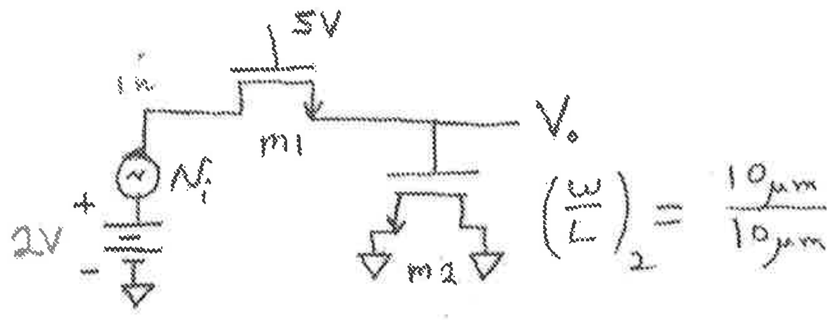
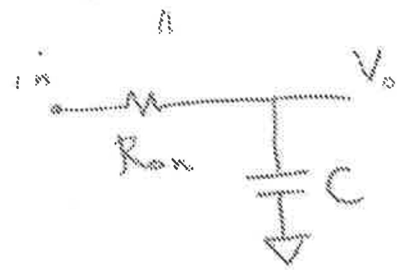
212 Midterm Solution Winter 2021

5 pt

1. A first-order RC filter that uses only MOS transistors is shown below. Assume that the AC input signal is small compared to the DC input bias voltage. What W/L ratio is needed for M1 to give a -3 dB frequency of 10 MHz? Ignore all junction and overlap capacitances.





$$C = C_{gs}(m2) = C_{ox} \cdot W \cdot L = 3.5\ fF/\mu m^2 \times 10\mu m \times 10\mu m$$
$$= 350\ fF$$

m1 triode:

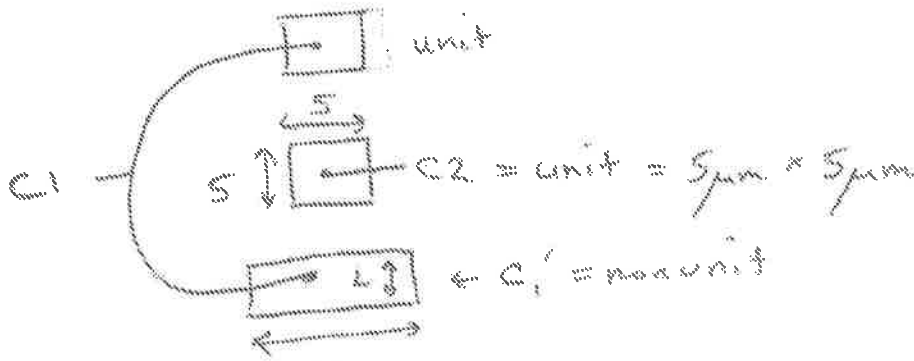
$$R_{on} = \frac{1}{\mu C_{ox} \frac{W}{L}(V_{GS}-V_T)} = \frac{1}{180\frac{\mu A}{V^2}\left(\frac{W}{L}\right)\left[5-2-1\right]V}$$
$$= \frac{2778\Omega}{\frac{W}{L}}$$

want $\frac{1}{2\pi R_{on} C} = 10\,MHz \Rightarrow R_{on} = 45.5\,k\Omega$

$$\Rightarrow \frac{W}{L} = 0.061$$

6

2. Two capacitors C1 and C2 are needed with a very accurately defined ratio of C1/C2 = 2.6, with the constraint that the maximum area that can be used for C2 is 25 $(\mu m)^2$. Draw a top view of the layout of the two capacitors. Show the dimensions of the capacitors on your drawing.



