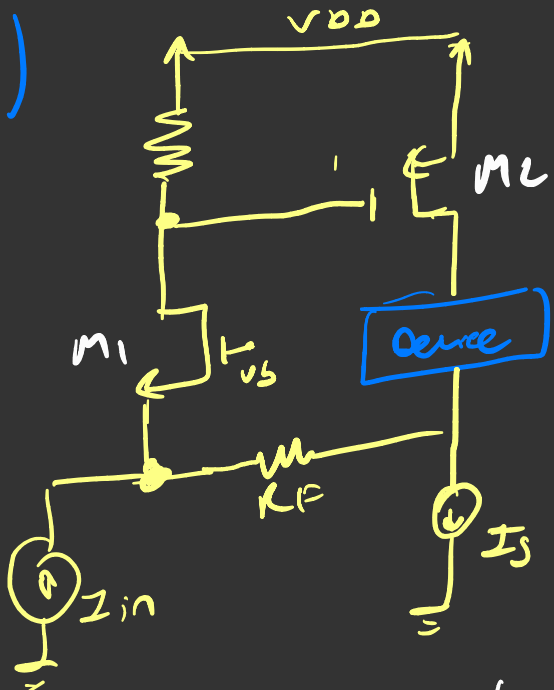
Homework - 6 Solutions

1)



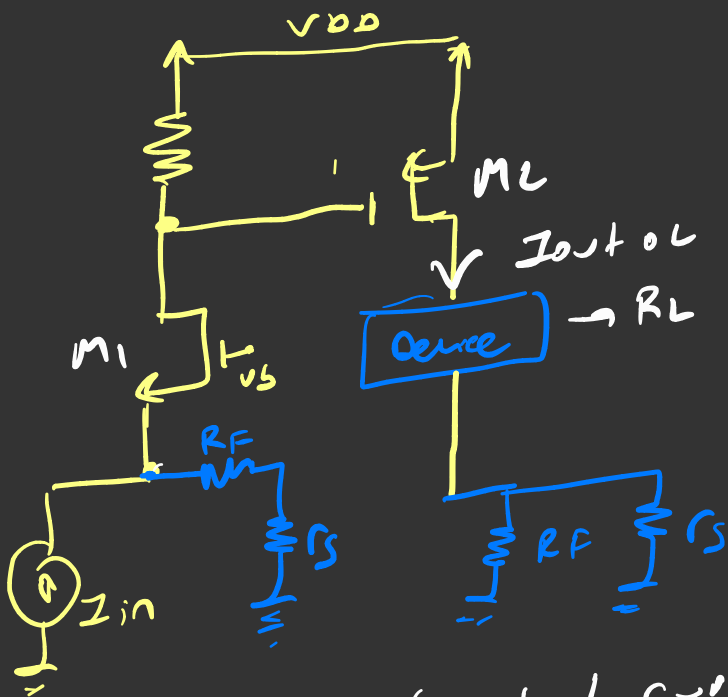
The feedback returns to the same terminal as input current source. Thus, we have shunt feedback at the input.

The output device processes the current of M2. Thus the output is series.

∴ we have shunt-series feedback.

→ Assuming Is has the output resistance rs, let's draw open-loop circuit with loading.

① Open-loop circuit with loading.



Assuming $r_s = \infty$ (ideal current source)

$$I_{in} \cdot RD \cdot g_{m2} \frac{r_{o2}}{r_{o2} + R_L + R_F} = I_{out\,OL}$$

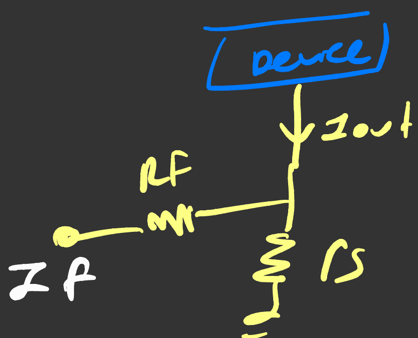
$$\boxed{A_{OL} = g_{m2} RD \cdot \frac{r_{o2}}{r_{o2} + R_L + R_F}}$$

