EE5320 : Analog IC Design
Jan - May 2024
Assignment 5

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Roll Number : EE21B019

Question 5.1

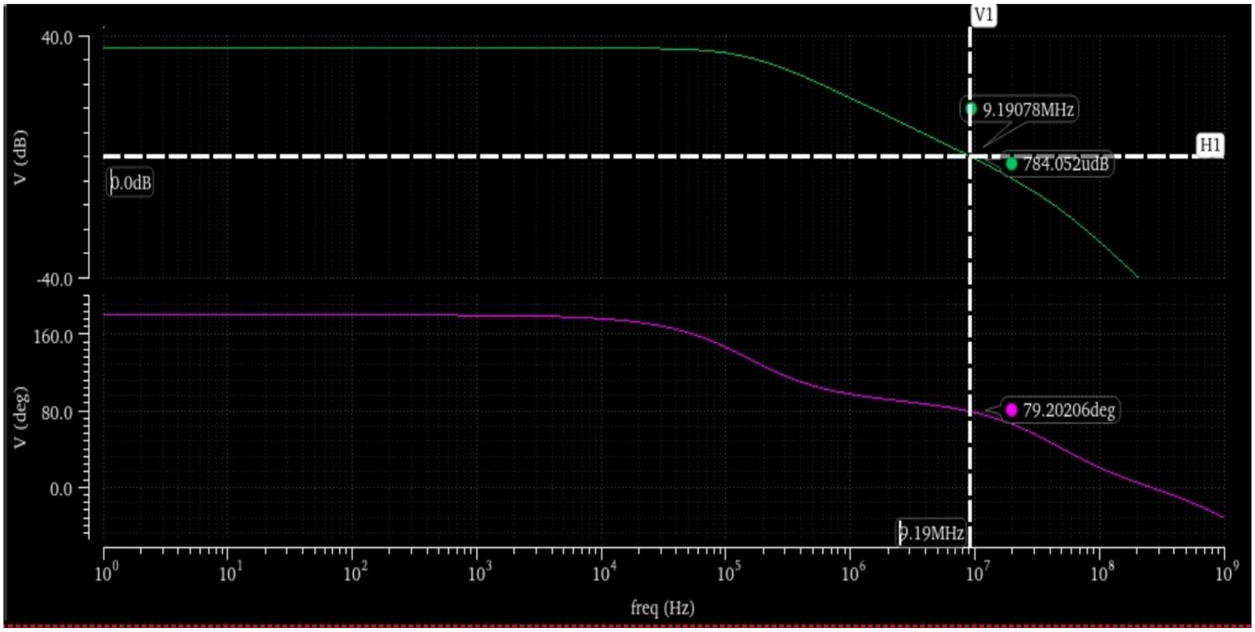
Table 1: Specifications	
Closed loop dc gain	15
Closed loop bandwidth	11 MHz
Load capacitor CL	24 pF
Load resistor RL	1205.719 Ω
Input resistance Ri	19 kΩ
Rf	285 kΩ
Cc	1 pF

Table 2: Simulation results	
Closed loop dc gain	14.76
Closed loop 3dB frequency	12.7598 MHz
Unity loop gain frequency	9.19078 MHz
Phase margin	79.20 degrees
Low frequency output noise PSD	76.9454 fV^2/Hz
Low frequency input noise PSD	353.163 aV^2/Hz
Percentage noise contributions from:	
Ri	89.18 %
Rf	5.95 %
RL	0 %
Gm1	4.83 %
Gm2	0 %

The unity gain frequency of the Loop gain transfer function is also equal to the 3-dB bandwidth of the closed loop transfer function. If given an input of 1V sinusoid signal, the expected output voltage must be 15V sinusoid. Hence a log-y plot of the output voltage can be used to determine DC gain and 3-dB bandwidth. Hand calculations are shown later.
The simulation results are shown below -

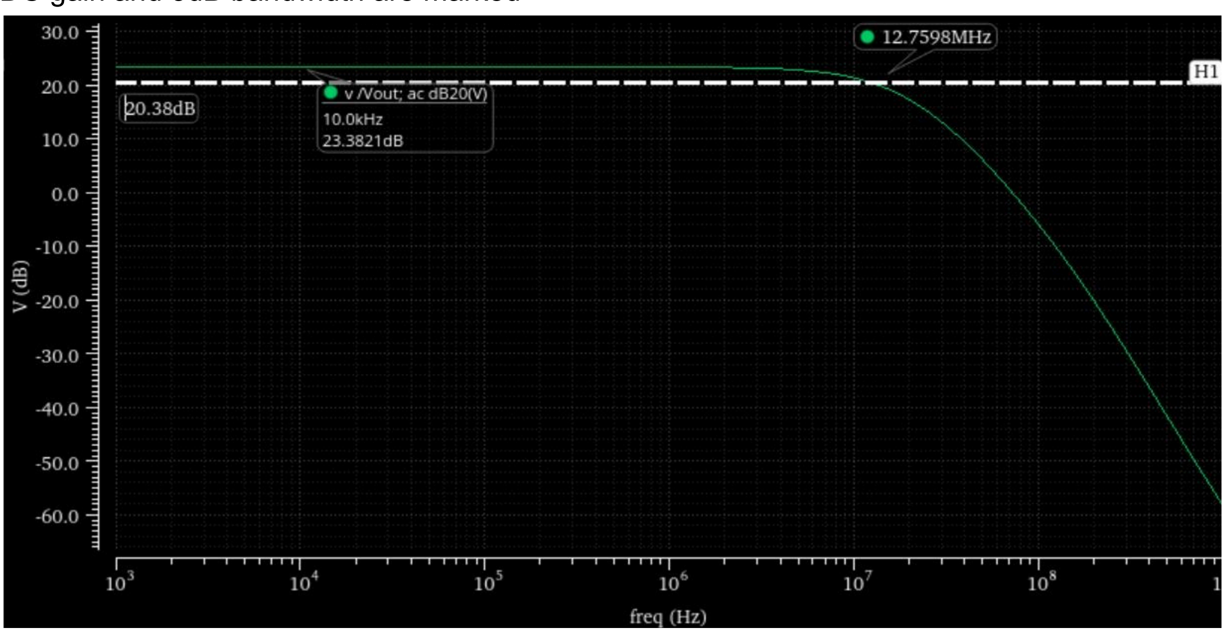
Plots:

- Loop gain magnitude(dB) and phase(degree) versus frequency(log);
  Unity loop gain frequency and phase margin are marked.



