EE140 LAB1 report

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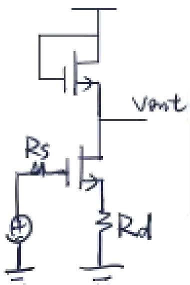
PART1

Hand-Calculation: 1.A

1. A. $I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$ $I_{D1}=I_{D2}$

$R_d=0$. $V_{B1}=1.1V$. $V_{GS1}=1.1V$.



$I_D = 40.5\mu A$.

$g_{m1} = 2.7\times10^{-4}\,S$

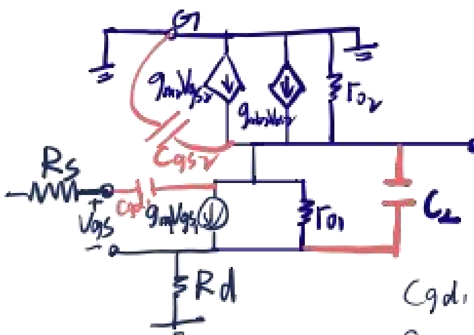
$$g_{m_2}=\mu C_{ox}\frac{W_2}{L_2}(V_{GS}-V_{TH})=\frac{2I_D}{V_{GS}-V_{TH}}=\sqrt{2\mu C_{ox}\frac{W_2}{L_2}I_D} = 2.8\times10^{-5}S \Rightarrow \frac{1}{g_{m_2}}=3.5\times10^4$$

$$r_{o2}=r_{o1}=\frac{1}{\lambda I_D}=2.47\times10^6\,\Omega$$

$g_{m2}=2.8\times10^{-4}\,s$.

$r_{out}=r_o // \frac{1}{g_{m2}} = 2.8\times10^4\,\Omega$.

$g_{m1}=\sqrt{2\mu C_{ox}\frac{W_1}{L_1}I_D}=2.7\times10^{-4}\,s$.



$A_v = \frac{g_{m1}}{g_{m2}+g_{mb2}} = 7.8$.

$C_{ox1} = \frac{\varepsilon_r\varepsilon A}{t_{ox}} = \frac{W_1 L_1 \varepsilon}{t_{ox}} = 4.3\times10^{-10}F$

$C_{ox2} = \frac{\varepsilon_r\varepsilon A}{t_{ox}} = \frac{W_2 L_2 \varepsilon}{t_{ox}} = 1.55\times10^{-12}F$.

$C_{gd1} = 500\times10^{-12}\times 50\times10^{-6} = 2.5\times10^{-14}F$.

$C_{gs2} = \frac{2}{3}C_{ox2} = 1.55\times\frac{2}{3}\times10^{-12} = 1.03\times10^{-12}F$

$\tau_1 = r_{out}C_L = 2.5\times10^{-12}\times 2.8\times10^4 = 70\,ns$

$$\tau_2 = r_{out1}C_{gd1} = \left[(r_o+R_s)\left(1-\frac{r_o // \frac{r_o}{1+g_{m1}R_d}}{r_o}\right) + r_o // \frac{r_o}{1+g_{m1}R_d}\cdot R_s\right]C_{gd}.$$

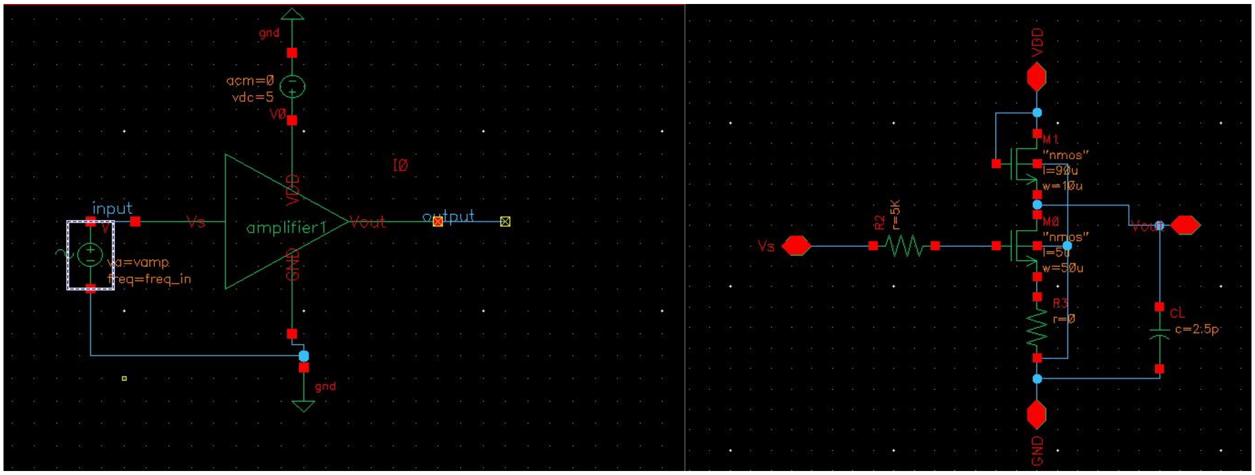
= very small.

$$\tau_3 = r_{out2}C_{gs2} = \left(r_{o2} \,||\, \frac{1}{g_{m2}+g_{mb2}}\right)C_{gs2}.$$

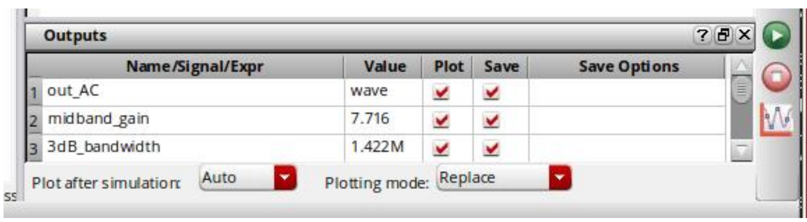
$= 28.8\times10^3\times1.03\times10^{-12}F = 30\,ns$.

$$BW = \frac{1}{(\tau_1+\tau_2+\tau_3)} = \frac{1}{2\pi\cdot100\times10^{-9}} = 1.6\,MHz.$$