→ open loop current gain

$$R_{in\,OL} = \frac{1}{g_{m1}}$$ → open loop Rin

$$R_{out\,OL} = R_F + R_L + r_{o2}$$ → open loop Rout

Let's zoom in to the feedback network.



$$\frac{I_f}{I_{out}} = \frac{r_s}{R_F + r_s} \approx 1$$

"unity gain current feedback"

$$\beta = 1$$

$$A_{CL} = \frac{g_{m2} R_D \dfrac{r_{o2}}{r_{o1} + R_L + R_F}}{1 + g_{m2} R_D \dfrac{r_{o2}}{r_{o1} + R_L + R_F}}$$

$$\boxed{R_{in\,CL} = \frac{R_{in\,OL}}{1 + A_{OL}} \qquad R_{out\,CL} = (1 + A_{OL})\, R_{out\,OL}}$$

→ You can insert A_{OL} to the equations above.

2) First, we can use the formula,

$$\phi = -\left[\arctan\left(\frac{f}{10^5}\right) + \arctan\left(\frac{f}{3\times10^5}\right) + \arctan\left(\frac{f}{10^6}\right)\right]$$

for 45^0 phase margin ϕ should be -135^0.

we need to find "f" frequency which provide -135^0 for ϕ.

ϕ means "phase shift".

using calculator, the f value is approximately 3.16×10^5 Hz which is not a coincidence.

Comment

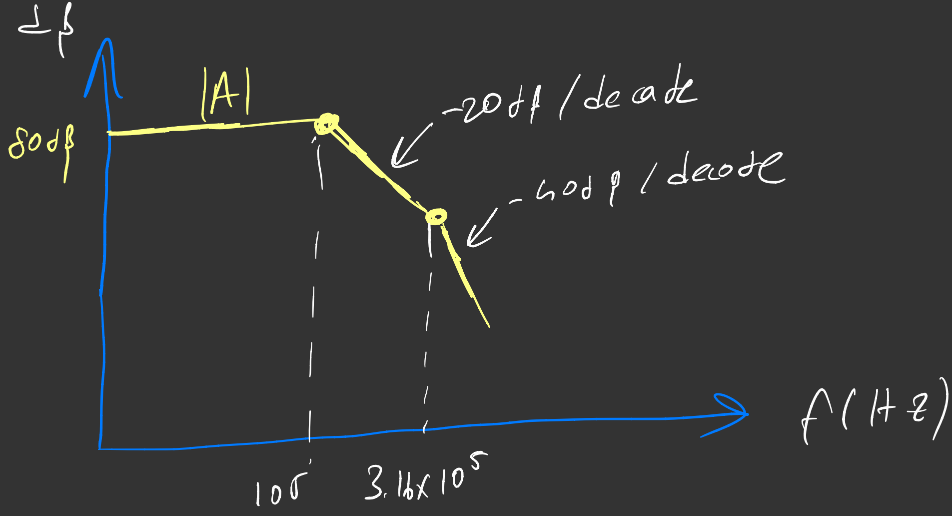
- The harmonic averge of 10^6 and 10^5 is around 3.16×10^5.
- The second pole 3.16×10^5 exactly brings a 45^0 phase shift at f.
- The first pole and third pole brings 90^0 phase shift at f.