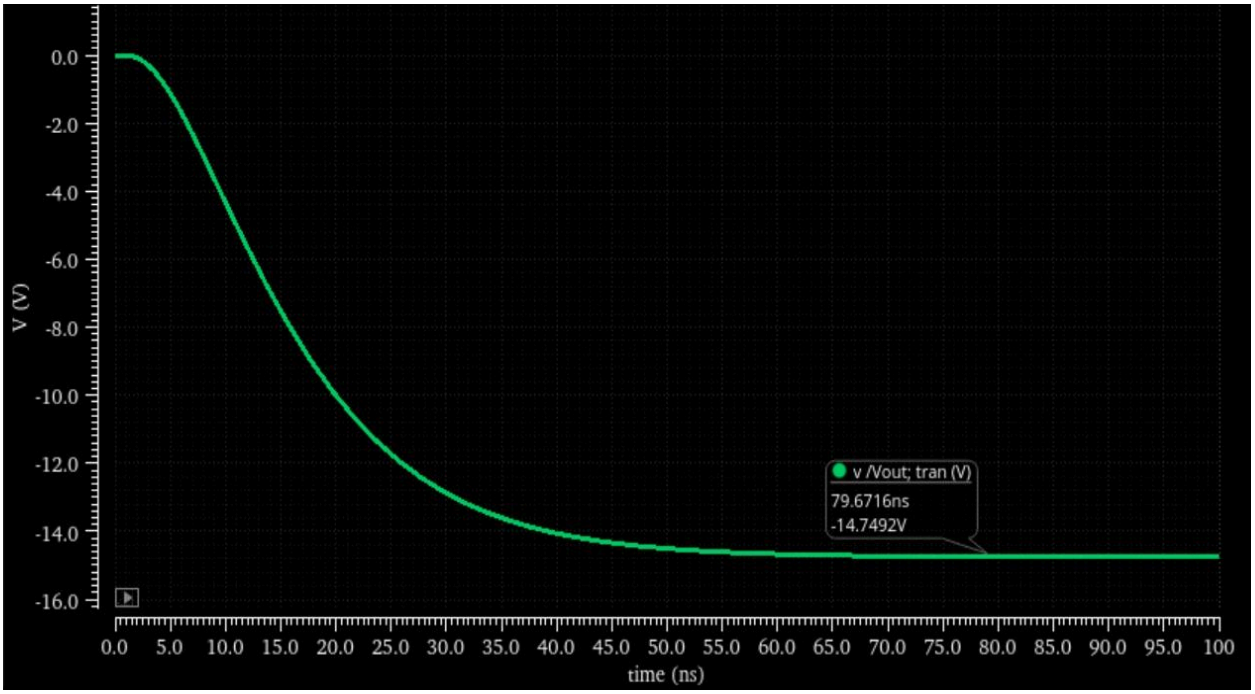
Unity Loop Gain Frequency : 9.19078 MHz
Phase Margin : 79.20 degrees

- Closed loop transfer function magnitude(log) versus frequency(log);
  DC gain and 3dB bandwidth are marked

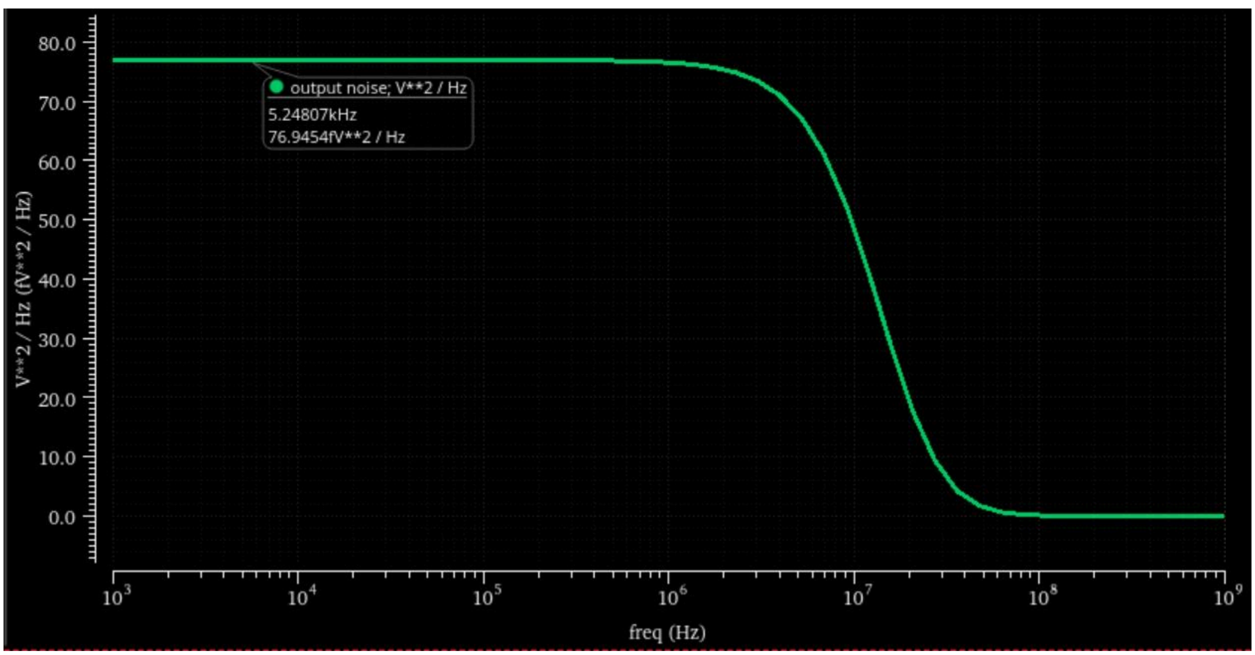


DC Closed Loop Gain = 23.3821 dB = 14.76
3dB Bandwidth = 12.7598 MHz

- Unit step response;

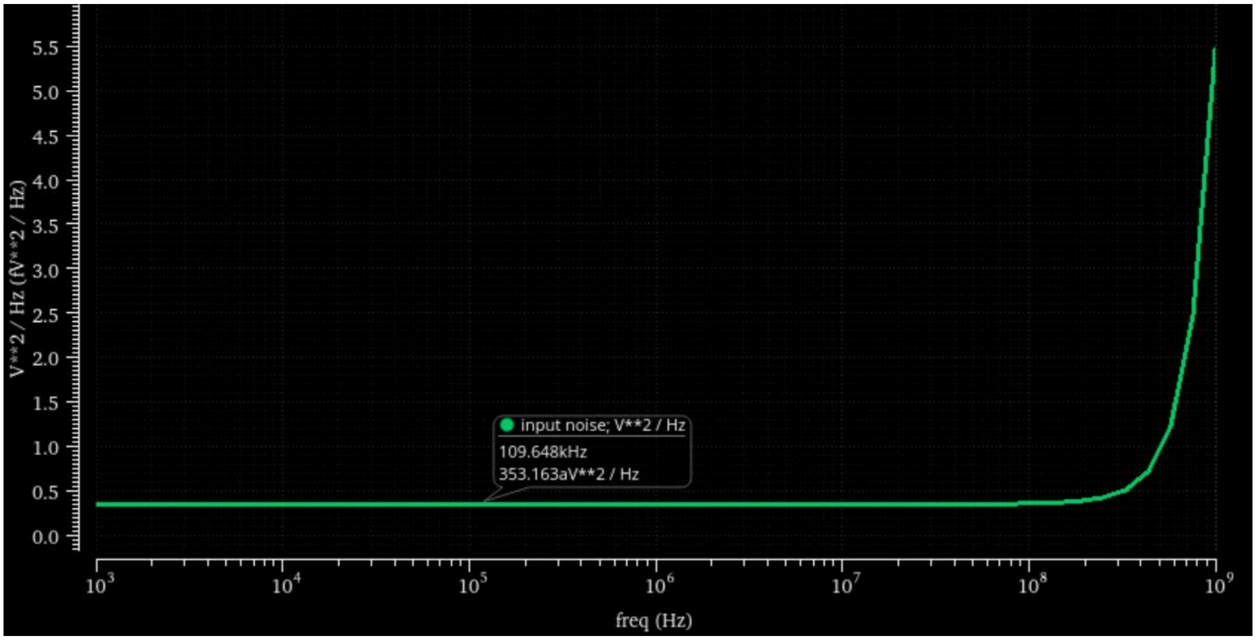


- Output noise PSD(V^2/Hz, log) versus frequency(log);
  Low frequency PSD is marked



