CMRR = \frac{-g_m R_D}{\frac{-g_m r_d R_D}{r_d + 2g_m r_d R_{SS}}}$$

$$= \frac{r_d [1 + 2g_m R_{SS}]}{r_d}$$

$$CMRR = 1 + 2g_m R_{SS}$$

$$(\therefore A_{DM} = -g_m R_D)$$