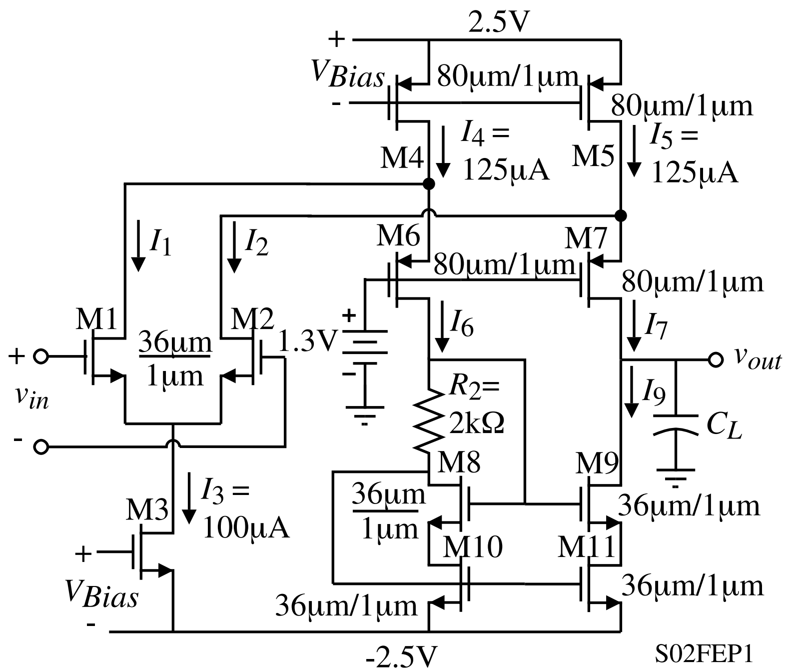
FINAL EXAMINATION - SOLUTIONS

(Average = 100, High = 120, and Low = 69)

Problem 1 - (20 points - This problem is required)

If the folded-cascode op amp shown having a small-signal voltage gain of 7464V/V is used as a comparator, find the dominant pole if C_L = 5pF. If the input step is 10mV, determine whether the response is linear or slewing and find the propagation delay time. Assume the parameters of the NMOS transistors are K_N'=110V/µA^2, V_{TN} = 0.7V, λ_N=0.04V^{-1} and for the PMOS transistors are K_P'=110V/µA^2, V_{TP} = -0.7V, λ_P=0.05V^{-1}.



Solution

V_{OH} and V_{OL} can be found from many approaches. The easiest is simply to assume that V_{OH} and V_{OL} are 2.5V and –2.5V, respectively. However, no matter what the input, the values of V_{OH} and V_{OL} will be in the following range,

$$(V_{DD}\text{-}2V_{ON}) < V_{OH} < V_{DD} \quad \text{and} \quad V_{DD} < V_{OH} < (V_{SS}+2V_{ON})$$

The reasoning is as follows, suppose V_{in} >0. This gives $I_1 > I_2$ which gives $I_6 < I_7$ which gives $I_9 < I_7$. V_{out} will increase until I_7 equals I_9. The only way this can happen is for M5 and M7 to leave saturation. The same reasoning holds for V_{in} <0.

Therefore assuming that V_{OH} and V_{OL} are 2.5V and –2.5V, respectively, we get

$$V_{in}(\min) = \frac{5\text{V}}{7464} = 0.67\text{mV} \quad \rightarrow \quad k = \frac{10\text{mV}}{0.67\text{mV}} = 14.93$$

Problem 1 – Continued

The folded-cascode op amp as a comparator can be modeled by a single dominant pole. This pole is found as,

$$p_1 = \frac{1}{R_{out}C_L} \text{ where } R_{out} \approx g_{m9}r_{ds9}r_{ds11}||[g_{m7}r_{ds7}(r_{ds2}||r_{ds5})]$$

$g_{m9}=\sqrt{2\cdot 75\cdot 110\cdot 36}=771\mu S$, $g_{ds9}=g_{ds11}=75\text{x}10^{-6}\cdot 0.04 = 3\mu S$, $g_{ds2}=50\text{x}10^{-6}(0.04)=2\mu S$

$g_{m7}=\sqrt{2\cdot 75\cdot 50\cdot 80}=775\mu S$, $g_{ds5}=125\text{x}10^{-6}\cdot 0.05 = 6.25\mu S$, $g_{ds7}=50\text{x}10^{-6}(0.05)=3.75\mu S$

$$g_{m9}r_{ds9}r_{ds11}= (771\mu S)\left(\frac{1}{3\mu S}\right)\left(\frac{1}{3\mu S}\right) = 85.67M\Omega$$

$$g_{m7}r_{ds7}(r_{ds2}||r_{ds5} \approx (775\mu S)\left(\frac{1}{3.75\mu S}\right)\left(\frac{1}{2\mu S}||\frac{1}{6.25\mu S}\right) = 25.05M\Omega\ ,$$

$$R_{out} \approx 85.67M\Omega||25.05M\Omega = 19.4M\Omega$$

The dominant pole is found as, $p_1 = \frac{1}{R_{out}C_L} = \frac{1}{19.4\text{x}10^6 5\text{pF}} = 10{,}318 \text{ rps}$

The time constant is $\tau_1 = 96.9\mu s$.