Simulation: 1.A



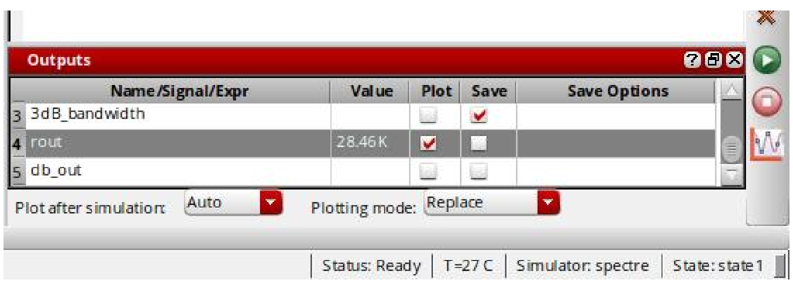
vout/vs & Bandwidth


Outputs

	Name/Signal/Expr	Value	Plot	Save	Save Options
1	out_AC	wave	✓	✓	
2	midband_gain	7.716	✓	✓	
3	3dB_bandwidth	1.422M	✓	✓	

Plot after simulation: Auto Plotting mode: Replace

Rout

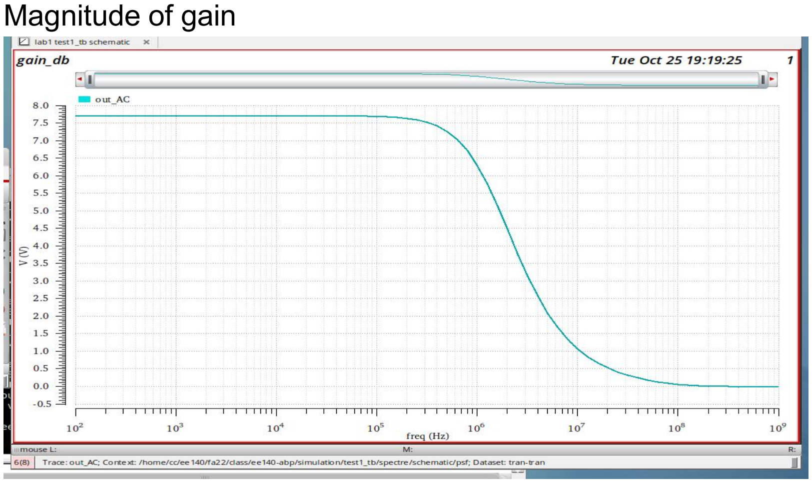

Outputs

	Name/Signal/Expr	Value	Plot	Save	Save Options
3	3dB_bandwidth			✓	
4	rout	28.46K	✓		
5	db_out				

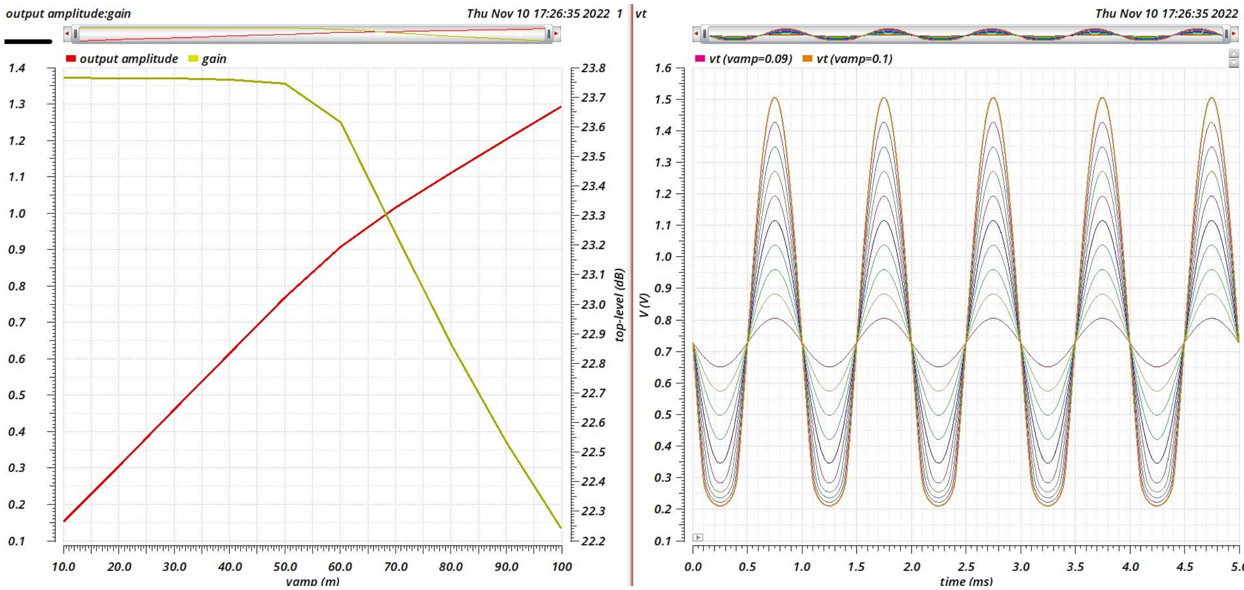
Plot after simulation: Auto Plotting mode: Replace

Status: Ready | T=27 C | Simulator: spectre | State: state1

Magnitude of gain



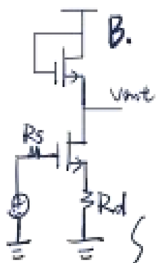
Maximum output voltage swing



Output swing: 1.5V - 0.2V = 1.3V

In this part, we found that the differences of hand-calculation and simulation is not very noticeable(table1), but it can't be ignored. Due to the fact that in the process of hand calculation, we ignored lateral diffusion and sometimes we ignored body effect, so the Rout and mid-band gain from hand-calculation and simulation are different in a small degree. Especially for bandwidth, we learned that in the process of hand-calculation, we used the asymptotic approximation technique, so it has a very obvious difference.