- what should be the β value at this "f" frequency?
- we always investigate for $|A\beta| = 1$ or $20 \log |A\beta| = 0\,dB$ for phase margin and stability behaviour analysis.

$$20 \log |A\beta| = 20 \log |A(f)| - 20 \log \frac{1}{\beta}$$

So we need to investigate the frequency which provides,

$$\boxed{20 \log |A(f)| = 20 \log \frac{1}{\beta}}$$



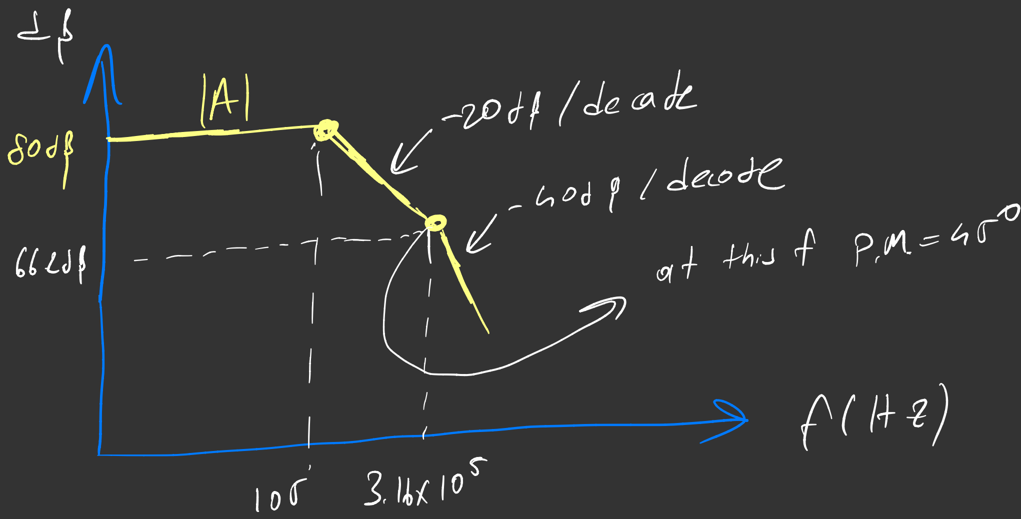
What is the |A| at this frequency?

$10^4 \rightarrow$ low frequency gain

$$|A| = \left| \frac{10^4}{\underbrace{\left(1 + j\frac{3.16\times10^5}{10^5}\right)}_{p_1} \underbrace{\left(1 + j\times\frac{3.16\times10^5}{3.16\times10^5}\right)}_{p_2} \underbrace{\left(1 + j\times\frac{3.16\times10^5}{10^6}\right)}_{p_3}} \right|$$

$$\underset{\text{at } 3.16\times10^5\,\text{Hz}}{|A|} = \frac{10^4}{3.31 \times 1.41 \times 1.05}$$

$$\cong 66.2\ \text{dB}$$



$$\boxed{20 \log \frac{1}{\beta} = 66.2\,dB}$$

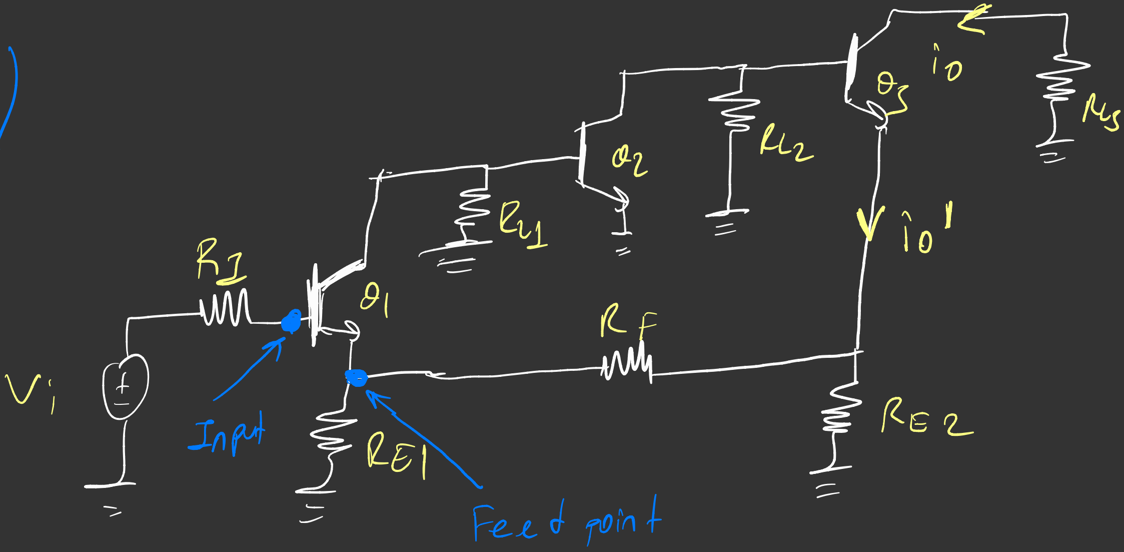
$$\frac{1}{\beta} \simeq 2000, \quad \beta = 5 \times 10^{-4}$$