For a dominant pole system, the step response is, $v_{out}(t) = A_{vd}(1-e^{-t/\tau_1})V_{in}$

The slope is the largest at $t = 0$. Evaluating this slope gives,

$$\frac{dv_{out}}{dt} = \frac{A_{vd}}{\tau_1}e^{-t/\tau_1}V_{in} \quad \text{For } t = 0\text{, the slope is } \frac{A_{vd}}{\tau_1}V_{in} = \frac{7464}{96.9\mu s}(10mV) = 0.77V/\mu s$$

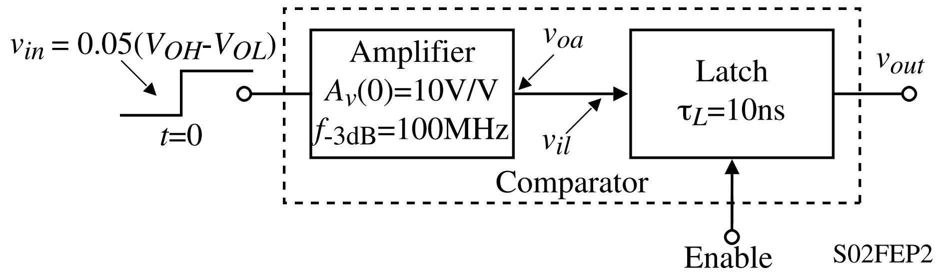
The slew rate of this op amp/comparator is $SR = \frac{I_3}{C_L} = \frac{100\mu A}{5pF} = 20V/\mu s$

Therefore, the comparator does not slew and its propagation delay time is found from the linear response as,

$$t_P = \tau_1\ln\left(\frac{2k}{2k-1}\right) = 96.9\mu s\cdot\ln\left(\frac{2\cdot 14.93}{2\cdot 14.93-1}\right) =(96.9\mu s)(0.0341) = \underline{\underline{3.3\mu s}}$$

Problem 2 - (20 points - This problem is required)

A comparator consists of an amplifier cascaded with a latch as shown below. The amplifier has voltage gain of 10V/V and $-f_{-3dB}$ = 100MHz and the latch has a time constant of 10ns. The maximum and minimum voltage swings of the amplifier and latch are V_{OH} and V_{OL}. When should the latch be enabled after the application of a step input to the amplifier of $0.05(V_{OH}-V_{OL})$ to get minimum overall propagation time delay? What is the value of the minimum propagation time delay? It may useful to recall that the propagation time delay of the latch is given as $t_p = \tau_L \ln\left(\frac{V_{OH}-V_{OL}}{2v_{il}}\right)$ where v_{il} is the latch input (ΔV_i of the text).



Solution

The solution is based on the figure shown.
We note that,

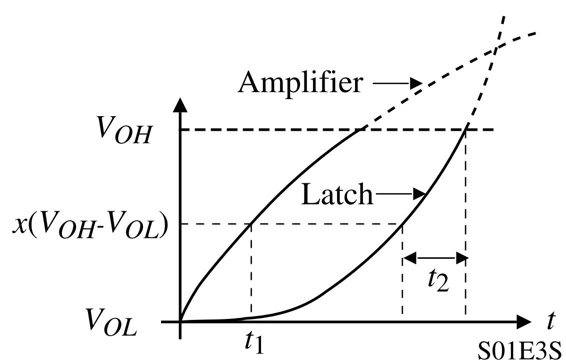
$$v_{oa}(t) = 10[1-e^{-\omega_{-3dB}t}]0.05(V_{OH}-V_{OL}).$$

If we define the input voltage to the latch as,

$$v_{il} = x\cdot(V_{OH}-V_{OL})$$

then we can solve for t_1 and t_2 as follows:

$$x\cdot(V_{OH}-V_{OL}) = 10[1-e^{-\omega_{-3dB}t_1}]0.05(V_{OH}-V_{OL}) \rightarrow x = 0.5[1-e^{-\omega_{-3dB}t_1}]$$



This gives,

$$t_1 = \frac{1}{\omega_{-3dB}} \ln\left(\frac{1}{1-2x}\right)$$

From the propagation time delay of the latch we get,

$$t_2 = \tau_L \ln\left(\frac{V_{OH}-V_{OL}}{2v_{il}}\right) = \tau_L \ln\left(\frac{1}{2x}\right)$$