Hand-calculation: 1.B



B. assume both M_1, M_2 are in sat.

$I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$

$V_{GS2} = 5V - V_{out}$ $V_{DS2} = 5V - V_{out}$.

$V_{GS1} = 0.4 - I_D \cdot 2.5K$. $V_{DS1} = V_{out} - V_{S1}$. $V_{S1} = I_D \cdot 2.5K$.

$I_{D2} = \frac{1}{2}\cdot 50\times10^{-6}\times 10\times(5-V_{out})^2\cdot(1+0.01\cdot(5-V_{out}))$

$I_{D1} = \frac{1}{2}\cdot 90\times10^{-6}\times10\times(0.4-2.5\times10^3\cdot I_{D1})^2(1+0.01\cdot(V_{out}-2.5\times10^3 I_D))$

$I_{D1} = I_{D2}$

$\Rightarrow$ $I_D = 40.3\mu A$. $V_{out} = 1.36V$ $V_{S1} = I_D \cdot R_d = 0.1V$

$V_{DS1} > V_{GS1} - V_{TH1}$ ✓ $V_{DS2} > V_{GS2} - V_{TH2}$ ✓.

∴ both in sat is correct.

$r_o = r_{o1} = r_{o2} = \frac{1}{\lambda_n I_D} = \frac{1}{0.01\times40.3\times10^{-6}} = 2.48M\Omega$.

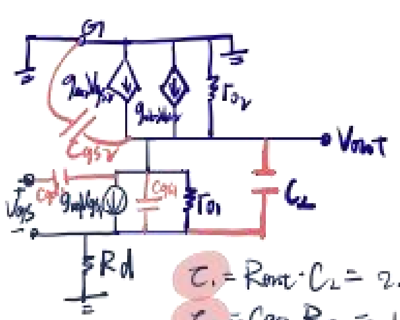
$g_{m1} = \frac{2I_D}{\Delta V_1} = \frac{2I_D}{V_{out}-V_{S1}-V_{TH}} = 175\mu S$ $g_{m2} = \frac{2I_D}{\Delta V_2} = \frac{2I_D}{5V-V_{out}-V_{TH}} = 28.4\mu S$.

$g_{mb1} = \frac{\gamma g_{m1}}{2\sqrt{2|\phi_F|+V_{SB1}}} = \frac{0.8\times175\times10^{-6}}{2\sqrt{2\times0.7+1.2}} = 4.34\times10^{-5}S$ $g_{mb2} = \frac{\gamma g_{m2}}{2\sqrt{2|\phi_F|+V_{SB2}}} = \frac{0.8\times28.4\times10^{-6}}{2\sqrt{2\cdot0.7+5}} = 4.5\times10^{-6}S$.

$R_{out} = \left[\frac{1}{g_{m2}+g_{mb2}} // r_{o2}\right] // \left[r_{o1} + R_d + r_{o1}R_d(g_{mb1}+g_{m1})\right]$

$= 30.4K // 3.74\times10^6\Omega \approx 30.4k\Omega$

$A_V = -G_m \cdot R_{out}$ $G_m = \frac{i_{sc}}{V_{in}} = \frac{g_{m1}}{R_d\cdot(g_{m1}+\frac{1}{r_o}+\frac{1}{R_d})} = 185\mu S$ $A_V = -5.6$



$C_{ox1} = \frac{\varepsilon_r\varepsilon A}{t_{ox}} = \frac{W\cdot L\cdot\varepsilon}{t_{ox}} = 4.3\times10^{-10}F$

$C_{ox2} = \frac{\varepsilon_r\varepsilon A}{t_{ox}} = \frac{W\cdot L\varepsilon}{t_{ox}} = 1.55\times10^{-12}F$.

$C_{gd1} = 500\times10^{-12}\times50\times10^{-6} = 2.5\times10^{-14}F$.

$C_{gs2} = \frac{2}{3}C_{ox2} = 1.55\times\frac{2}{3}\times10^{-12} = 1.03\times10^{-12}F$

$C_{gs1} = \frac{2}{3}C_{ox1} = 2.87\times10^{-10}F$.

$\tau_1 = R_{out}\cdot C_L = 2.5pF\cdot30.4k\Omega = 7.6\times10^{-8}s$

$\tau_2 = C_{gs2}R_2 = 1pF\cdot35k\Omega = 3.52\times10^{-8}s$.

$i_t - g_{m2}V_{out} - \frac{V_{out}}{r_{o2}} = \frac{V_{out}}{r_{o1}} + \frac{V_{out}}{r_{o1}(\frac{1}{R_d}+g_{mb1})}$

$\Rightarrow R_2 = \frac{V_{out}}{i_t} = \frac{1}{g_{m2}+\frac{1}{r_{o1}}+\frac{1}{r_{o2}}+\frac{1}{r_{o1}(g_{mb1}+\frac{1}{R_d})}} = 35.2k\Omega$

$\tau_3 = C_{gd1}\cdot R_{gd1}$ = very small.

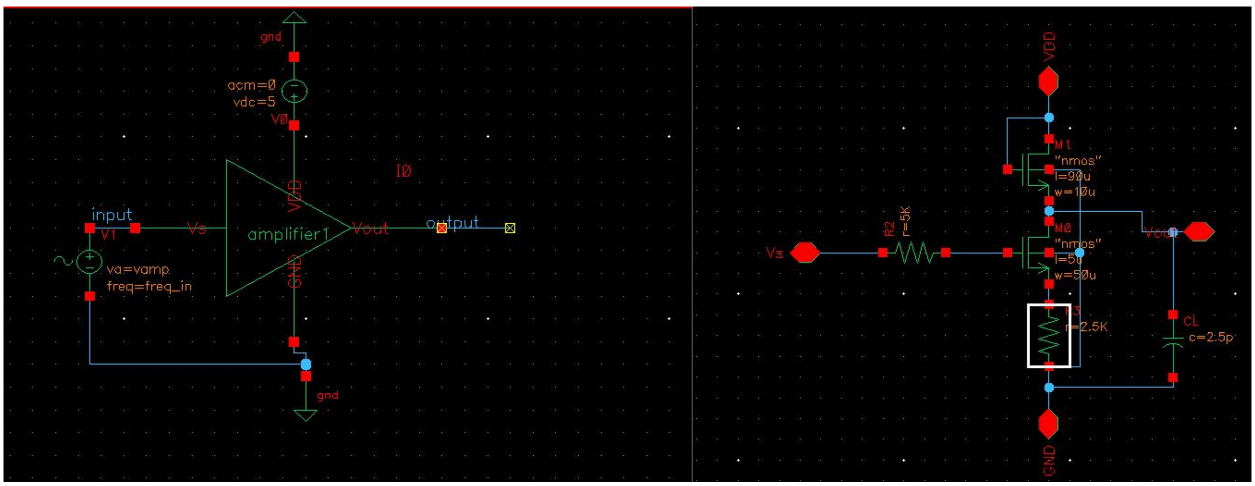
$\tau_4 = C_{gs1}\cdot R_{gs1} = 2.87\times10^{-10}\times 1.5\times10^{3} = 4.3\times10^{-7}s.$