Closed loop Gain

$$A_{CL} = \frac{A}{1 + A\beta} = \frac{10000}{1 + \frac{10000}{2000}} = \frac{10000}{6}$$

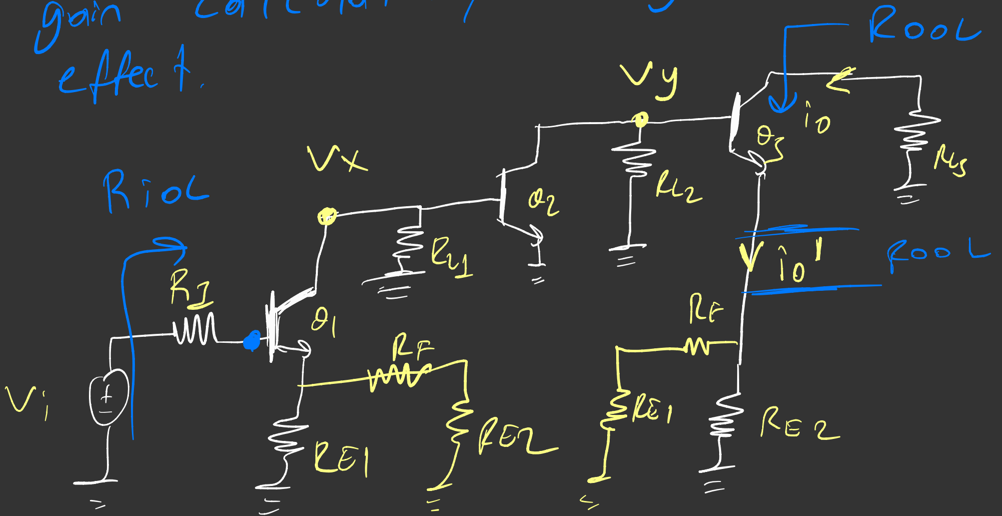
$$= 1666 \text{ or } \simeq 64.4\,dB$$

3)



- Since input voltage signal and feeding point of the feedback network at different terminal we have series feedback at the input.
- At the output we are sensing a current (emitter current of Q3), we have series feedback at the output.
- Overall we have series-series or voltage-current feedback.

Equivalent circuit for open loop gain calculation, including the loading effect.



$$\left.\begin{aligned} R_{E1} \,//\, (R_F + R_{E2}) &= RA \\ R_{E2} \,//\, (R_F + R_{E1}) &= RB \end{aligned}\right\}$$ for simplicity

$$\frac{V_x}{V_i} = \frac{\beta\left(\frac{1}{g_{m1}} + RA\right)}{\beta\left(\frac{1}{g_{m1}} + RA + R_I\right)} \cdot \frac{\left(R_{L1} \,//\, \frac{\beta}{g_{m2}}\right)}{\frac{1}{g_{m1}} + RA}$$

$$\frac{V_y}{V_x} = g_{m2} \cdot \left(R_{L2} \,//\, \beta\left(\frac{1}{g_{m3}} + RB\right)\right.$$