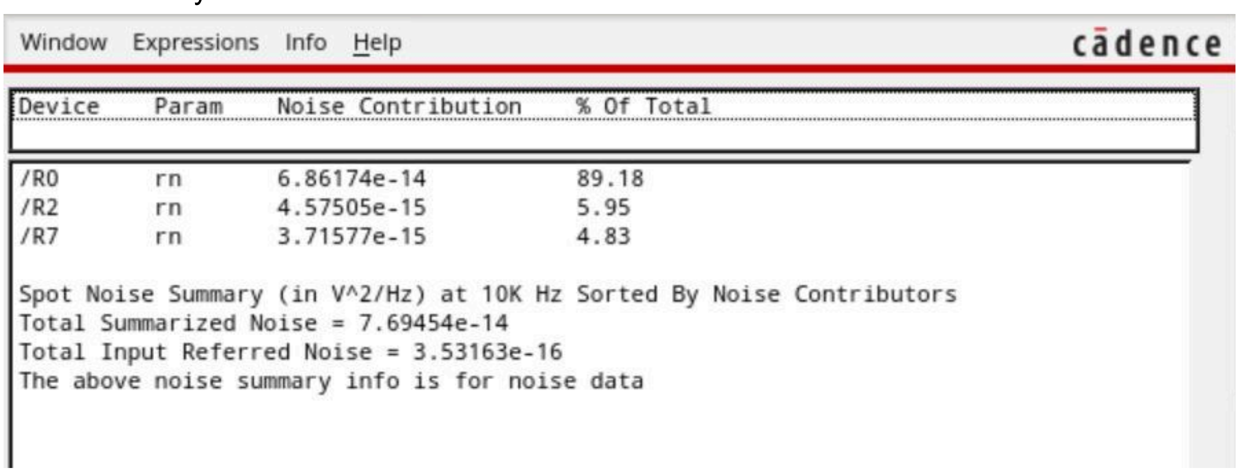
Low Frequency Output Noise PSD = 76.9454 fV^2/Hz

- Input referred noise PSD(V^2/Hz, log) versus frequency(log);
  Low frequency PSD is marked



Low Frequency Input Noise PSD = 353.163 aV^2/Hz
Noise contribution by Gm1 = 4.83 %, Rf = 5.95 %, Ri = 89.18 %, Gm2 = 0%, Rl = 0%

- Noise Summary



Device	Param	Noise Contribution	% Of Total
/R0	rn	6.86174e-14	89.18
/R2	rn	4.57505e-15	5.95
/R7	rn	3.71577e-15	4.83

Spot Noise Summary (in V^2/Hz) at 10K Hz Sorted By Noise Contributors
Total Summarized Noise = 7.69454e-14
Total Input Referred Noise = 3.53163e-16
The above noise summary info is for noise data

<u>Comments</u> :

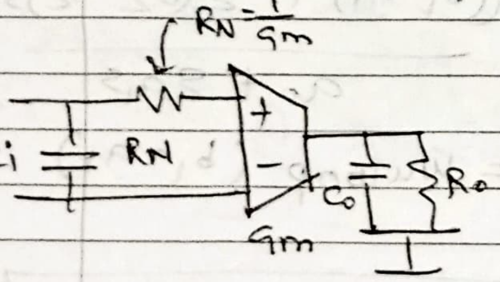
1. While simulating loop gain, the input capacitance of Gm1 has been lumped at the output with load capacitance Cl. This is because the loop is broken at the input of Gm1.
2. For hand calculations, it is assumed that unity gain frequency of loop gain is almost equal to the closed loop 3dB bandwidth
3. The simulations were performed using Cadence. The path to the simulations is - **<u>Path</u>** : ee21b019@ams117~/EE5320_Assignment_5

EE5320: Analog IC Design
Jan-May 2024
Assignment 5

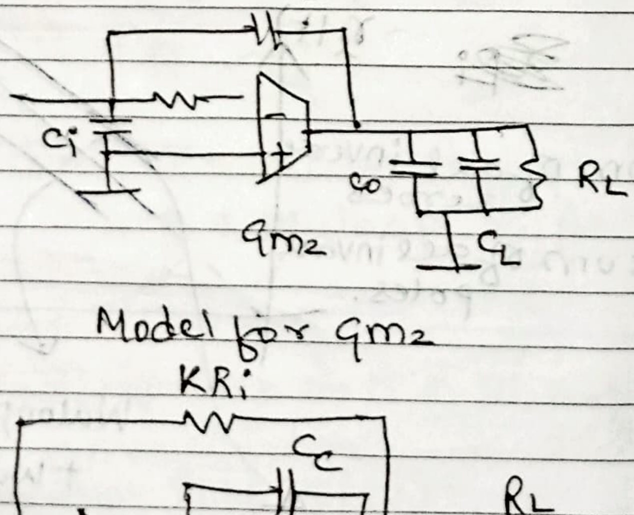
5.1 (a) $C_c = 1pF$
$P_2 = 4W_u$, loop

Roll No: EE21B019

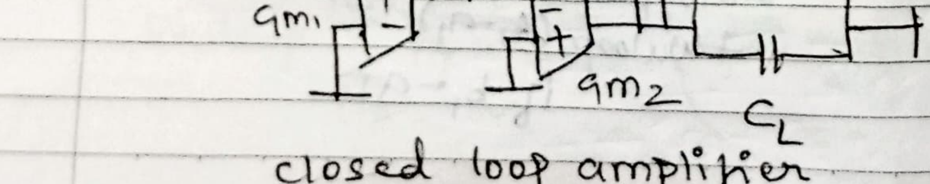
Given specifications:
DC gain $K = 19 + 6 = 15$
closed loop bandwidth $f_B = 20 - 9 = 11$ MHz
Load capacitance : $C_L = 5 + 19 = 24$ pF
Load resistor: $\frac{1}{\pi f_B C_L} =$
Input resistance: $10 + 9 = 19\,K\Omega$



Model for g_{m_1}



Model for g_{m_2}



closed loop amplifier

Let the opamp have transfer function $A(s)$ with poles p_1 and p_2 (non-dominant) (including loading of R_L and C_L).

We will break the loop at the input of g_{m1} and give a test voltage V_t.

$$V_o = A(s) V_t$$
$$V_{fb} = \frac{V_o}{K+1} = \frac{A(s)\, V_t}{K+1}$$

$$L(s) = \frac{A(s)}{K+1}$$

$$\omega_{u,loop} = \frac{A_o p_1}{K+1}$$

p_1: Dominant pole
A_o: DC gain of $A(s)$

$$A_o = g_{m1} g_{m2} R_{o1e} R_{o2e}$$
$$p_1 \approx \frac{1}{g_{m2} R_{o1e} R_{o2e} C_c}$$

R_{o1e}, R_{o2e}: Equivalent output resistance of g_{m1} and g_{m2}.