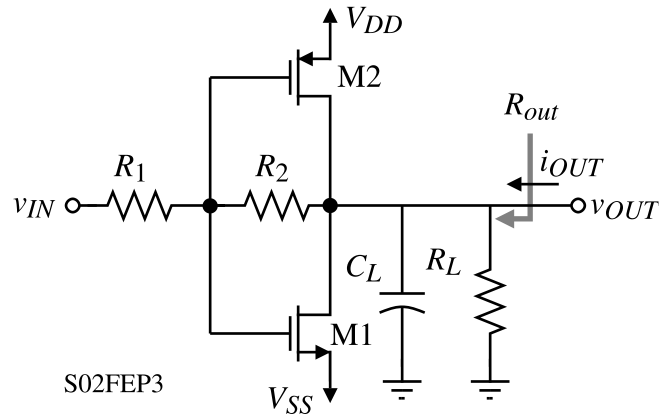
$$\therefore \quad t_p = t_1 + t_2 = \frac{1}{\omega_{-3dB}} \ln\left(\frac{1}{1-2x}\right) + \tau_L \ln\left(\frac{1}{2x}\right) \rightarrow \frac{dt_p}{dx} = 0 \text{ gives } x = \frac{\pi}{1+2\pi} = 0.4313$$

$$t_1 = \frac{10\text{ns}}{2\pi} \ln(1+2\pi) = 1.592\text{ns}\cdot 1.9856 = \underline{\underline{3.16\text{ns}}} \text{ and } t_2 = 10\text{ns} \ln\left(\frac{1+2\pi}{2\pi}\right) = 1.477\text{ns}$$

$$\therefore \quad t_p = t_1 + t_2 = 3.16\text{ns} + 1.477\text{ns} = \underline{\underline{4.637\text{ns}}}$$

Problem 3 - (20 points - This problem is optional)

If $R_1 = R_2$ of the circuit shown, find an expression for the small-signal output resistance R_{out} ignoring R_L. Repeat including the influence of R_L on the output resistance. Let R_1=R_2 and R_L = 1kΩ, dc currents through M1 and M2 be 500µA, W_1/L_1 = 100µm/1µm and W_2/L_2 = 200µm/1µm. Find the value of R_{out}.



Solution

The loop-gain for this network can be written from inspection as,

$$LG = \left(\frac{R_1}{R_1+R_1}\right)\left(\frac{g_{m1}+g_{m2}}{g_{ds1}+g_{ds2}+G_L}\right)$$

Therefore, since the output is shunt feedback we can solve for output resistance as,

$$R_{out} = \frac{r_{ds1}||r_{ds2}||R_L}{1+\left(\frac{R_1}{R_1+R_1}\right)\left(\frac{g_{m1}+g_{m2}}{g_{ds1}+g_{ds2}+G_L}\right)}$$

Setting $G_L = 0$ ($R_L = \infty$) gives the output resistance not including the load resistor, R_L, as

$$R_{out} = \frac{r_{ds1}||r_{ds2}}{1+\left(\frac{R_1}{R_1+R_1}\right)\left(\frac{g_{m1}+g_{m2}}{g_{ds1}+g_{ds2}}\right)}$$

Calculating the small-signal parameters gives,

$$g_{m1} = \sqrt{2\cdot 110\cdot 500\cdot 100} = 3.316\text{mS},\ g_{m2} = \sqrt{2\cdot 50\cdot 500\cdot 200} = 3.162\text{mS},$$

$$r_{ds1} = \frac{10^6}{0.04\cdot 500} = 50\text{k}\Omega \text{ and } r_{ds2} = \frac{10^6}{0.05\cdot 500} = 40\text{k}\Omega$$

$$\therefore \quad R_{out}(R_L=\infty) = \frac{50\text{k}\Omega||40\text{k}\Omega}{1 + 0.5\left(\frac{3316+3162}{25+20}\right)} = \frac{22.22\text{k}\Omega}{72.98} = 304\Omega$$

$$R_{out}(R_L=1\text{k}\Omega) = \frac{50\text{k}\Omega||40\text{k}\Omega||1\text{k}\Omega}{1 + 0.5\left(\frac{3316+3162}{25+20+1000}\right)} = \frac{957\Omega}{4.0995} = \underline{\underline{233\Omega}}$$

As usual, straight-forward small-signal models are faster, summing the currents at the output,

$$I_{out} = V_{out}\left[\frac{1}{r_{ds1}} + \frac{1}{r_{ds2}} + \frac{1}{R_1+R_2} + \frac{g_{m1}+g_{m2}}{2} + \frac{1}{R_L}\right] \approx V_{out}\left[\frac{1}{r_{ds1}} + \frac{1}{r_{ds2}} + \frac{g_{m1}+g_{m2}}{2} + \frac{1}{R_L}\right]$$

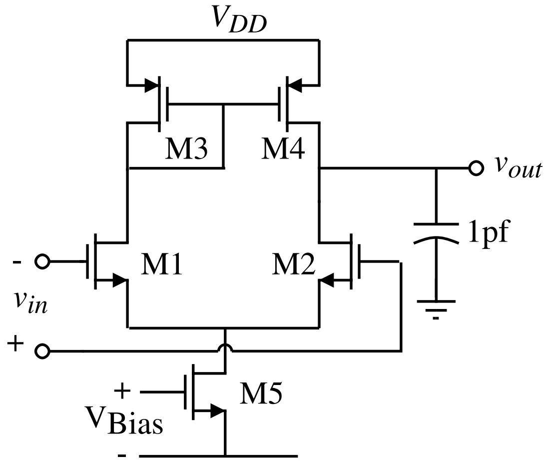
$$\therefore \quad R_{out} = \left[\frac{1}{r_{ds1}} + \frac{1}{r_{ds2}} + \frac{g_{m1}+g_{m2}}{2} + \frac{1}{R_L}\right]^{-1} = 304\Omega\ (R_L=\infty)$$

$$R_{out} = \underline{\underline{233\Omega}}\ (R_L=1\text{k}\Omega)$$

(Principle: Feedback is a great concept tool but a terrible analysis tool.)