$$i_t + g_{mb1}(-V_t) + \frac{V_{out}}{r_{o1}} = g_{m2}\cdot V_{out} + \frac{V_{out}}{r_{o2}} \qquad V_{out} = \frac{V_t}{R_d(g_{m2}+\frac{1}{r_{o2}})}$$

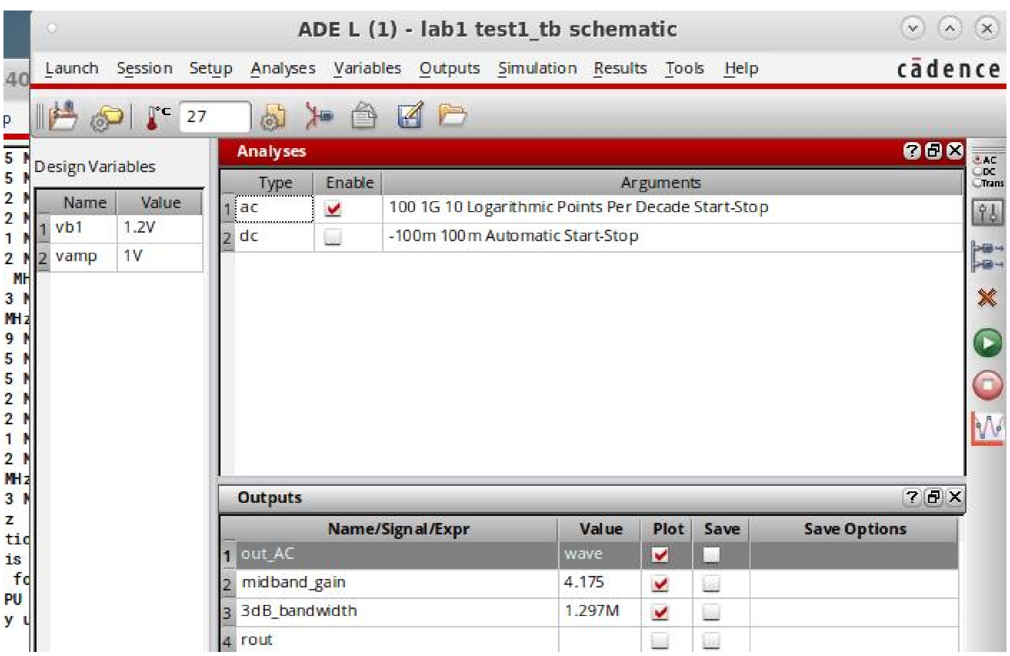
$$\Rightarrow R_{gs1} = \frac{V_t}{i_t} = 1.5K\Omega.$$

