EE 332 **Circuits and Devices II** **Autumn 2021**

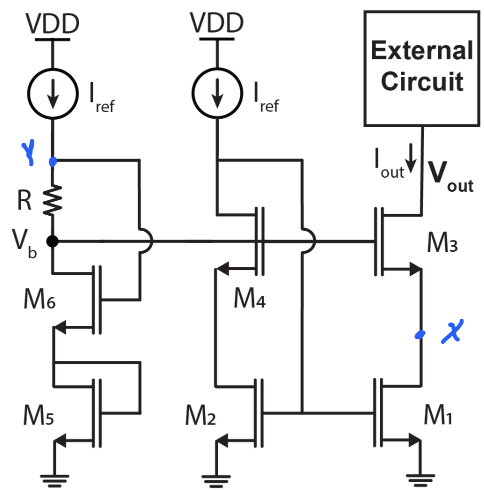
Final Exam **Date: Dec. 14 (8:30-10:20am)**

Full Name: .... **Grade:** ...... /100

SID : ....

Assume for all the problems: L=65nm, VDD=1.2V, $|V_{th_{n,p}}|$=0.3V, $\mu_n C_{ox} = \frac{0.5mA}{V^2}$, $\mu_n = 2\mu_p$, $\lambda_p = \lambda_n = 0.1V^{-1}$, $\gamma = 0$ for both NMOS and PMOS devices.

1. (~~20~~ 25 pts) For the current mirror shown below assume: $I_{Ref} = 100\mu A$ and ***all transistors have the V_{od} of 0.2V***.



a) What should be the ratio of $(W/L)_1/(W/L)_2$ to provide an I_{out} of 1mA?

Since $V_{gs_1} = V_{gs_2}$ & $V_{ds_1} = V_{ds_2}$:

$$\frac{(W/L)_1}{(W/L)_2} = \frac{I_{out}}{I_{ref}} = \frac{1mA}{1..\mu A} \boxed{= 1.}$$

b) What is the minimum V_{out} (as a function of V_b) and also V_b to make sure all devices remain in saturation? What would be minimum acceptable V_{out} for the optimal V_b values?

1 opts.

$$V_{out,Min} = V_b - V_{th} = \boxed{V_b - 0.3V}$$

$$V_{b,Min} = \underbrace{V_{x,Min}}_{=V_{od_1}} + V_{gs_3} = V_{od_1} + V_{od_3} + V_{th}$$

$$= 0.2 + 0.2 + 0.3 = \boxed{0.7V}$$

$$\Rightarrow \boxed{V_{out,Min} = 0.4V}$$

c) What should be the value of R to ensure V_b will be at the optimal value from part b?

$$V_b = \underbrace{V_Y}_{V_{GS_5}+V_{GS_6}} - R.I_{ref} = 2V_{od} + V_{th}$$

$$\Rightarrow 2\cancel{V_{od}} + 2V_{th} - RI_{ref} = 2\cancel{V_{od}} + V_{th}$$

$$\Rightarrow R = \frac{V_{th}}{I_{ref}} = \frac{0.3V}{0.1\,mA} = \boxed{3k\Omega}$$

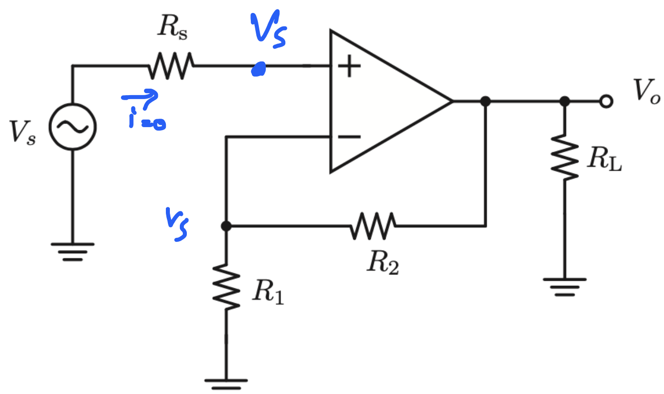
d) If there will be a fabrication error of 20% increase in the value of the resistor R, will the current mirror be still functional? Why?

if R %20 ⇒ V_b will be droped by $\underbrace{V_{th} \times \% 20}_{60mV}$

Since M_1 & M_2 were biased by V_b at the edge of triode/saturation, drop in V_b pushes M_1 & M_2 to go to triode & current mirror will not function properly any more.

2. (35 pts) An op-amp is configured to provide gain (V_O/V_S) of 5V/V to a $R_L = 1k\Omega$ load. Model the op-amp with the following parameters:

- $R_{in} = \infty$ (ideal)
- $R_{out} = 0$ (ideal)
- $A_0 = 100$ (not infinite)
- $f_0 = 10MHz$ (not ideal: finite 3dB-bandwidth frequency)



e) What should be the ratio of R_2/R_1 to achieve the target close-loop gain assuming amplifier has an infinite gain.

$$A_{cl} = 1 + \frac{R_2}{R_1} = 5 \Rightarrow \boxed{\frac{R_2}{R_1} = 4}$$

f) How does the closed-loop gain change if R_s or R_L changes?