Problem 4 - (20 points - This problem is optional)

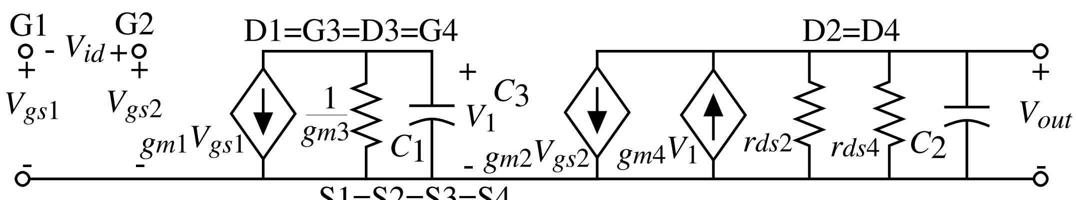
A current mirror load, CMOS differential amplifier is shown. The current in M5 is 100μA. Assume the parameters of the NMOS transistors are K_N' =110V/μA^2, V_{TN} = 0.7V, λ_N =0.04V^{-1} and for the PMOS transistors are K_P' =110V/μA^2, V_{TP} = 0.7V, λ_P =0.04V^{-1}. (a.) Find the small-signal output resistance and voltage gain if the W/L ratio of M1 and M2 is 100μm/1μm. (b.) If the W/L ratio of M3 and M4 is 50μm/1μm and C_{ox} = 24.7x10^{-4}F/m^2, and the effective output capacitance is 1pF, find all roots of this amplifier (ignore the influence of C_{gd4}). (c.) What is the –3dB frequency in Hertz?



SO2FEP3

Solution

The small-signal model suitable for this problem is shown below.



S02FES4

C_1 = 2(0.667)(50x10^{-12}m^2)(24.7x10^{-4}F/m^2) = 0.1647pF $\quad g_{m3} = \sqrt{2\cdot 50\cdot 50\cdot 50}$ = 500μS

$$V_{out} = (g_{m4}V_1 - g_{m2}V_{gs2})Z_{out} = \left(\frac{g_{m4}g_{m1}V_{gs1}}{g_{m3} + sC_1} - g_{m2}V_{gs2}\right)Z_{out}$$

$$= \left[\left(\frac{1}{s\frac{C_1}{g_{m3}} + 1}\right)\left(\frac{-g_{m1}V_{in}}{2}\right) - \frac{g_{m2}V_{in}}{2}\right]\left(\frac{1}{sC_L+g_{ds2}+g_{ds4}}\right)$$

$$= -g_{md}\left(\frac{s\frac{C_1}{g_{m3}} + 2}{s\frac{C_1}{g_{m3}} + 1}\right)\left(\frac{1}{sC_2+g_{ds2}+g_{ds4}}\right)\frac{V_{in}}{2} = -g_{md}\left(\frac{s\frac{C_1}{2g_{m3}} + 1}{s\frac{C_1}{g_{m3}} + 1}\right)\left(\frac{1}{sC_2+g_{ds2}+g_{ds4}}\right)V_{in}$$

The small-signal ourput resistance and voltage gain is,

$$R_{out} = \frac{1}{g_{ds2}+g_{ds4}} = \frac{10^6}{50\ (0.05+0.04)} = \underline{\underline{222\text{k}\Omega}} \qquad A_{vd} = -g_{m1}R_{out}$$

$$g_{m1} = g_{m1} = \sqrt{2\cdot 110\cdot 100\cdot 50} = 1.049\text{mS} \Rightarrow A_{vd} = -g_{m1}R_{out} = (1.049)(222) = \underline{\underline{-233\text{V/V}}}$$

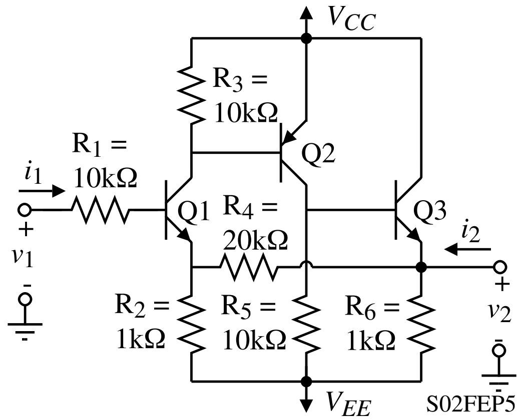
The roots of this circuit are,

$$p_1 = -\frac{g_{m3}}{C_1} = -\frac{500\mu\text{S}}{0.1647\text{pF}} = \underline{\underline{-3.036\text{x}10^9\text{rps}}},\ z_1 = 2p_1 = \underline{\underline{-6.072\text{x}10^9\text{rps}}},$$

and $p_2 = -\dfrac{g_{ds2}+g_{ds4}}{C_2} = -\dfrac{1}{222\text{k}\Omega\cdot 1\text{pF}} = \underline{\underline{-4.504\text{x}10^6\text{ rps}}} \Rightarrow f_{-3\text{dB}} = \dfrac{4.504\text{x}10^6}{2\pi} = \underline{\underline{717\text{kHz}}}$