C_2 = biggest unit cap possible = $5\mu m \times 5\mu m$

C_1 = 1 unit + 1 non unit

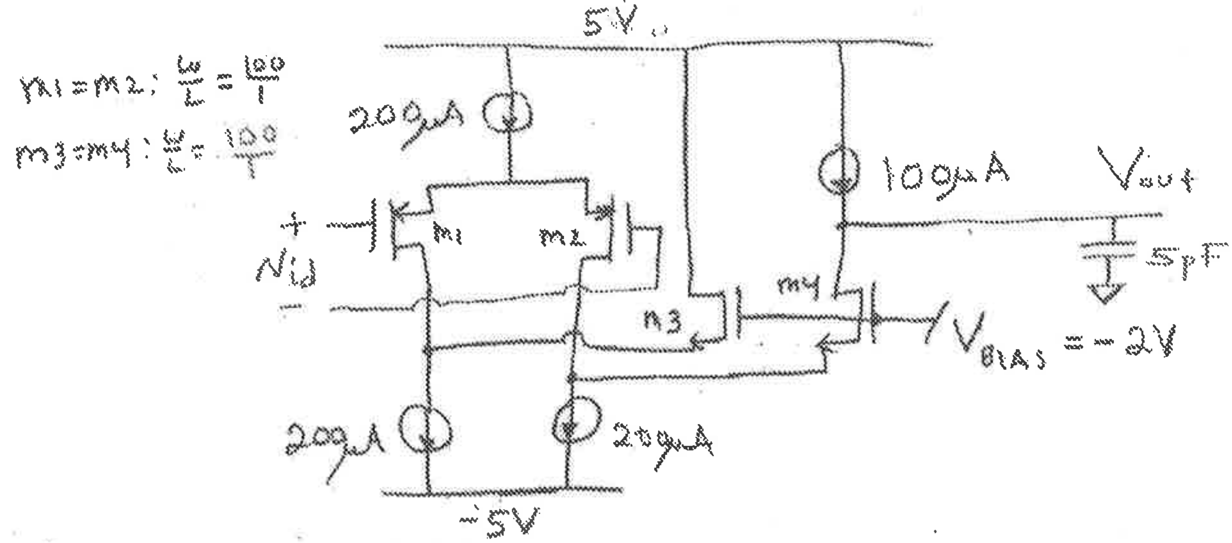
C_1' = nonunit ; area = $WL = 1.6(25\mu m^2) = 40\mu m^2 = W \cdot L$

& $\frac{per}{area}(C_1') = \frac{per}{area}(\text{unit}) = \frac{20\mu m}{25\mu m^2} \Rightarrow W + L = \frac{20}{25}(40)\cdot\frac{1}{2} = 16\mu m$

$W + L = W + \frac{40}{W} = 16 \Rightarrow W = 12.9\mu m$

$\frac{40}{W} = 3.1\mu m$

3. For the op amp shown below, assume DC biasing places the transistors in the saturation region. (NOTE: This op amp is slightly different than the standard folded-cascode op amp.)



5 a) What is the low-frequency gain? V_{out}/V_{id} = ________

$$a_v = \tfrac{1}{2} g_{m_2} R_{out} = \tfrac{1}{2}(1100\ \tfrac{\mu A}{V})(950\ M\Omega) = \underline{522k}$$

$$g_{m_2} \cong \sqrt{2(60\ \tfrac{\mu A}{V^2})(100)(100\mu A)} = 1100\ \tfrac{\mu A}{V}$$

$$R_{out} \cong r_{o4}(1 + g_{m4} r_{o2}) = 500k\left[1 + (1900\ \tfrac{\mu A}{V})\ 1M\Omega\right] = 950\ M\Omega$$

$$r_{o4} = \frac{1}{0.02\ \tfrac{1}{V} \cdot 100\mu A} = 500k\ \Omega$$

$$g_{m4} = \sqrt{2(180\ \tfrac{\mu A}{V^2})(100)(100\mu A)} = 1900\ \tfrac{\mu A}{V}$$

$$r_{o2} = \frac{1}{(0.01\ \tfrac{1}{V})(100\mu A)} = 1M\Omega$$

3 b) What is the positive output slew rate? SR^+ = ________

$$\frac{dV_o^+}{dt} = \frac{100\mu A}{5pF} = \underline{20 \times 10^6\ \tfrac{V}{s}}$$

(3) c) What is the dominant pole for this op amp? p_1 = ____________

$$p_1 \approx \frac{-1}{R_{out} C_L} = \frac{-1}{(950 M\Omega)(5 pF)} = -210 \frac{rad}{s}$$

(3) d) Estimate the frequency at which the magnitude of the voltage gain falls to one. Ignore the nondominant poles for this calculation. (This is the GBW.) f_u = 17.5 MHz

$$a_{v_0} \cdot |p_1| = 1 \cdot \omega_u$$

$$(522k)(210 \tfrac{r}{s}) = \omega_u = 110 M \tfrac{rad}{s}$$

$$\omega_u = 2\pi f_u$$

(3) e) Estimate the negative output swing limit.

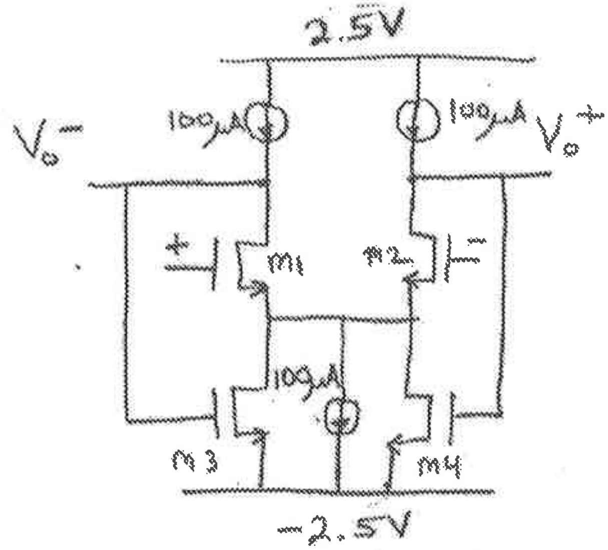
Negative output swing limit = ____________

can swing down until m4 goes triode

(when $V_{GD}(m4) = V_T = 1V$)

$$\hat{V}_o^- = -2V - V_{GD}(m4) = -2V - 1V = \underline{-3V}$$

4. A fully differential one-stage op amp with common-mode feedback is shown. The common-mode feedback is provided by M3 and M4. Assume all transistors are saturated, and assume M1 = M2, M3 = M4.