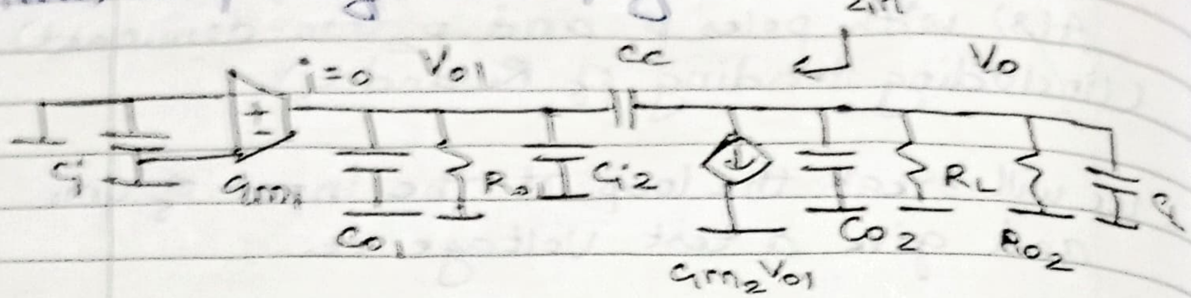
$$\omega_{u,loop} = \frac{1}{K+1} \frac{g_{m1}}{C_c}$$

$$\omega_{u,loop} = 2\pi f_B$$

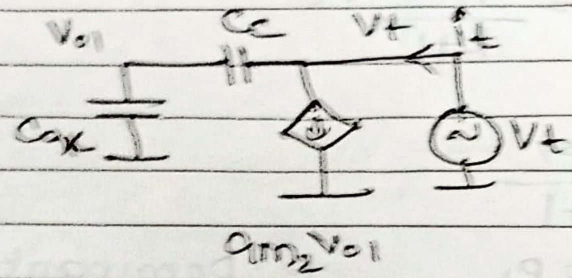
$$g_{m1} = (2\pi f_B)(K+1) C_c$$
$$= 2\pi \times 11 \times 10^6 \times 16 \times 10^{-12}$$
$$= 1.10584 \text{ mS}$$

$$\boxed{\therefore 1(b)\ g_{m1} = 1.10584 \text{ mS}}$$

Now, computing the loop gain:



Neglect output conductance of g_{m1}

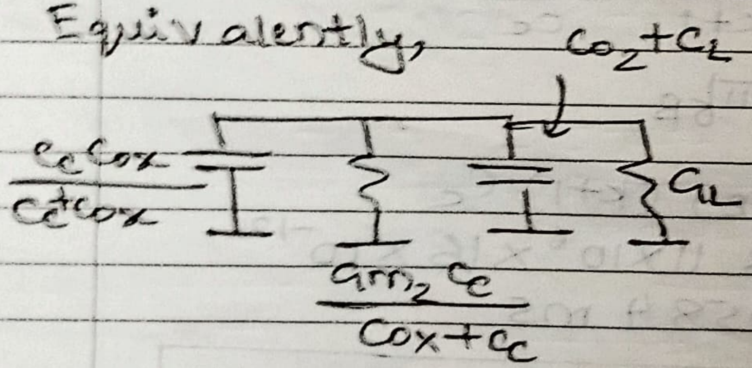


$$C_{ox} = C_{o1} + C_{i2}$$

$$V_{o1} = \frac{C_c}{C_{ox}+C_c} V_t$$

$$i_t = \underbrace{\frac{g_{m2} C_c}{C_{ox}+C_c}}_{g_{m\,eff}} V_t + \underbrace{\frac{s\, C_c C_{ox}}{C_{ox}+C_c}}_{c_{eff}} V_t$$

Equivalently,



$$P_2 \approx \frac{\frac{g_{m2} C_c}{C_{ox}+C_c} + G_L}{\frac{C_c C_{ox}}{C_c + C_{ox}} + C_{o2} + C_L}$$

given, $C_i' = C_o = \frac{g_m}{\omega_T}$; $\omega_T = 2\times10^{10}$ rad/s

$P_2 = 4\omega_u$ loop

$(C_{ox} \equiv C_x)$

$$8\pi f_{S8} = \frac{g_{m2}C_c + g_L(C_c + C_x)}{C_c C_x + (C_{o2} + C_L)(C_c + C_x)}$$

$$8\pi f_{S8} = \frac{g_{m2}C_c + g_L(C_c + C_{o1} + C_{i2})}{C_c(C_{o1} + C_{i2}) + (C_{o2} + C_L)(C_c + C_{o1} + C_{i2})}$$

$$8\pi f_{S8}\left[C_c\left(\frac{g_{m1}}{\omega_T} + \frac{g_{m2}}{\omega_T}\right) + \left(\frac{g_{m2}}{\omega_T} + C_L\right)\left(C_c + \frac{g_{m1}}{\omega_T} + \frac{g_{m2}}{\omega_T}\right)\right]$$

$$= g_{m2}C_c + g_L\left(C_c + \frac{g_{m1}}{\omega_T} + \frac{g_{m2}}{\omega_T}\right)$$

$$\frac{g_{m1}}{\omega_T} = \frac{1.10584\ mS}{2\times10^{10}} = 5.529\times10^{-14}$$

$R_L = 1205.719\,\Omega$

$$8\times\pi\times11\times10^{6}\left[10^{-12}\left[5.529\times10^{-14} + \frac{g_{m2}}{\omega_T}\right] + \left(\frac{g_{m2}}{\omega_T} + 24\times10^{-12}\right)\left(10^{-12} + 5.7175\times10^{-14} + \frac{g_{m2}}{\omega_T}\right)\right]$$

$$= g_{m2}\times10^{-12} + g_L\left(10^{-12} + 5.7175\times10^{-14} + \frac{g_{m2}}{\omega_T}\right)$$

$$1.5285\times10^{-17} + 1.3823\times10^{-14}\,g_{m2} + 1.3823\times10^{-14}\,g_{m2} + 7.0144\times10^{-15} + 7.0903\times10^{-16}\,g_{m2} + 3.3175\times10^{-13}\,g_{m2} + 6.9115\times10^{-13}\,g_{m2}^2$$