$$\frac{i_o'}{v_y} = \frac{1}{\frac{1}{g_{m3}} + R_B} \quad , i_o' \simeq i_o$$

So, open loop transconductance gain

$$A_{OL} = \frac{v_x}{v_i} \frac{v_y}{v_x} \frac{i_o}{v_y}$$

I won't write the whole expression

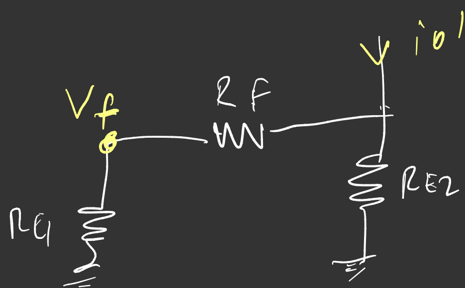
You got the point ✓

$$R_{iOL} = R_I + \beta\left(\frac{1}{g_{m1}} + R_A\right)$$

Output resistance is a little bit tricky. Because we are applying the feedback from emitter of Q_3 rather than output collector of Q3. we must find Rooc' first.

$$R_{ooc}' \cong R_B + \frac{1}{g_{m3}}$$ (output resistance at emitter of Q3 for open loop condition)

The feedback network



$$\boxed{\beta = \frac{i_o'}{V_f} = \frac{R_{E2}}{R_{E1}+R_{E2}+R_F} \cdot R_{E1}}$$

Closed Loop Gain

$$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} \rightarrow \text{put } A_{OL} \text{ and } \beta$$

Closed loop input resistance

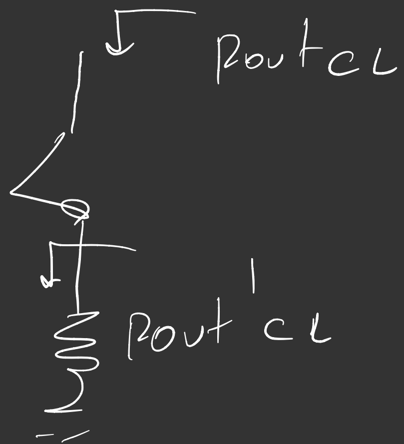
$R_{in\,CL} = (1 + A_{OL}\beta) \cdot R_{iOL}$

└→ increases due to series feedback

$R_{out}'{}_{CL} = (1 + A_{OL}\beta)\, R_{oOL}'$

└→ output impedance when we look at from emitter of Q3

A short discussion and $R_{out\,CL}$ (looking from collector of Q_3)