M1=M2: $\frac{W}{L} = 100$

M3=M4

(4) a) What should W/L be for M3 and M4 so that the the common-mode output voltage is 0V ?

W/L = ____________

want $I_{D_3} = I_{D_4} = 50\mu A = \frac{1}{2}\left(180\frac{\mu A}{V^2}\right)\frac{W}{L}\big(\underbrace{0-(-2.5V)}_{V_{GS}}-1V\big)^2$

$\frac{W}{L} = 0.25$

(4) b) What is the differential-mode (DM) voltage gain?

v_{od}/v_{id} = ____________

$a_v = g_{m_1} r_{o_1} = \sqrt{2\left(180\frac{\mu A}{V^2}\right)(100)(100\mu A)} \times \frac{1}{0.02V^{-1} \cdot 100\mu A}$

$= 950$

(4) c) For this op amp, estimate the lower limit of the common-mode input voltage.

Lower CM input limit = ______________

limit when M3 goes triode:

$$\min V_{in}^{-}(cm) = -2.5V + V_{DSAT}(M3) + V_{GS}(M1)$$

$$= -2.5V + \sqrt{\frac{2 I_{D3}}{\mu C_{ox_n} \frac{W}{L}_3}} + \left(V_{T_N} + \sqrt{\frac{2 I_{D1}}{\mu C_{ox_n} \frac{W}{L}_1}}\right)$$

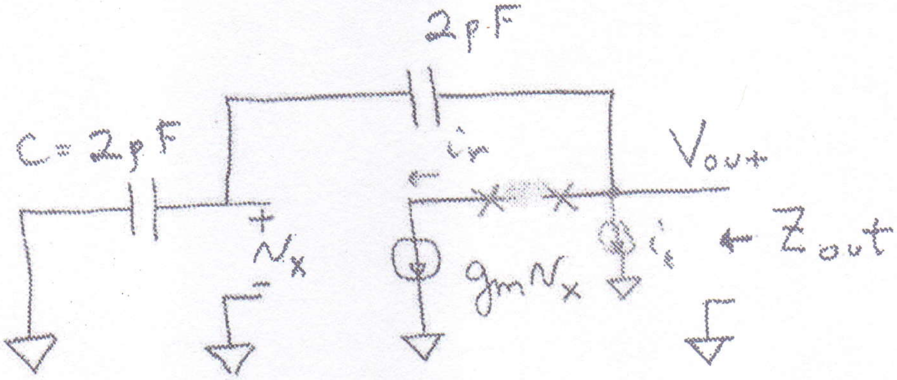
$$= -2.5V + 1.49V + (1V + 0.11)V$$

$$= \underline{\underline{0.1V}}$$

(4)

5. a) Find the frequency at which the magnitude of the return ratio equals 1 for the circuit below.

ω_u' = Frequency where |RR| = 1 : g_m/C ; $C = 2pF$



$$\left.\begin{aligned} v_x &= -\frac{1}{j\omega C} i_t \\ i_r &= g_m v_x \end{aligned}\right\} \quad i_r = -\frac{g_m}{j\omega C} i_t$$

$$RR = -\frac{i_r}{i_t} = \frac{g_m}{j\omega C}$$

$$|RR| = 1 = \frac{g_m}{\omega C}$$

$$\omega = \frac{g_m}{C}$$

$$C = 2pF$$

(4)

5 (continued)

b) Use Blackman's impedance formula to compute the magnitude of the output impedance at the frequency computed in part (a).

$|Z_{out}| = \dfrac{\sqrt{2}}{g_m}$

$w/\ g_m = 0: \quad Z_{out} \leftrightarrow 1pF = (2pF \| 2pF)$

$RR(\text{out shorted}) = 0$

$RR(\text{out open}) = \dfrac{g_m}{j\omega C} = \dfrac{1}{j} = -j \quad @\omega_u'$

$$Z_{out}(\omega_u') = \frac{\frac{1}{j\omega_u'(1pF)}(1+0)}{1-j}$$

$$|Z_{out}(\omega_u')| = \frac{1}{\omega_u'(1pF)}\left|\frac{1}{1-j}\right|$$

$$= \frac{1}{\frac{g_m}{C}(1pF)} \cdot \frac{1}{\sqrt{2}} =$$

$$= \frac{2}{g_m} \cdot \frac{1}{\sqrt{2}} = \frac{\sqrt{2}}{g_m}$$

$C = 2pF$