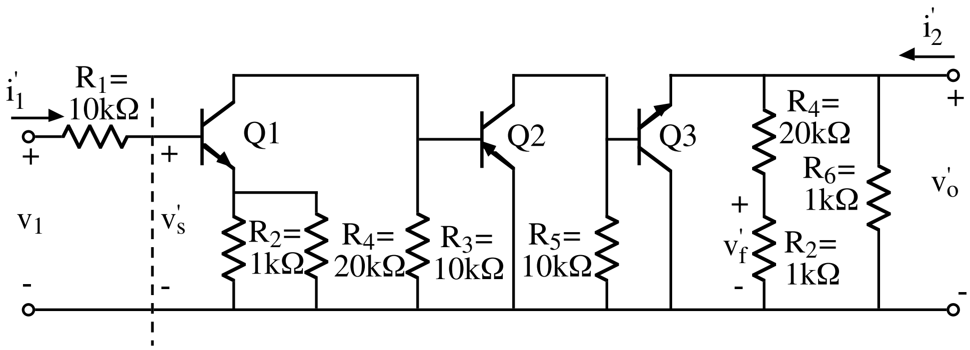
Problem 5 - (20 points - This problem is optional)

The simplified schematic of a feedback amplifier is shown. Use the method of feedback analysis to find v_2/v_1, $R_{in} = v_1/i_1$, and $R_{out} = v_2/i_2$. Assume that all transistors are matched and that $\beta = 100$, $r_\pi = 5k\Omega$ and $r_o = \infty$.

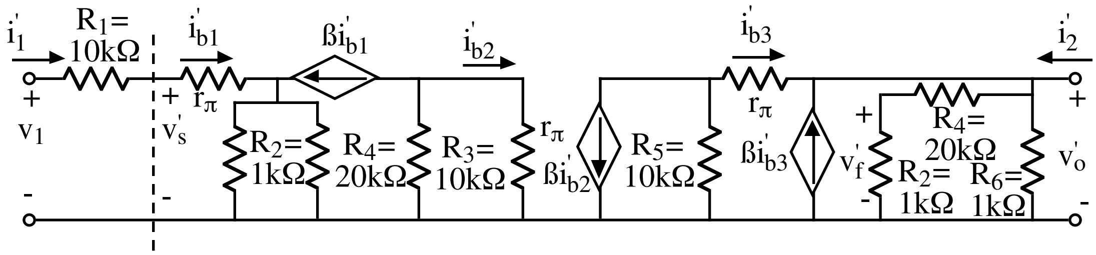


Solution

Open-loop, quasi-ac model:



Small-signal, open-loop model:



$$R_i = \frac{v_s'}{i_{b1}'} = r_\pi + (1+\beta)(R_2||R_4) = 5k\Omega + (101)(1k\Omega||20k\Omega) = 101.19k\Omega$$

$$a = \frac{v_o'}{v_s'} = \left(\frac{v_o'}{i_{b3}'}\right)\left(\frac{i_{b3}'}{i_{b2}'}\right)\left(\frac{i_{b2}'}{i_{b1}'}\right)\left(\frac{i_{b1}'}{v_s'}\right)$$

$$= (1+\beta)[R_6||(R_2+R_4)]\left(\frac{-\beta R_5}{R_5+r_\pi+(1+\beta)[R_6||(R_2+R_4)]}\right)\left(\frac{-\beta R_3}{R_3+r_\pi}\right)\left(\frac{1}{R_i}\right)$$

$$= [(101)(954.55)](-8.976)(-66.67)(1/101.19k\Omega) = 570.16 \text{ V/V}$$

$$f = \frac{R_2}{R_2+R_4} = \frac{1}{21} = 0.0476 \quad \text{and } R_o = \frac{v_o'}{i_2'} = R_6||(R_2+R_4)||\left(\frac{r_\pi+R_5}{1+\beta}\right) = 128.5\Omega$$

Closed-loop quantities are:

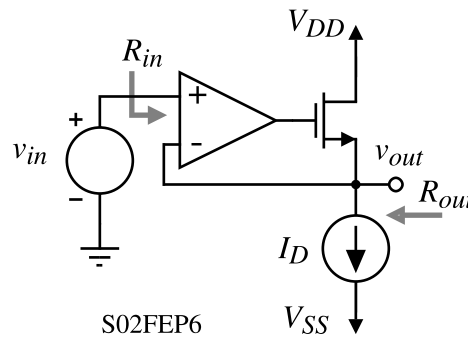
$$A_{vf} = \frac{v_o}{v_s} = \frac{a}{1+af} = \frac{570.16}{1+27.15} = 20.25, \; R_{if} = (1+af)R_i = 2.848M\Omega$$

$$\therefore \quad \boxed{R_{out} = R_{of} = \frac{R_o}{1+A_v\beta_f} = \frac{128.5\Omega}{28.15} = 4.565\Omega}$$

$$\boxed{R_{in} = R_1+R_{if} = 2.858M\Omega} \quad \text{and} \quad \boxed{\frac{v_2}{v_1} = A_{vf}\frac{R_{if}}{R_1+R_{if}} = 20.18 \text{ V/V}}$$