$$R_{out\,CL} = g_{m3} r_{o3} R'_{out\,CL}$$

Since $r_{o3} = \infty$ $(V_A = \infty)$

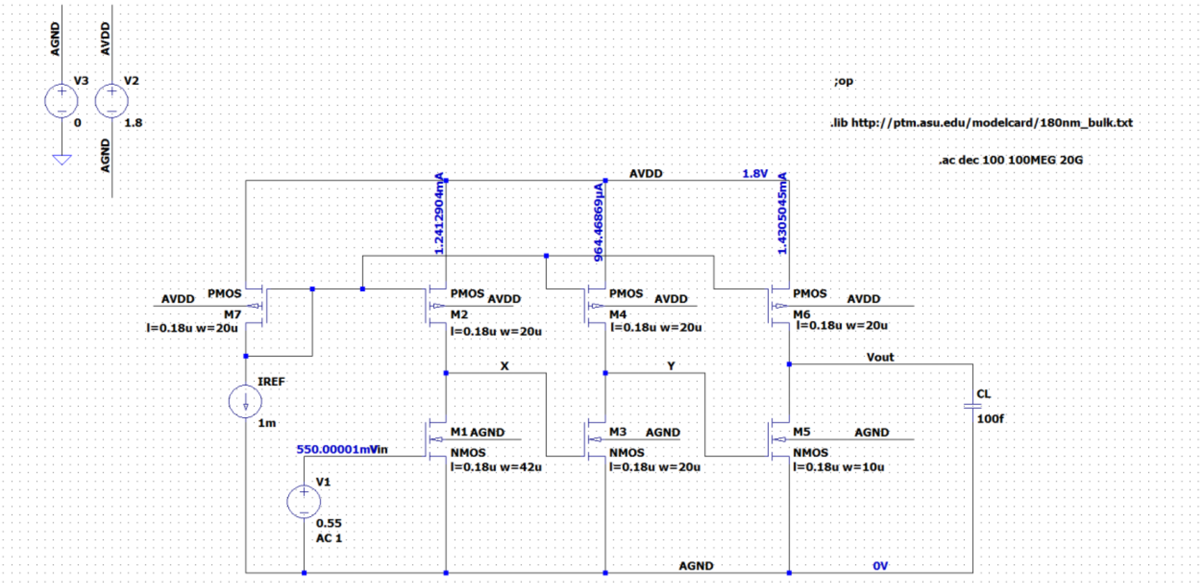
$\Rightarrow$ $R_{out\,CL} = \infty$

$\Rightarrow$ In reality it will be really high even if $V_A \neq \infty$!!

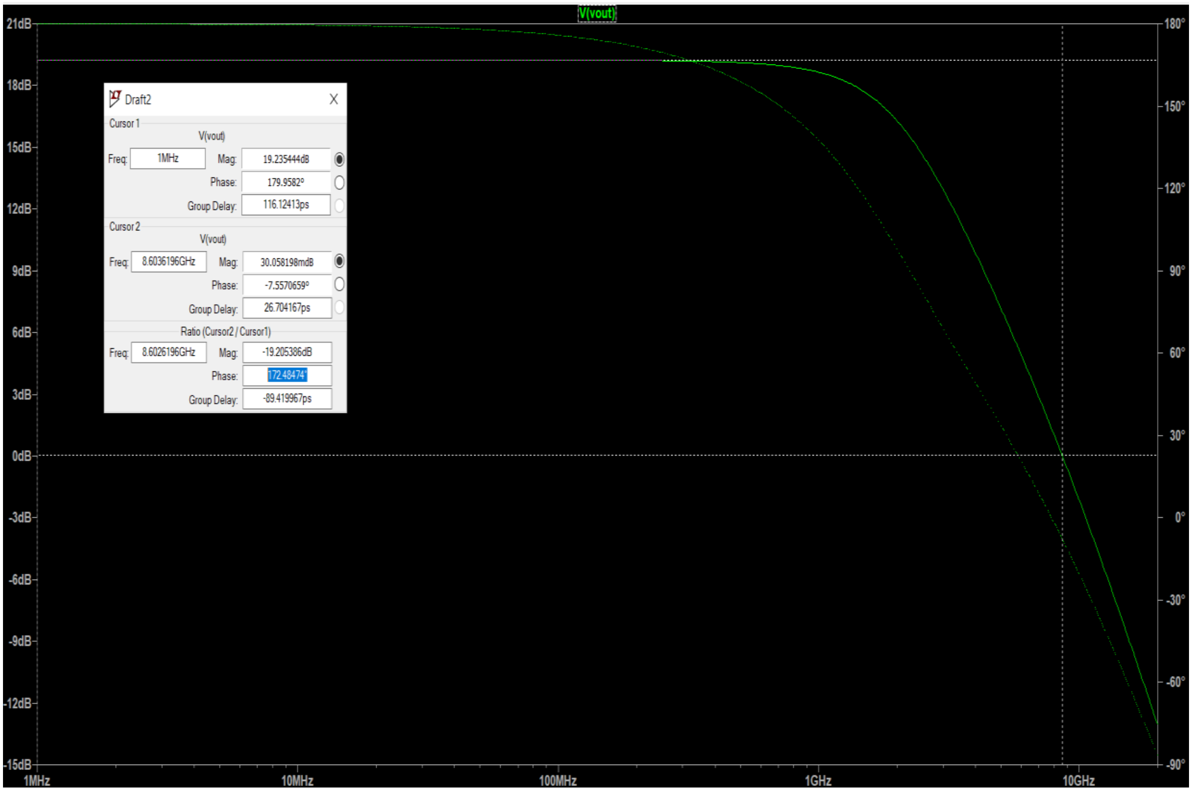
4) See comments for LTSpice at the next page