$$= g_{m2}\times10^{-12} + 8.768\times10^{-16} + 4.1469\times10^{-14}\,g_{m2}$$

$\Rightarrow 6.152885 \times 10^{-15} - 6.81287 \times 10^{-15} g_{m2}$

$+ 6.9115 \times 10^{-13} g_{m2}^{2} = 0$

Solving, we get

$g_{m2} = 0.9766 S$ and $9.1155\ mS$

We pick $g_{m2} = 9.1155\ mS$

$$\boxed{\therefore 1(a)\ g_{m2} = 9.1155\ mS}$$

Calculations

Component Values

$G_{m1} = 1.10584\ mS$

$G_{m2} = 9.1155\ mS$

Given

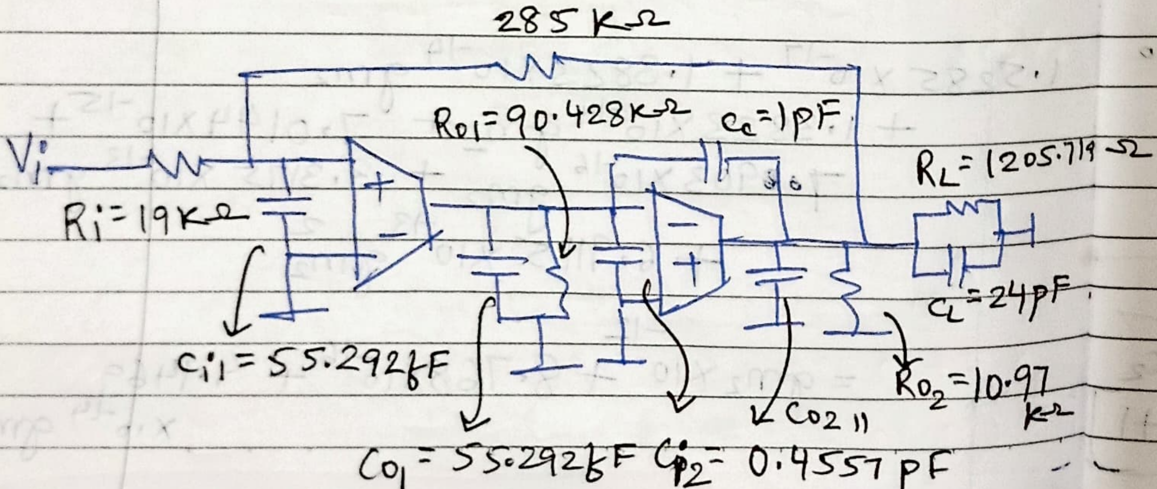
$K = 15$

$f_B = 11\ MHz$

$C_L = 24\ pF$

$R_L = 1205.719\ \Omega$

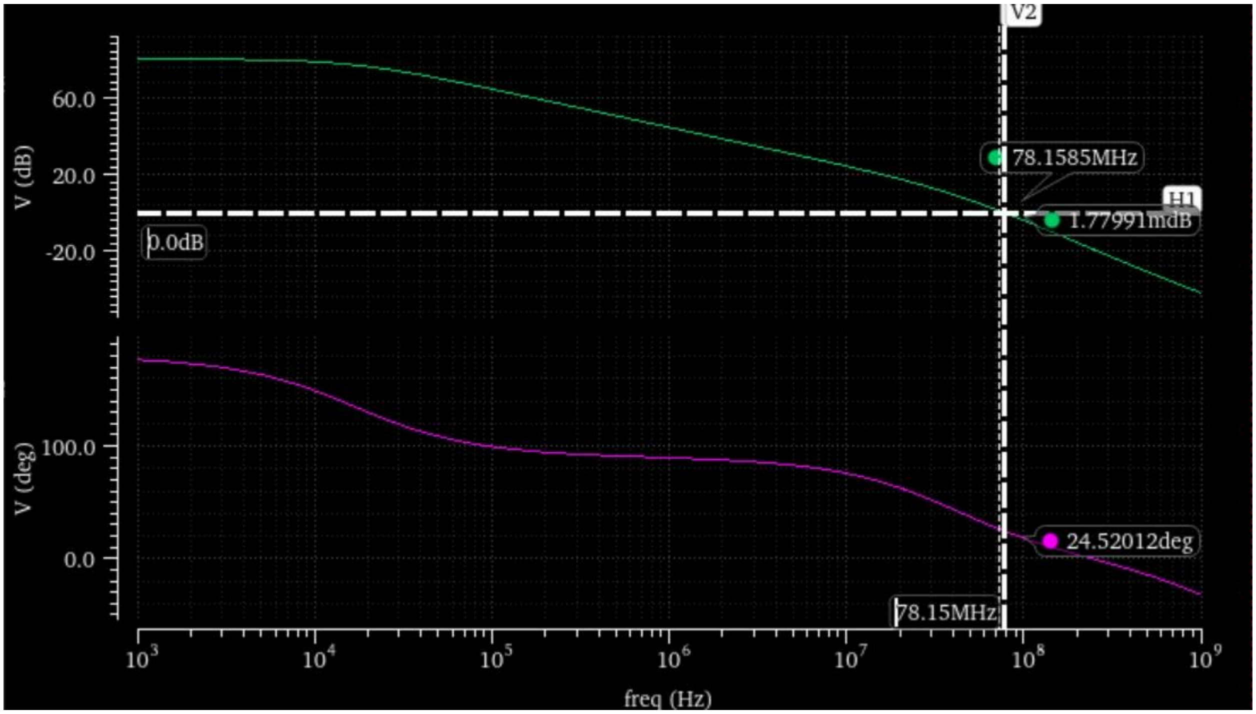
$R_i = 19\ k\Omega$



	Component	Parasitics
	C_i	55.292 fF
	C_o	55.292 fF
Gm_1	R_o	90.428 kΩ
	R_N	904.29 Ω
	C_i	0.4557 pF
Gm_2	C_o	0.4557 pF
	R_o	10.970 kΩ
	R_N	109.7 Ω

Question 5.2

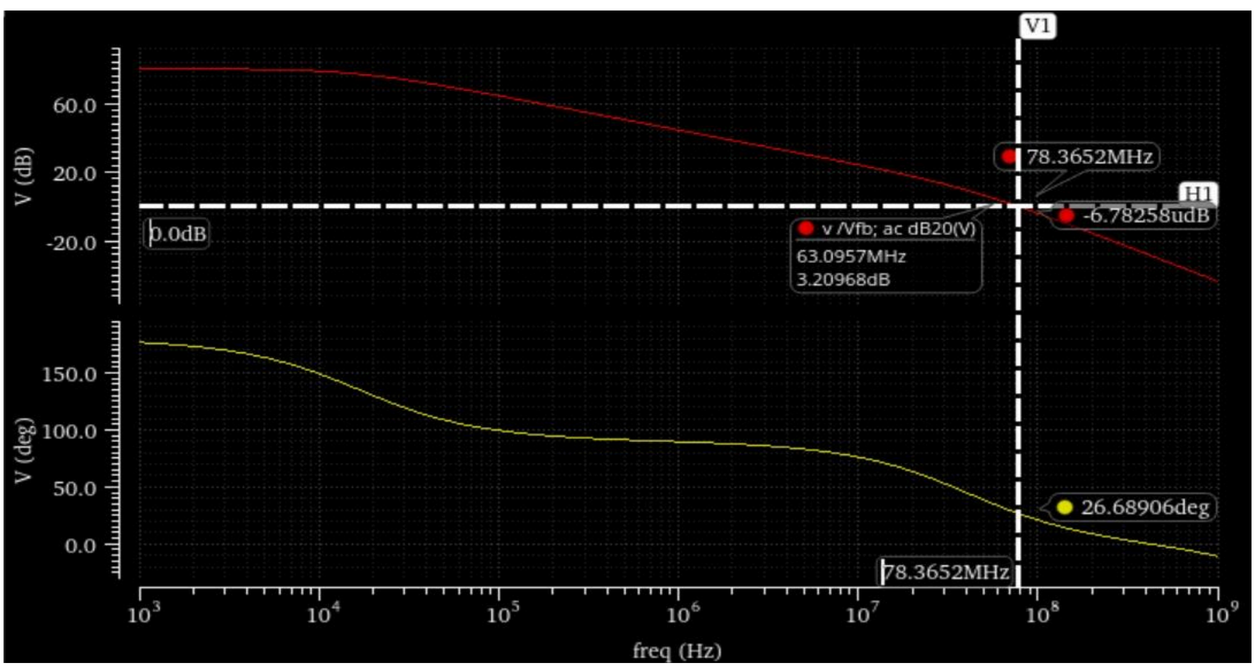
a. Two Stage Miller Compensated Opamp in Unity Feedback