$$BW = \frac{1}{(\tau_1+\tau_2+\tau_3+\tau_4)} = 1.443\,MHz.$$

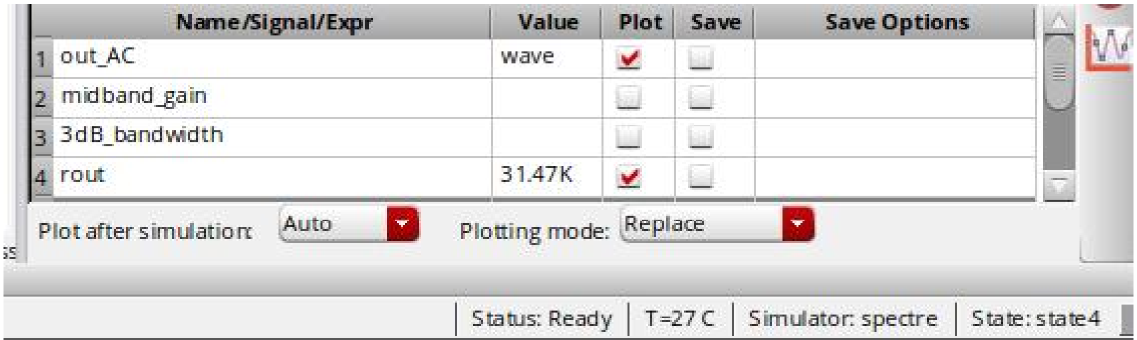
Simulation : 1.B



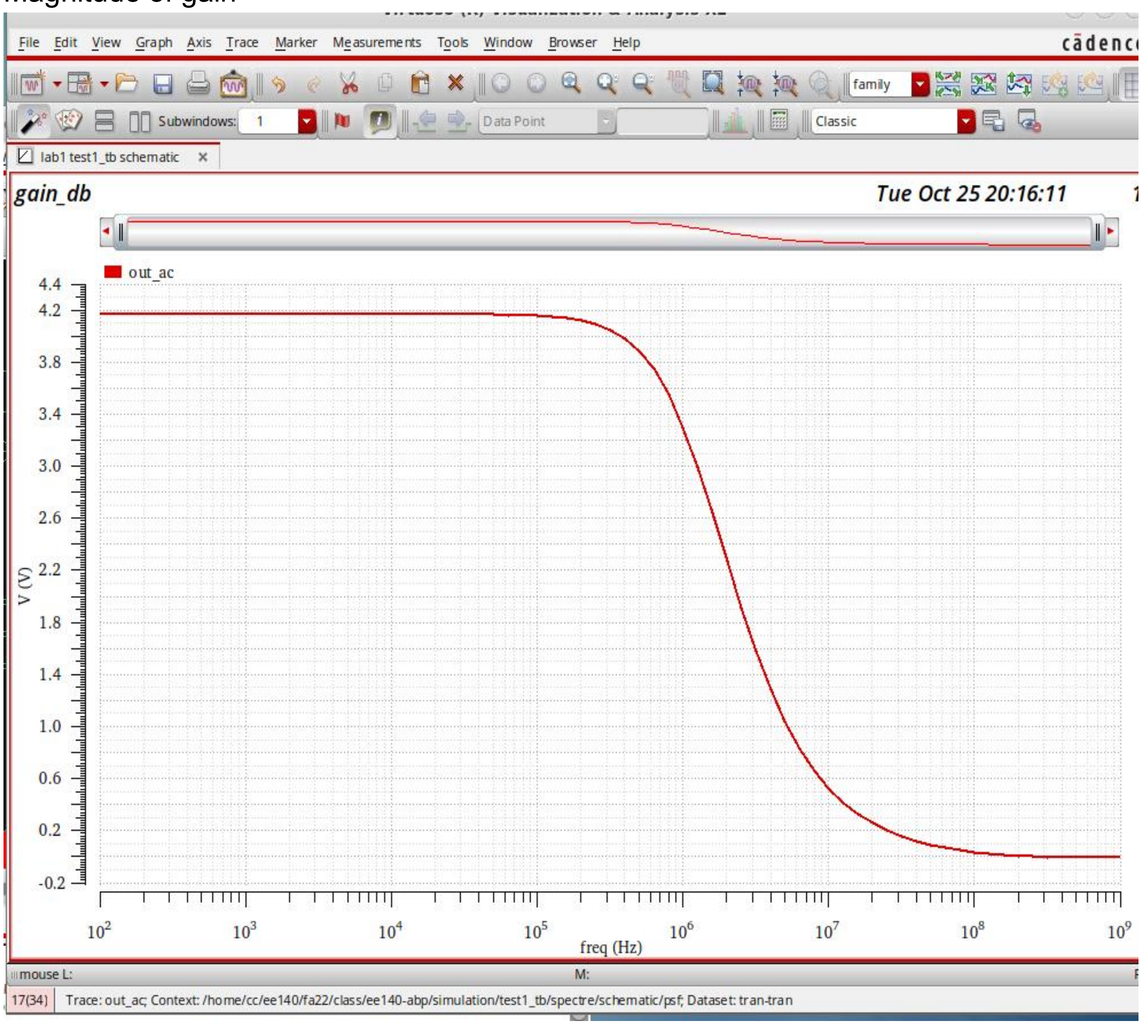
vout/vs & Bandwidth



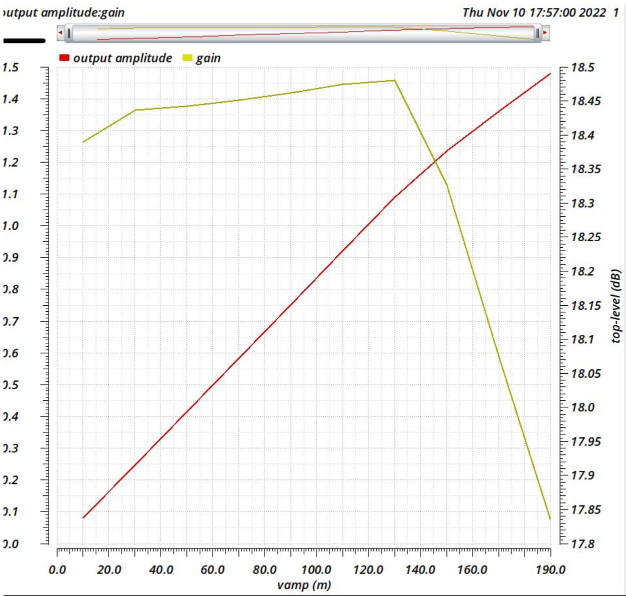
Rout

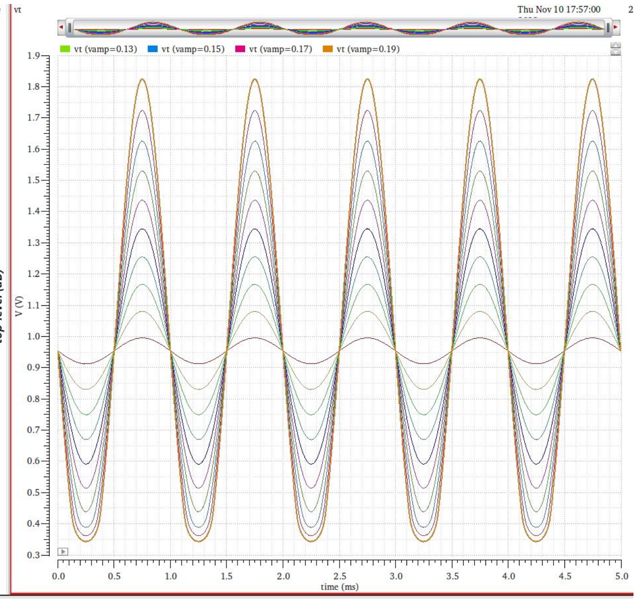


Magnitude of gain



Maximum output voltage swing





When vamp=0.15V, we got the maximum output swing: 1.82V - 0.35 V = 1.47 V

In part B, we found that the differences of hand-calculation and simulation is much more obvious than part A(table1), it is because we have Rd=2.5kΩ, not 0, the mid-band gain is influenced a lot.

Due to the fact that in the process of hand calculation, we ignored lateral diffusion and sometimes we ignored body effect, the Rout from hand-calculation and simulation are different in a small degree.