Problem 6 - (20 points - This problem is optional)

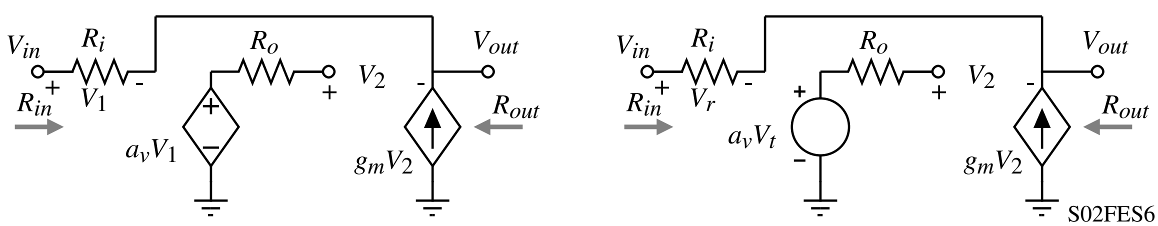
A voltage follower feedback circuit is shown. For the MOS transistor, I_D = 0.5mA, K' = 180μA/V^2, $r_{ds} = \infty$, and W/L = 100. Although, the bulk effect, g_{mbs}, should be considered, for simplicity ignore the bulk effects in this problem. For the op amp, assume that R_i = 1MΩ, R_o = 10kΩ, and a_v = 1000. Calculate the input resistance and output resistance using Blackman's formula given below.



$$R_{out} = R_{out}\text{ (Controlled Source Gain=0)}\left[\frac{1 + RR(\text{output port shorted})}{1 + RR(\text{output port open})}\right]$$

Solution

Circuit for calculating the return ratios.



Input Port:

$R_{in}(a_v{=}0) = R_i + (1/g_m)$, $\quad g_m = \sqrt{2\cdot 500\cdot 100\cdot 180} = 4.243\text{mS}$

$R_{in}(a_v{=}0) = 1\text{M}\Omega + 236\Omega \approx 1\text{M}\Omega$

RR(input port shorted):

$$V_r = -g_mR_i\,V_2 \text{ and } V_2 = a_vV_t - g_mR_i\,V_2 \quad\rightarrow V_r = \frac{-a_v\,g_mR_i}{1+g_mR_i}V_t$$

$$RR(\text{input port shorted}) = -\frac{V_r}{V_t} = \frac{-a_v\,g_mR_i}{1+g_mR_i} = -\frac{1000\cdot 4.243\text{mS}\cdot 1\text{M}\Omega}{1+4.243\text{mS}\cdot 1\text{M}\Omega} = -999.8$$

RR(input port open):

RR(input port open) = 0 because $V_r = 0$

$$\therefore \quad R_{in} = R_{in}\,(a_v{=}0)\left[\frac{1 + RR(\text{output port shorted})}{1 + RR(\text{output port open})}\right] = 1\text{M}\Omega(1+999.8) = \underline{\underline{1000.8\text{M}\Omega}}$$

Output Port:

$R_{out}(a_v{=}0) = R_i\,||(1/g_m) \approx 236\Omega$

RR(output port shorted):

RR(output port shorted) = 0 because $V_r = 0$

RR(output port open):

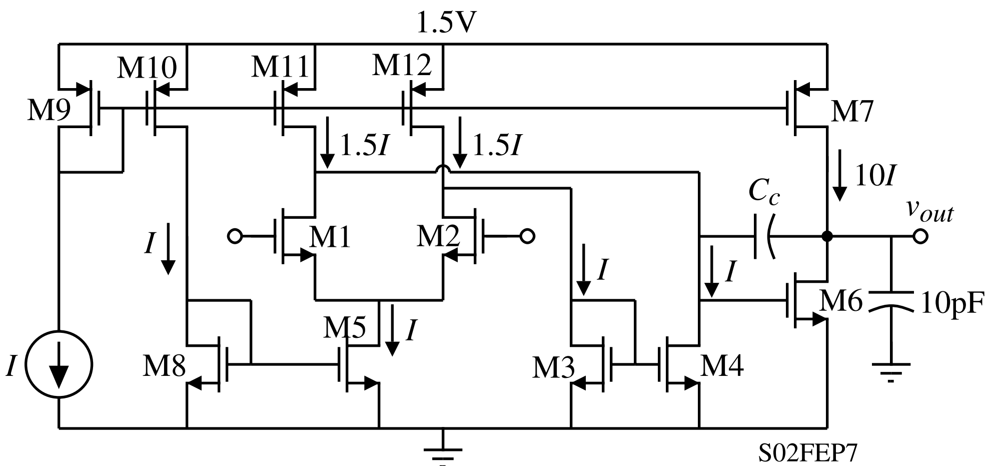
Same as the RR for the input port shorted.

$$\therefore \quad R_{out} = R_{out}\,(a_v{=}0)\left[\frac{1 + RR(\text{output port shorted})}{1 + RR(\text{output port open})}\right] = 236\Omega\left(\frac{1+0}{1+999.8}\right) = \underline{\underline{0.236\Omega}}$$

Problem 7 – (20 points – This problem is optional)

A CMOS op amp capable of operating from 1.5V power supply is shown. All device lengths are 1µm and are to operate in the saturation region. Design all of the W values of every transistor of this op amp to meet the following specifications.