Unity Gain Frequency = 78.1585 MHz
Phase Margin = 24.52012 degrees

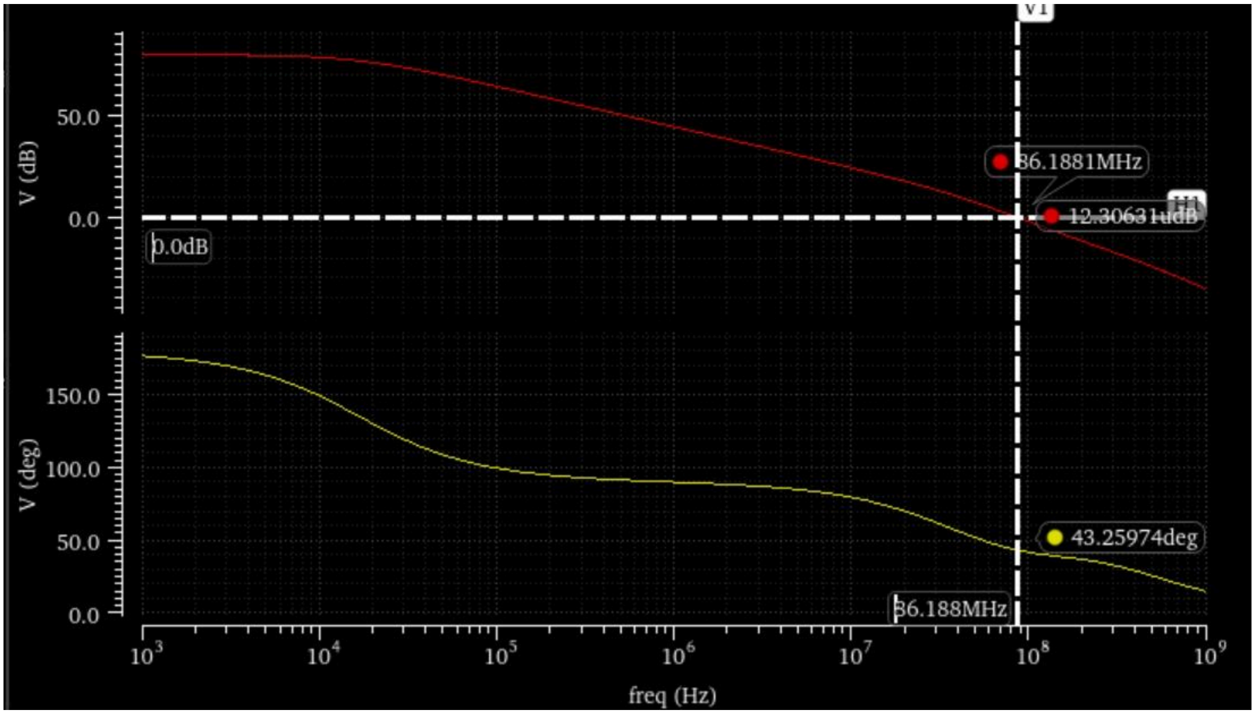
b. Two Stage Miller Compensated Opamp with series resistor Rz:

1. For Rz = 0, the results are same as (a) above.
2. For Rz = 1/Gm2, the results are shown below



Unity Gain Frequency = 78.3652 MHz
Phase Margin = 26.68906 degrees

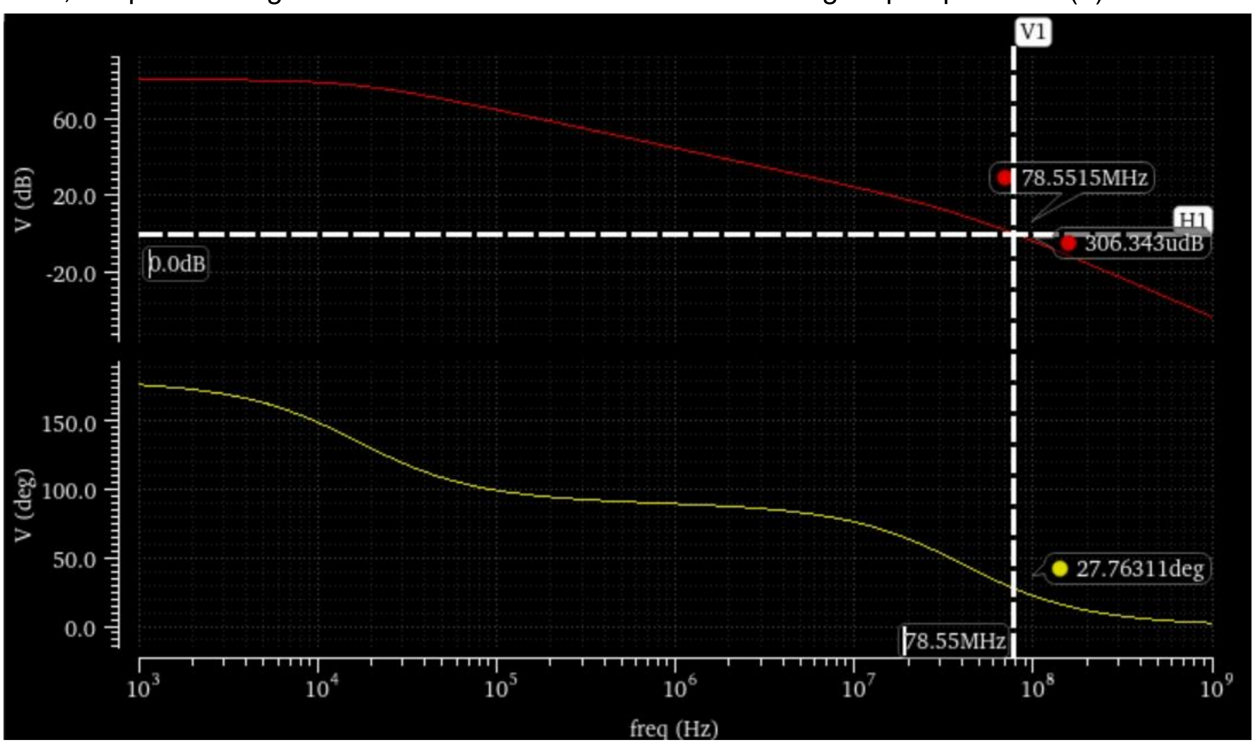
3. For Rz = 10/Gm2, the results are shown below



Unity Gain Frequency = 86.188 MHz
Phase Margin = 43.2597 degrees

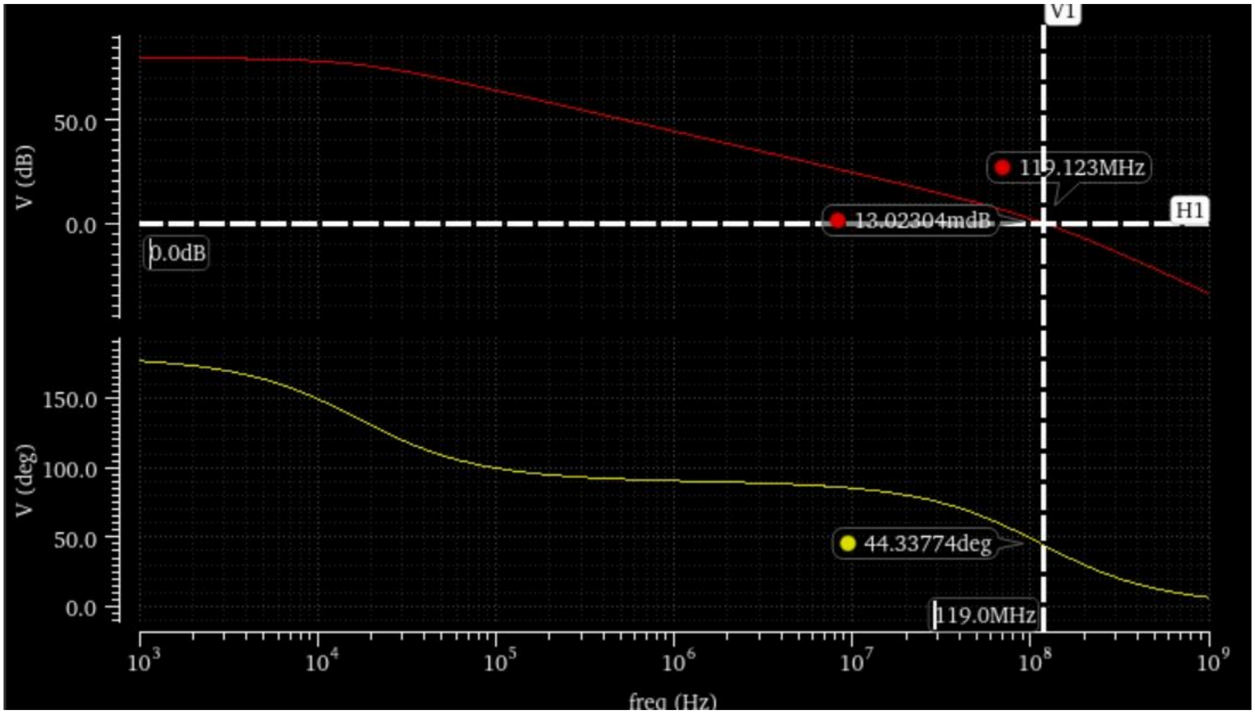
Here, as RZ increases from 0 to 10/Gm2, the phase margin increases and becomes more positive. Highest phase margin in the range is at 10/Gm2 and is 43.2597 degrees.