QUESTION-4 (LTSPICE SOLUTIONS)

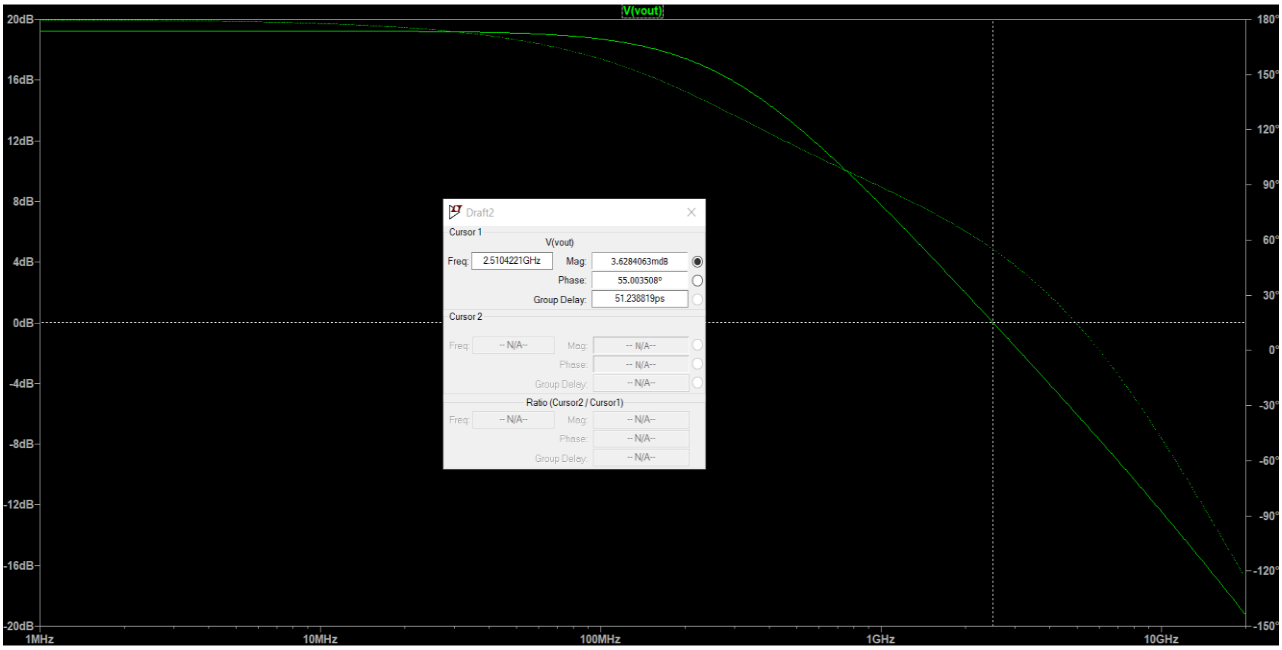
The DC conditions can be seen below in the schemactic.



For the phase margin, let's discuss the frequency response. Zoom in to the cursor and you will observe apprimately -8 degree phase margin, which means if you use this amplifier in the unity gain feedback mode you cannot provide the stability. It's expected as you have 3 poles that are very close to each other in frequency domain. So you need to use a compensation capacitor. (**5 pts)**



After putting a 83 fF capacitor between node X and Y. You can see the new phase margin and unity gain bandwidth below. Now the PM is 55 degree and GBW is 2.51 GHz. Actually we sacrificed from speed to provide stability to the amplifier. For the previous case GBW was around 8.6 GHz but we did not have stability. **(10 pts)**



After putting the 83 fF capacitor between X and ground, you can see the phase margin below. We expect less stability as we do not have the Miller effect. We have PM around 7 degree, which is not good since we could not even provide a 45 degree PM. In this practice you can see the benefit of Miller effect. Even though, in some cases we hate the Miller effect, for OPAMP or OTA design we exploit from that to provide stability while slowing down the operation. **(10 pts)**