Slew rate = ±10V/µs	$V_{out}(max) = 1.25V$	$V_{out}(min) = 0.75V$
$V_{ic}(min) = 1V$	$V_{ic}(max) = 2V$	GB = 10MHz
Phase margin = 60° when the output pole = 2GB and the RHP zero = 10GB. Keep the mirror pole ≥ 10GB ($C_{ox} = 0.5fF/\mu m^2$).		



Your design should meet or exceed these specifications. Ignore bulk effects in this problem and summarize your W values to the nearest micron, the value of C_c(pF), and I(µA) in the following table. Use the following model parameters: $K_N' = 24\mu A/V^2$, $K_P' = 8\mu A/V^2$, $V_{TN} = -V_{TP} = 0.75V$, $\lambda_N = 0.01V^{-1}$ and $\lambda_P = 0.02V^{-1}$.

Solution

1.) $p_2 = 2GB \Rightarrow g_{m6}/C_L = 2g_{m1}/C_c$ and $z = 10GB \Rightarrow g_{m6} = 10g_{m1}$. $\therefore$ $\boxed{C_c = C_L/5 = 2pF}$

2.) $I = C_c \cdot SR = (2x10^{-12}) \cdot 10^7 = 20\mu A$ $\therefore$ $\boxed{I = 20\mu A}$

3.) $GB = g_{m1}/C_c \Rightarrow$ $g_{m1} = 20\pi x10^6 \cdot 2x10^{-12} = 40\pi x10^{-6} = 125.67\mu S$

$$\frac{W_1}{L_1} = \frac{W_2}{L_2} = \frac{g_{m1}{}^2}{2K_N(I/2)} = \frac{(125.67x10^{-6})^2}{2 \cdot 24x10^{-6} \cdot 10x10^{-6}} = 32.9 \Rightarrow \boxed{W1 = W_2 = 33\mu m}$$

4.) $V_{ic}(min) = V_{DS5}(sat.) + V_{GS1}(10\mu A) = 1V \rightarrow V_{DS5}(sat.) = 1 - \sqrt{\frac{2 \cdot 10}{24 \cdot 33}} - 0.75 = 0.0908$

$$V_{DS5}(sat) = 0.0908 = \sqrt{\frac{2 \cdot I}{K_N S_5}} \rightarrow W_5 = \frac{2 \cdot 20}{24 \cdot (0.0908)^2} = 201.9\mu m \quad \boxed{W_5 = 202\mu m}$$

5.) $V_{ic}(max) = V_{DD} - V_{SD11}(sat) + V_{TN} = 1.5 - V_{SD11}(sat) + 0.75 = 2V \rightarrow V_{SD11}(sat) = 0.25V$

$$V_{SD11}(sat) \le \sqrt{\frac{2 \cdot 1.5I}{K_P \cdot S_{11}}} \rightarrow S_{11} = W_{11} \ge \frac{2 \cdot 30}{(0.25)^2 \cdot 8} = 120 \rightarrow \underline{\underline{W_{11} = W_{12} \ge 120\mu m}}$$

Problem 7 - Continued

6.) Choose $S_3(S_4)$ by satisfying $V_{ic}(max)$ specification then check mirror pole.

$$V_{ic}(max) \geq V_{GS3}(20\mu A) + V_{TN} \rightarrow V_{GS3}(20\mu A) = 1.25V \geq \sqrt{\frac{2\cdot I}{K_N\cdot S_3}} + 0.75V$$

$$S_3 = S_4 = \frac{2\cdot 20}{(0.5)^2\cdot 24} = 6.67 \Rightarrow \boxed{W_3 = W_4 = 7\mu m}$$

7.) Check mirror pole ($p_3 = g_{m3}/C_{Mirror}$).

$$p_3 = \frac{g_{m3}}{C_{Mirror}} = \frac{g_{m3}}{2\cdot 0.667\cdot W_3\cdot L_3\cdot C_{ox}} = \frac{\sqrt{2\cdot 24\cdot 6.67\cdot 20}\text{x}10^{-6}}{2\cdot 0.667\cdot 6.67\cdot 0.5\text{x}10^{-15}} = 17.98\text{x}10^9$$

which is much greater than 10GB ($0.0628\text{x}10^9$). Therefore, W_3 and W_4 are OK.