Additionally, for bandwidth, we learned that in the process of hand-calculation, we used the asymptotic approximation technique, so it has a very obvious difference.

	1A calculation	1A simulation	1B calculation	1B simulation
Rout	28.1k Ω	28.46k Ω	30.4kΩ	31.47k Ω
BW	1.6MHz	1.422MHz	1.443MHz	1.297MHz
|Mid-band gain|	7.8	7.7	5.6	4.175

Table 1 list of relevant perform parameters

From A to B, we got almost same bandwidth, but midband gain is lower.

PART2:

Parameter	Specification – EE140	Specification – EE240A
Midband gain	≥ 120 V/V	≥ 140 V/V
3 dB cutoff frequency (bandwidth)	≥ 180 kHz	≥ 200 kHz
Output voltage swing	≥ 3 Vpp	
Load capacitance	2.5 pF	
Source resistance	5 kΩ	
Supply voltage	VDD = 5 V, VSS = Ground = 0 V	

Hand-calculation 2:

In the process of doing hand-writing, firstly I choose the specification of my design. And I try to let every transistor is in satuation.

From these specs, I can get gm first. Then we find the Rout of this circuit as function of ID.
Due to the fact that gm can be calculate with ΔV_1 and ID, we use an approximation to let $Gm=gm_1$.

Now we can get the function of mid-band gain, which is only depends on ΔV_1, rather than Id.
With ΔV_1, gm, we are able to calculate Id.

As I have choose the specs of design. We got the boundary of ΔV_1 and ΔV_2 from output swing.

From the boundary of ΔV_1 and ΔV_2, we choose a pair of value to calculate Rout, mid-band gain as well as bandwidth until they meet requirements.

Now we got everything we need to calculation the right W1, W2.

As we are suggested to use correct mirror to bias M2, we do calculation to find the width of another pmos, and found the correct I_{bias}.

sat (even mV change)

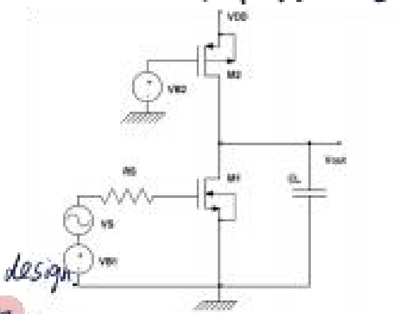
$(\mu C_{ox})_n = 90\mu A/V^2$ $(\mu C_{ox})_p = 30\mu A/V^2$

2. V_{B1}. V_{B2}. (current mirror) $\frac{W_1}{L_1} = \frac{W_1}{5\mu m}$ $\frac{W_2}{L_2} = \frac{W_2}{5\mu m}$

hint from instructions: $|V_{GS}| \geq 1V$

$$g_m = \mu C_{ox}\frac{W}{L}(V_{GS}-V_{TH}) = \frac{2I_D}{V_{GS}-V_{TH}} = \sqrt{2\mu C_{ox}\frac{W}{L}I_D}$$ $\lambda_1 = 0.01$ $\lambda_2 = 0.02$.

$$r_o = \frac{1}{\lambda I_D}$$



$$I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2(1+\lambda V_{DS})$$

$V_{DS1} = V_{DD} - V_{out}$ $V_{DS2} = V_{out}$

$V_{GS1} = V_{B2} - V_{out}$ $V_{GS2} = V_{B1}$.

To begin with, we choose the specifications of design:

① Midband-gain: 150 V/V. ② bandwidth: 250 kHz

③ outputs swing $= V_{DD} - \Delta V_2 - \Delta V_1 \geq 3V_{pp}$ $\Rightarrow$. $\Delta V_1 + \Delta V_2 \leq 2V$.

other constrains: ① $L = 5\mu m$. ② all in saturation. ③ $|V_{GS}| \geq 1V$

start calculation.

$$Af_{BW} = g_m R_{out} = \frac{1}{2\pi R_{out} C_L}$$

$$\therefore g_m = 2\pi \cdot C_L \cdot A \cdot f_{BW} = 2\pi \cdot 2.5\times10^{-12} \cdot 150 \cdot 250\times10^3 = 589\mu S.$$

$$R_{out} = r_{o1} // r_{o2} = \frac{1}{0.01 I_D} // \frac{1}{0.02 I_D} = \frac{1}{0.03 I_D}.$$

$A = g_m \cdot R_{out} \geq 150$ $\frac{2I_D}{\Delta V_1} \cdot \frac{1}{0.03 I_D} = \frac{200}{3\Delta V_1} \geq 150$ $\Delta V_1 \leq 0.44V$.

$\Delta V_1 + \Delta V_2 \leq 2V$ $\Rightarrow$. $\Delta V_2 \leq 1.56V$.

if we choose $\Delta V_1 = 0.39V$, $I_D = \frac{\Delta V_1 \cdot g_m}{2} = 1.17\times10^{-4}A$.

$\Rightarrow$ $r_{o1} = 852\ k\Omega$. $r_{o2} = 426\ k\Omega$

$R_{out} = 284\ k\Omega$.

$\Rightarrow$ $A_v = g_m R_{out} = 167$

$BW = \frac{1}{2\pi R_{out} \cdot C_L} = 224\ kHz$

$\Rightarrow$ These certificate that we can choose

$\Delta V_1 = 0.39V$ $V_{B1} = 1.19V$

$\Delta V_2 = 1.45V$ $V_{B2} = 2.25V$

$$W_1 = \frac{2 I_D L}{(\mu C_{ox})_n \Delta V_1^2} = \frac{2 \times 117 \times 50 \times 10^{-6}}{80 \times 0.39^2} = 80\,\mu m$$

$$W_2 = \frac{2 I_D L}{(\mu C_{ox})_p \Delta V_2^2} = \frac{2 \times 117 \times 50 \times 10^{-6}}{30 \times 1.45^2} = 24.4\,\mu m$$

current mirror. $V_{B2} = V_{B3} = 2.25\,V$. $V_{sg2} = V_{sg3}$

$$\frac{I_D}{I_{bias}} = \frac{\left(\frac{W}{L}\right)_2 (1+\lambda V_{sd})}{\left(\frac{W}{L}\right)_3 (1+\lambda(V_{DD}-V_{out}))} = 1 \Rightarrow \left(\frac{W}{L}\right)_3 \approx \left(\frac{W}{L}\right)_2 \quad W_3 = 24.4\,\mu m$$

when we use this W_3 to build a current mirror, we found that specs is what we want.