A_{cl} will not be impacted by either R_s nor R_L.

g) What's the gain error due to the non-infinite gain of amplifier?

$$\beta = \frac{R_1}{R_1+R_2} = \frac{1}{5}$$

$$A_{cl} = \frac{A_o}{1+A_o\beta} \approx \frac{1}{\beta}\left(1 - \underbrace{\frac{1}{A_o\beta}}_{\text{gain error}}\right)$$

$$\Rightarrow \text{gain error} = \frac{1}{\frac{1}{5}\times 100} = \boxed{\frac{1}{20} = 5\%}$$

h) What's the approximate 3dB bandwidth? *Hint*: You do not need to derive this result but simply state it from what you know about feedback amplifiers.

GBW product will remain Constant.

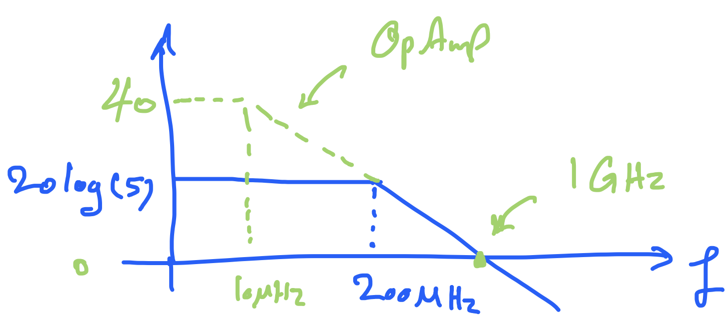
$\Rightarrow A_o \times f_o = A_{CL} \times f_{CL}$

$\Rightarrow f_{CL} = \dfrac{1\cancel{00}^{20} \times 10MHz}{\cancel{5}} = \boxed{200MHz}$

i) What's the unity-gain bandwidth for the closed-loop amplifier?

W_u remain the same as OpAmp Since GBW is Constant. $\Rightarrow f_u = A_o \times f_{3dB} = 100 \times 10MHz = \boxed{1GHz}$

j) Plot the magnitude Bode plot for closed-loop gain.

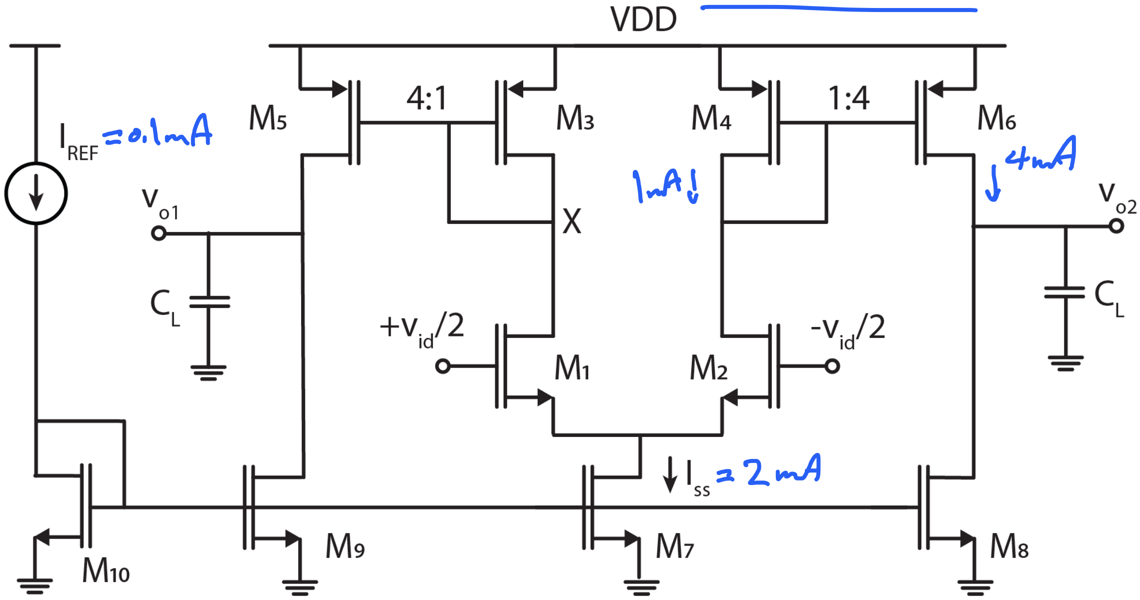


k) if R_{out} of OpAmp is non-zero with a value of 100Ω, calculate the output impedance assuming no loading effect R_1 & R_2.

$R_{out,CL} = R_{out} / (1 + \beta A_o)$

$= 100 / (1 + \underbrace{\tfrac{1}{5} \times 100}_{20}) \approx \boxed{5\Omega}$

3. (4~~5~~0 pts) For the fully differential amplifier shown below **all transistors** have the nominal channel length of **65nm** and should be biased such that $\mathbf{V_{od}\ (V_{GS}\text{-}V_{th}) = 0.2V}$:



$C_L = \cancel{100fF}\ 1pF,\ I_{Ref} = 100\mu A$

a) For I_{ss} to be 2mA, Find W for $M_{7\text{-}10}$ transistors.