8.) $g_{m6} = 10g_{m1} = 1256.7\mu S$

a.) $g_{m6} = \sqrt{2K_NS_6 10I} \Rightarrow W_6 = 164.5\mu m$

b.) $V_{out}(min) = 0.5 \Rightarrow V_{DS6}(sat) = 0.5 = \sqrt{\frac{2\cdot 10I}{K_NS_6}} \Rightarrow W_6 = 66.67\mu m$

Therefore, use $\boxed{W_6 = 165\mu m}$

Note: For proper mirroring, $S_4 = \frac{I_4}{I_6} S_6 = 8.25\mu m$ which is close enough to $7\mu m$.

9.) Use the $V_{out}(max)$ specification to design W_7.

$$V_{out}(max) = 0.25V \geq V_{DS7}(sat) = \sqrt{\frac{2\cdot 200\mu A}{8\text{x}10^{-6}\cdot S_7}}$$

$$\therefore \; S_7 \geq \frac{400\mu A}{8\text{x}10^{-6}(0.25)^2} \Rightarrow \boxed{W_7 = 800\mu m}$$

10.) Now to achieve the proper currents from the current source I gives,

$$S_9 = S_{10} = \frac{S_7}{10} = 80 \rightarrow \boxed{W_9 = W_{10} = 80\mu m}$$

and

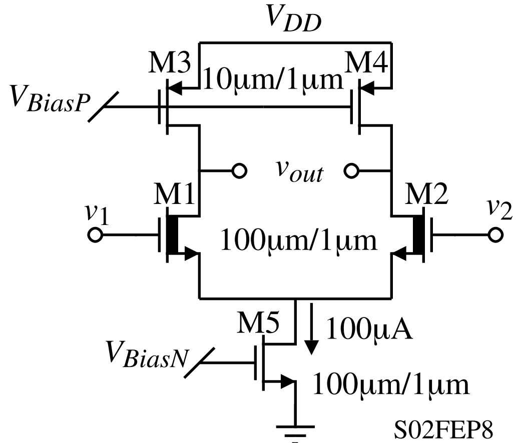
$S_{11} = S_{12} = \frac{1.5\cdot S_7}{10} = 120 \rightarrow W_{11} = W_{12} = 120\mu m$. We saw in step 5 that W_{11} and W_{12} had to be greater than $120\mu m$ to satisfy $V_{ic}(max)$. $\therefore$ $\boxed{W_{11}=W_{12}=120\mu m}$

11.) $P_{diss} = 15I\cdot 1.5V = 300\mu A\cdot 1.5V = 450\mu W$

C_c	I	$W_1=W_2$	$W_3=W_4$	$W_5=W_8$	W_6	W_7	$W_9=W_{10}$	$W_{11}=W_{12}$	P_{diss}
2pF	20μA	33μm	7μm	202μm	165μm	800μm	80μm	120μm	450μW

Problem 8 – (20 points – This problem is optional)

A differential CMOS amplifier using depletion mode input devices is shown. Assume that the normal MOSFETs parameters are K_N' =110V/μA^2, V_{TN} = 0.7V, λ_N =0.04V^{-1} and for the PMOS transistors are K_P' =110V/μA^2, V_{TP} = 0.7V, λ_P =0.04V^{-1}. For the depletion mode NMOS transistors, the parameters are the same as the normal NMOS except that V_{TN} = -0.5V. (a.) What is the maximum input common-mode voltage, V_{icm}^+(max)? (b.) What is the minimum input common-mode voltage, V_{icm}^-(min)? (c.) What value of V_{DD} gives an $ICMR = 0.5V_{DD}$?



Solution

(a.) $V_{icm}^+(\max) = V_{DD} - V_{SD3}(\text{sat}) - V_{DS1}(\text{sat}) + V_{GS1}(50\mu\text{A})$

$$i_D = \frac{\beta}{2}(V_{GS1} - V_{T1})^2 \rightarrow \qquad V_{GS1} = \sqrt{\frac{2i_D}{\beta}} + V_{T1} = V_{DS1}(\text{sat}) + V_{T1}$$

∴ $V_{icm}^+(\max) = V_{DD} - V_{SD3}(\text{sat}) + V_{T1} = V_{DD} - \sqrt{\frac{2I_{D3}}{\beta_3}} + V_{T1}$

$V_{icm}^+(\max) = V_{DD} - 0.4472 - 0.5 = \underline{\underline{V_{DD} - 0.9472}}$

(b.) $V_{icm}^-(\min) = V_{DS5}(\text{sat}) + V_{GS1}(50\mu\text{A}) = V_{DS5}(\text{sat}) + V_{DS1}(\text{sat}) + V_{T1}$

$$V_{icm}^-(\min) = \sqrt{\frac{2I_{D5}}{\beta_5}} + \sqrt{\frac{2I_{D1}}{\beta_1}} + V_{T1} = 0.1348 + 0.0953 - 0.5 = \underline{\underline{-0.2698\text{V}}}$$

(c.) $ICMR = V_{icm}^+(\max) - V_{icm}^-(\min) = V_{DD} - 0.9472 + 0.2698 = V_{DD} - 0.6774$

∴ $V_{DD} - 0.6774 = 0.5V_{DD} \qquad \rightarrow \qquad V_{DD} = 2(0.6774) = \underline{\underline{1.355\text{V}}}$