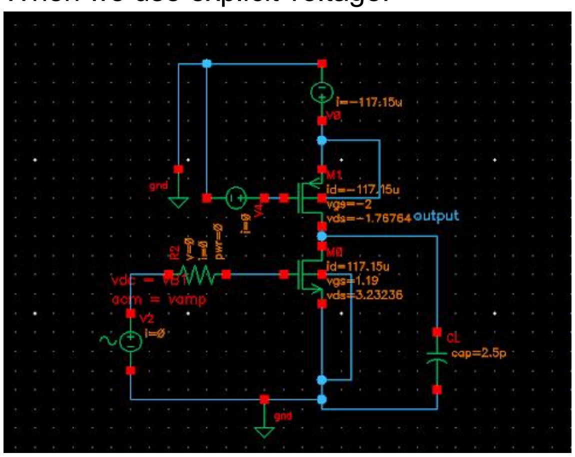
$I_{bias} = I_{D1} = I_{D2}$.

$$I_{D1} = \frac{1}{2} (\mu C_{ox})_n \Delta V_1^2 \cdot (1+\lambda_n V_{ds1})$$

$$\Rightarrow I_{bias} = \frac{1}{2} \cdot 70 \cdot 10^{-6} \cdot 0.39^2 \cdot (1+0.01 \cdot 3) = 1.17 \times 10^{-4} A.$$

Simulation 2:

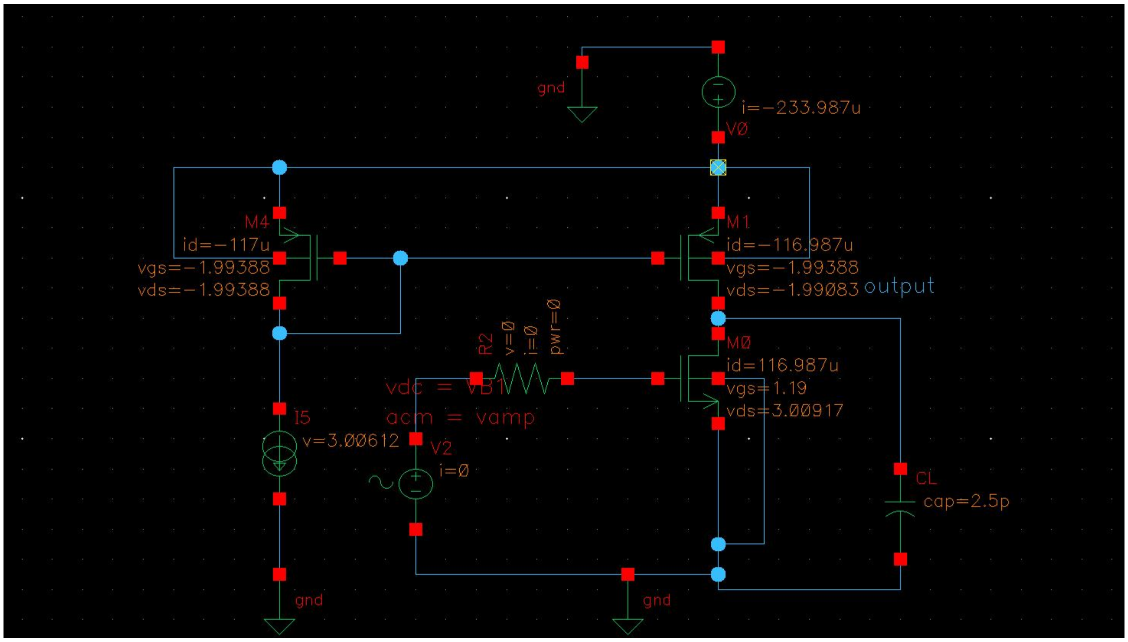
When we use explicit voltage:

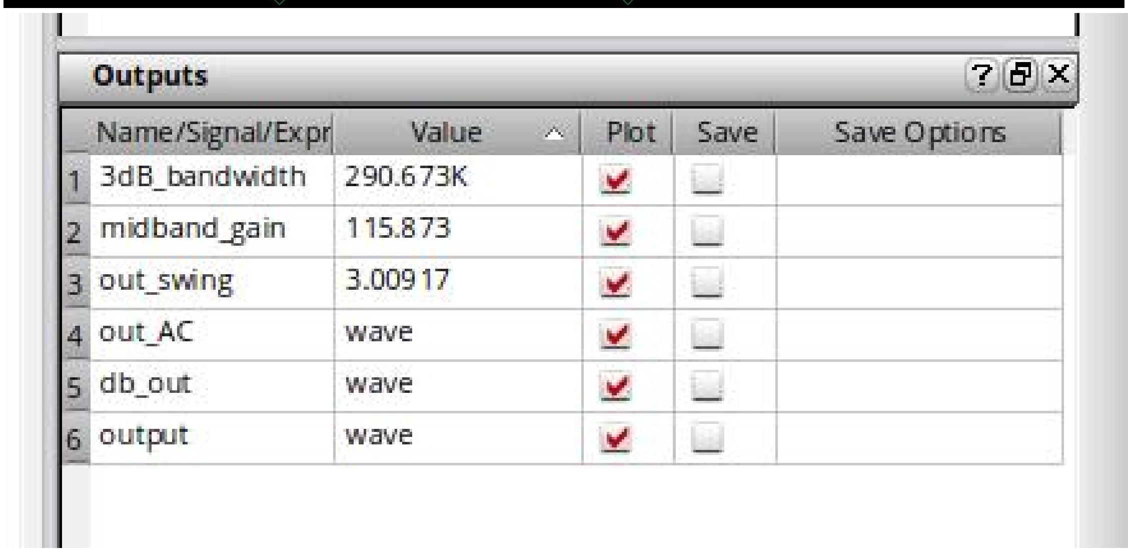


Outputs

	Name/Signal/Expr	Value	Plot	Save	Save Options
1	3dB_bandwidth	326.624K	✔	☐	
2	midband_gain	103.614	✔	☐	
3	out_swing	3.23236	✔	☐	
4	out_AC	wave	✔	☐	
5	db_out	wave	✔	☐	
6	output	wave	✔	☐	