c. Two stage Miller compensated Opamp with a voltage buffer in series with miller capacitor - Here, the phase margin is better than the normal Miller Two Stage Opamp in case (a)



Unity Gain Frequency = 78.55 MHz
Phase Margin = 27.76311 degrees

d. CCCS included in the model of the Opamp



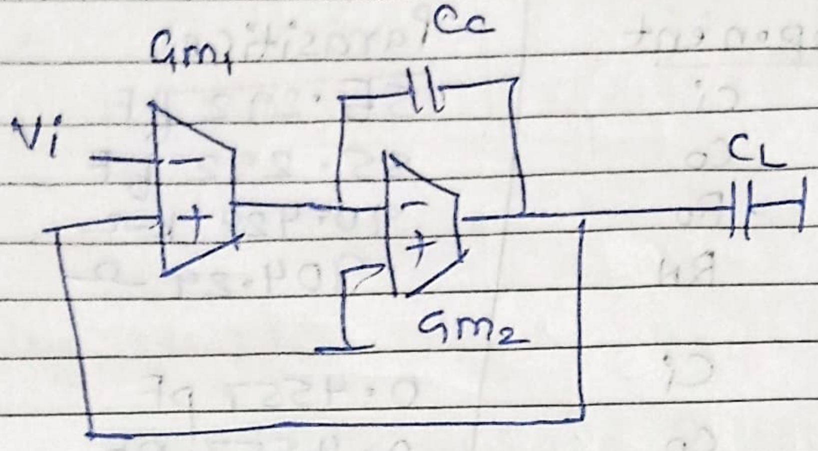
Unity Gain Frequency = 119.123 MHz
Phase Margin = 44.3377 degrees

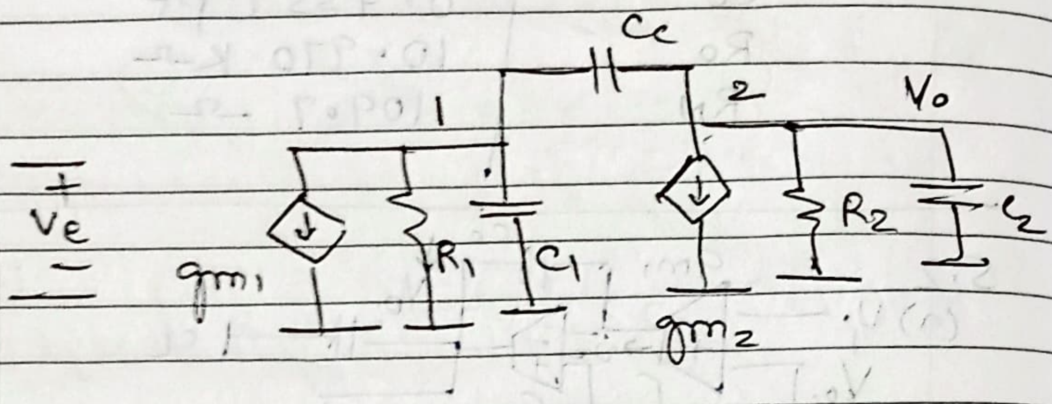
Here, of all the cases presented, the phase margin is maximum here.

Case	Unity Gain Frequency (MHz)	Phase Margin (degrees)
A	78.1585	24.52012
B with Rz = 1/Gm2	78.3652	26.68906
B with Rz = 10/Gm2	86.188	43.2597
C	78.55	27.76311
D	119.123	44.3377

5.2

(a)





@ 2

$$sC_c(V_o - V_1) + g_{m2}V_1 + \frac{V_o}{R_2} + sC_2V_o = 0$$

$$V_o\left(sC_c + \frac{1}{R_2} + sC_2\right) + V_1(g_{m2} - sC_c) = 0$$

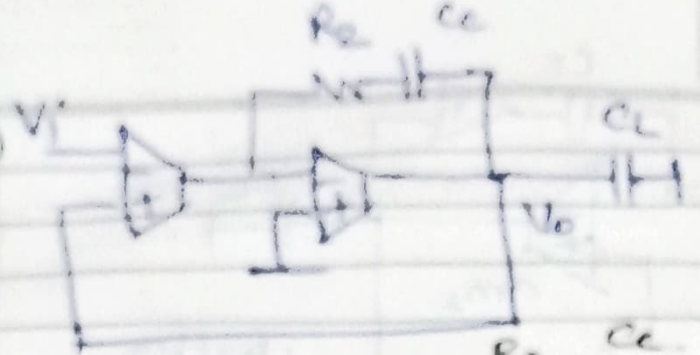
@ 1

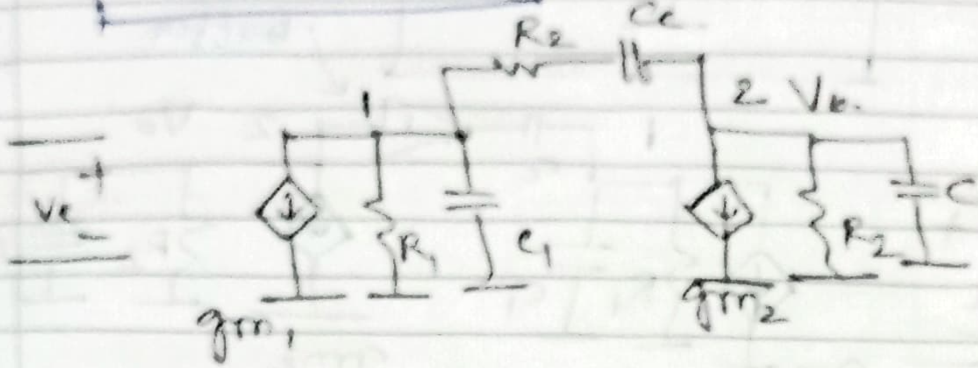
$$sC_1V_1 + \frac{V_1}{R_1} + g_{m1}V_e + sC_c(V_1 - V_2) = 0$$

$$\frac{V_o\left(sC_2 + \frac{1}{R_2} + sC_2\right)\left(\frac{1}{R_1} + sC_1 + sC_c\right)}{sC_c - g_{m2}} - sC_cV_o = -g_{m1}V_e$$

$$\boxed{\therefore \frac{V_o}{V_e} = \frac{g_{m1}g_{m2}R_1R_2\left(1 - sC_c/g_{m2}\right)}{\left[s^2R_1R_2(C_1C_2 + C_1C_c + C_2C_c) + s(R_1C_1 + R_2C_2 + C_c(R_1+R_2) + g_{m2}C_cR_1R_2) + 1\right]}}$$

(b)





We will replace sC_c obtained in (a)