$M_{10}: \ 100\mu A = \frac{1}{2} \times \frac{500\,\mu A}{V^2} \times \left(\frac{W}{L}\right)_{10} \times (0.2)^2 \Rightarrow \left(\frac{W}{L}\right)_{10} = 10 \Rightarrow \boxed{W_{10} = 650nm}$

$M_7: \ W_7 = W_{10} \times \frac{2}{0.1} = W_{10} \times 20 = \boxed{13\,\mu m}$

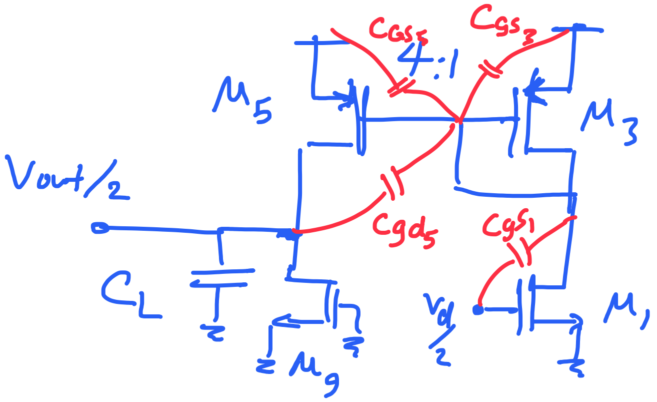
$M_{8,9}: \ W_8 = W_9 = 2 \times W_7 = \boxed{26\,\mu m}$

b) Find W for $M_{3\text{-}\cancel{4}6}$ transistors.

$M_{3,4}: \ 1mA = \frac{1}{2} \times \frac{250\,\mu A}{V^2} \times \overset{200}{\left(\frac{W}{L}\right)} \times 0.2^2 \Rightarrow \boxed{W_{3,4} = 13\mu m}$

$M_{5,6}: \ W_{5,6} = 4 \times W_{3,4} = \boxed{52\,\mu m}$

c) Draw the half-circuit model for differential mode.



d) Find the small-signal differential gain (V_{out}/V_{id}), where $V_{out}=V_{o1}-V_{o2}$.

$$A_v = g_{m_1} \times 4 \times (r_{o_5} \| r_{o_9})$$

$$= \frac{2I_1}{V_{od}} \times 4 \times \left(\frac{1}{\lambda I_5} \| \frac{1}{\lambda I_9} \right)$$

$$= \frac{2\cancel{mA}}{0.2} \times \cancel{4} \times \frac{1}{2} \times \frac{1}{0.1 \times \cancel{4mA}} = \boxed{50}$$

e) What's the output differential peak-to-peak output swing?

$$v_{sw,pp} = 2 \times \underbrace{v_{sw,pp,\,single\text{-}ended}}_{V_{DD}-V_{od_5}-V_{od_9} = 1.2-0.4=0.8V} = \boxed{1.6V}$$

f) Estimate output node pole (ω_{out}) location (ignore all other parasitics)

$$\omega_{out} = \frac{1}{\underbrace{R_{out}}_{\frac{1}{2} \times \frac{1}{0.1 \times 4mA} = 1.25k\Omega} \times C_L} = \frac{\cancel{1}\,0.8\,G}{1.25\,k\Omega \times 1\,pF}$$

$$\Rightarrow \boxed{\omega_{out} = 800\ Mrad/s}$$

g) If M~~1~~3-6 have $C_{GS} = C_{GD} = 1fF/\mu m$ (per μm unit width), estimate the mirro pole location at node X (ω_X) using the Miller approximation and node-pole associations method. (ignore all other parasitic capacitances)

$$R_X \simeq 1/g_{m_3} = \frac{V_{od}}{2I_3} = \frac{0.2V}{2\times 1mA} = \underline{100\Omega} \qquad \underbrace{\frac{V_{out}}{V_X}}_{A}$$

$$\frac{2I}{V_{od}} = \frac{2\times 4mA}{0.2} = 40mS$$

$$C_X \simeq C_{GS_3} + C_{GS_5} + C_{GD_5}\times(1+A)$$

$$= 1\frac{fF}{\mu m}(13\mu m + 52\mu m) + 1\frac{fF}{\mu m}\times 52\mu m \times (1+g_{m_5}\times R_{out})$$

$$= 65fF + 52fF\times(1+\overset{50}{\cancel{40\times 1.25}}) = 2.5pF$$

$$\omega_X = \frac{1}{R_X C_X} = \frac{1 \quad \cdots G}{0.1\cancel{k}\Omega \times 2.5\cancel{f}F} = \boxed{4\ Grad/s}$$

h) Assuming that first pole is dominant in this amplifier, what is the unity-gain bandwidth (ω_u)?

Since $W_{out} \ll W_X$, dominant pole will be W_{out}

$$\Rightarrow W_u = A_d \times W_{out} = 50 \times 800\ Mrad/s$$

$$\Rightarrow \boxed{W_u = 40\ Grad/s}$$