When we use current mirror:





Outputs

	Name/Signal/Expr	Value	Plot	Save	Save Options
1	3dB_bandwidth	290.673K	☑	☐	
2	midband_gain	115.873	☑	☐	
3	out_swing	3.00917	☑	☐	
4	out_AC	wave	☑	☐	
5	db_out	wave	☑	☐	
6	output	wave	☑	☐	

	Hand-calculation	Simulation with current mirror	Simulation with explicit voltage bias
bandwidth	224kHz	290.673kHz	326.624kHz
Midband gain	120	115.873	103.614
Out swing	3.15	3.01	3.23

Now we can explain some questions of our designs.

1. We found that using explicit voltage sources to bias amplifiers is not good practice, it is because as we need different voltage to bias transister, it is not very realistic that a piece of IC connected to many different power supplies. Additionally, explicit voltage sources introduce noises to the system.

2. As we rework the biasing network and simulate the gain and bandwidth of our amplifier. These values are different from the gain and bandwidth of your original amplifier. There are several reasons. The Id is very sensitive due to the change of ΔV with explicit voltage bias, the ΔV_2 wouldn't adapted all the time, but with use current mirror, Id is only depends on the ratio of width of M2 and M3. In this part, we ignore the effect of body effect. As we use asymptotic approximation technique, bandwidth is not accurate.

3. Calculate the output resistance of the final amplifier and compare it with the output resistance of the CS amplifier used in Task a of Part 1.

In part 1, Rout = 30kΩ approximately as it mainly depends on 1/gm . But in Part2 Rout is very large because output connect to the drain of PMOS and NMOS Rout = 284 kΩ. In next question we explan why we use this topology.

4. How output resistance affect the gain and bandwidth?

In this design, Rout is very large because output connect to the drain of PMOS and NMOS. So the dominant pole is set by Rout*CL. We got

$$\mathrm{BW} = \frac{1}{2\Pi \mathrm{R_{OUT}} \mathrm{C_L}}$$

$$\rightarrow \mathrm{BW} \propto \frac{1}{\mathrm{R_{OUT}}}$$

Midband gain = gm*R_{out},

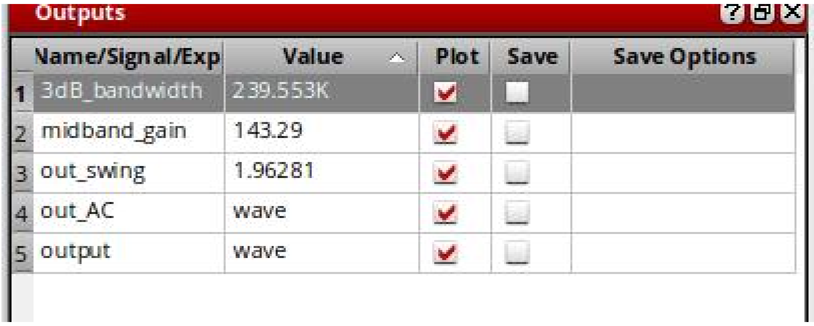
$$\rightarrow \text{midband gain} \propto R_{out}$$

From how output resistance affect the gain and bandwidth, we learned that bandwidth is a trade off of midband gain. From part1 to Part2, we try to get larger gain as bandwidth is reduced. So we are suggested to choose parameters widely.

Appendix:

Here we gave out some designs didn't meet all the design specifications before we got the final design. And we provide some solutions to fix them.

1. When we choose VB1 = 1.2V rather than final design VB1=1.19V.

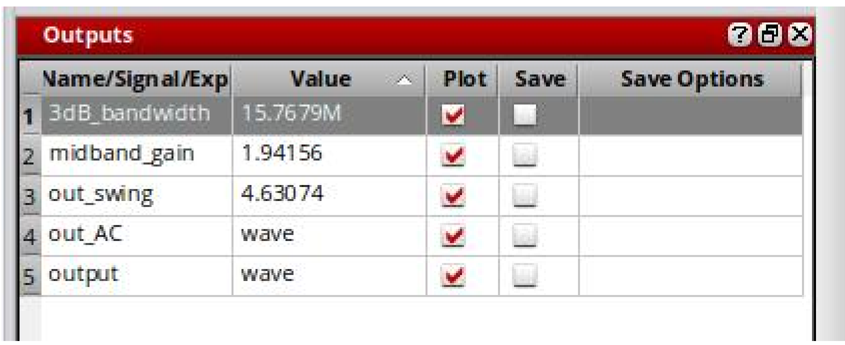


Outputs

	Name/Signal/Exp	Value	Plot	Save	Save Options
1	3dB_bandwidth	239.553K	✔		
2	midband_gain	143.29	✔		
3	out_swing	1.96281	✔		
4	out_AC	wave	✔		
5	output	wave	✔		

Output swing is too small.

2. At very beginning, we use explicit voltage bias to bias M2, only change the voltage 200mV lower, we got a very large output swing and everything in a mess. It is because one of transisters is in triode.



Outputs

	Name/Signal/Exp	Value	Plot	Save	Save Options
1	3dB_bandwidth	15.7679M	✔		
2	midband_gain	1.94156	✔		
3	out_swing	4.63074	✔		
4	out_AC	wave	✔		
5	output	wave	✔		

I tried to change the value of specs and calculated again. And I found that with same expected Id, using current mirror can solve this problem. It is because if we use a current mirror, whether a transistor in saturation or not is not depends on Vbias anymore, the current is set by Ibias.