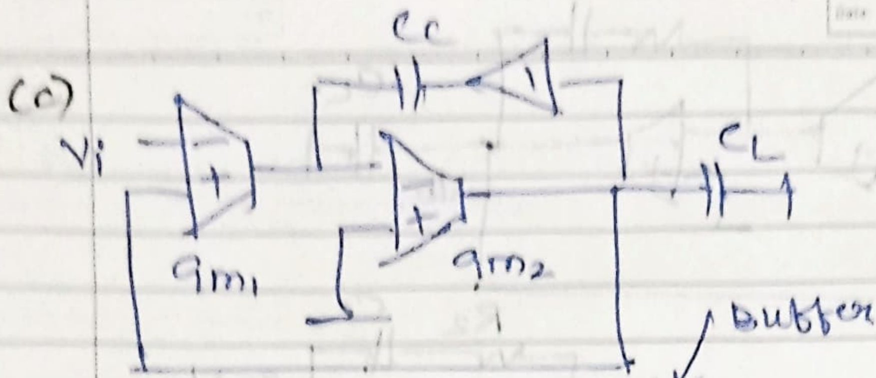
with $Y_c = \left(\frac{sC_cR_2+1}{sC_c}\right)^{-1} = \frac{sC_c}{1+sC_cR_2}$

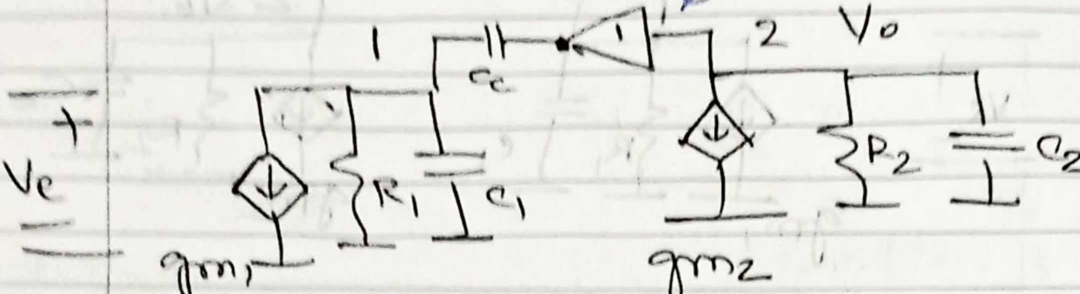
$$\frac{V_o}{V_e} = \frac{g_{m1}g_{m2}R_1R_2\left(1-\frac{sC_c}{g_{m2}(1+sC_cR_2)}\right)}{\left[sR_1R_2(C_1+C_2)\left(\frac{sC_c}{1+sC_cR_2}\right)+s^2R_1R_2C_1C_2 + sR_1C_1+sR_2C_2+(R_1+R_2)\left(\frac{sC_c}{1+sC_cR_2}\right) + g_{m2}R_1R_2\left(\frac{sC_c}{1+sC_cR_2}\right)+1\right]}$$

$$\therefore \frac{V_o}{V_e} = \frac{g_{m1}g_{m2}R_1R_2\left(1+sC_c\left(R_2-\frac{1}{g_{m2}}\right)\right)}{\left[s^3R_1R_2R_2C_1C_cC_2 + s^2[R_1R_2(C_1C_2+C_1C_c+C_eC_c) + R_1R_2C_cC_1 + R_2C_2C_cR_2] + s[R_1C_1+R_2C_2 + C_cR_2+C_c(R_1+R_2)+C_cg_{m2}R_1R_2]+1\right]}$$

3 poles + 1 zero @ $S = \frac{g_{m2}}{C_c(1-g_{m2}R_2)}$

(c)





@ 1

$$g_{m1}V_e + \frac{V_1}{R_1} + sC_1V_1 + sC_c(V_1 - V_o) = 0$$

$$g_{m2}V_1 + \frac{V_o}{R_2} + sC_2V_o = 0$$

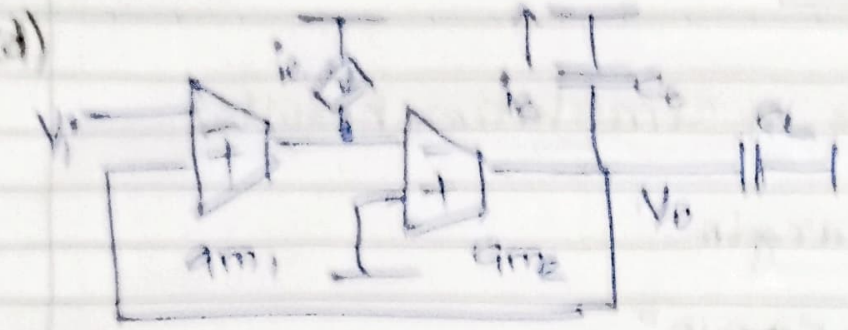
$$V_1 = \frac{-V_o}{g_{m2}}\left(\frac{1}{R_2} + sC_2\right)$$

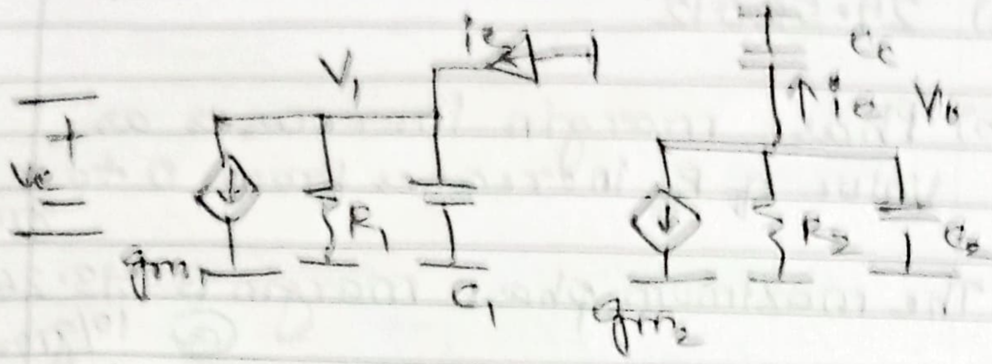
$$g_{m1}V_e = V_o\left[sC_c + \frac{\left(sC_c + sC_1 + \frac{1}{R_1}\right)\left(\frac{1}{R_2} + sC_2\right)}{g_{m2}}\right]$$

$$\therefore \frac{V_o}{V_e} = \frac{g_{m1}g_{m2}R_1R_2}{\left[s^2R_1R_2C_2(C_1+C_c) + sC_2R_2 + sR_1(C_1+C_c) + sC_cg_{m2}R_1R_2 + 1\right]}$$

The miller zero does not appear due to the introduction of VCVS. (buffer)

(d)





$$(sC_c + sC_2)V_o + \frac{V_o}{R_2} = -gm_2 V_1$$

$$i_c = sC_c V_o$$

$$gm_1 V_e + \frac{V_1}{R_1} + sC_1 V_1 + sC_c V_o (-1) = 0$$

$$gm_1 V_e = \left[sC_c + \frac{\left(sC_1 + \frac{1}{R_1}\right)\left(\frac{1}{R_2} + s(C_c + C_2)\right)}{gm_2} \right] V_o$$

$$\boxed{\Rightarrow \therefore \frac{V_o}{V_e} = \frac{gm_1 gm_2 R_1 R_2}{\left[s^2 R_1 R_2 C_1 (C_c + C_2) + s(C_c + C_2)R_2 + sR_1C_1 + sC_c gm_2 R_1 R_2 + 1 \right]}}$$

As in the previous case, the miller zero does not appear.

Comments on Simulation Results:

Phase Margin

(a) 24.52012°

(b) Phase margin increases as Value of R_2 increases from 0 to $\frac{10}{gm_2}$

The maximum phase margin is 43.26° @ $10/gm_2 = R_2$

(c) Phase margin = 27.76°

It is better than case (a)

(d) Phase margin = 44.34°

It is significantly better than (a).