Faculty of Information Engineering & Technology
Electrical & Electronics Department
Course: Electronic Circuits [ELCT 604]

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Sheet-6 solution

MOS Differential Amplifiers, Current sources and Active loads

Problem 1:

Given: $A_v = \frac{v_o}{v_i} = 60$ at biasing current $I_{SS} = 10\ \mu A$; $\lambda_n = 0.01\ V^{-1}$at L=10µm; $\lambda_p = 0.02\ V^{-1}$at L=10µm; $\mu_n C_{OX} = 2\mu_P C_{OX} = 20\ \mu A/V^2$, the channel length of all transistors is 10µm and the W/L ratio of M3, M4, M5, and M6 is two

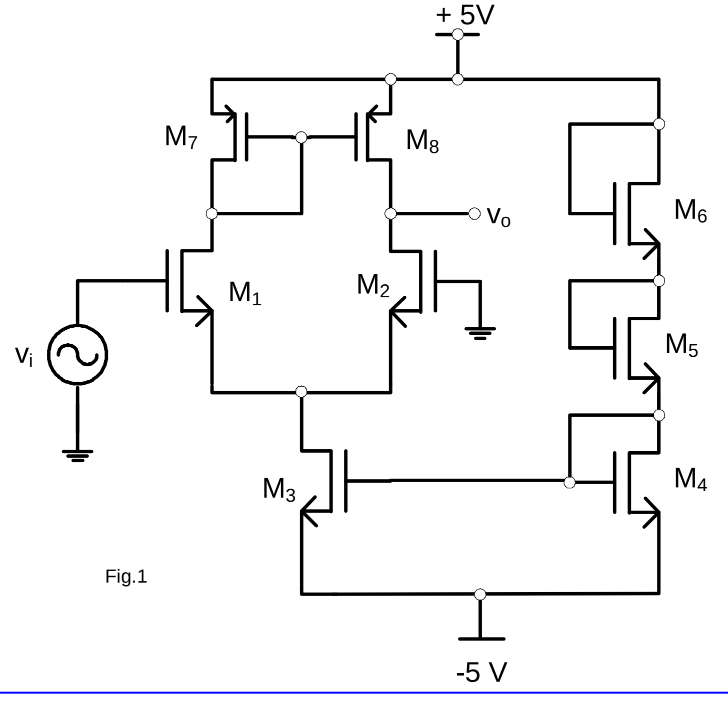


Fig.1

Required:

a) Determine the W/L ratios of the MOSFETS and the threshold voltage V_T
b) Repeat (a) assuming the channel length of all transistors is 5µm
c) Use PSPICE to find the small signal gain Av for vi = 1mV

Solution:

a) To get the threshold voltage we need to find DC operating point for the current source used using the MOS current equation and a KVL equation

M4, M5 and M6 operating in the saturation mode as

$$V_{GD} < V_T$$

$$\therefore I_D = \frac{k_n}{2}(V_{GS} - V_{TN})^2$$

Since M4, M5 and M6 are connected in series then their drain currents are the same

$$I_{D4} = I_{D5} = I_{D6} = 10\ \mu A$$

The transistors have same W/L

$$k_4 = k_5 = k_6 = 40\ \mu A/V^2$$

$$\therefore V_{GS6} = V_{GS5} = V_{GS4} = V_{GS}$$

KVL in the outer loop

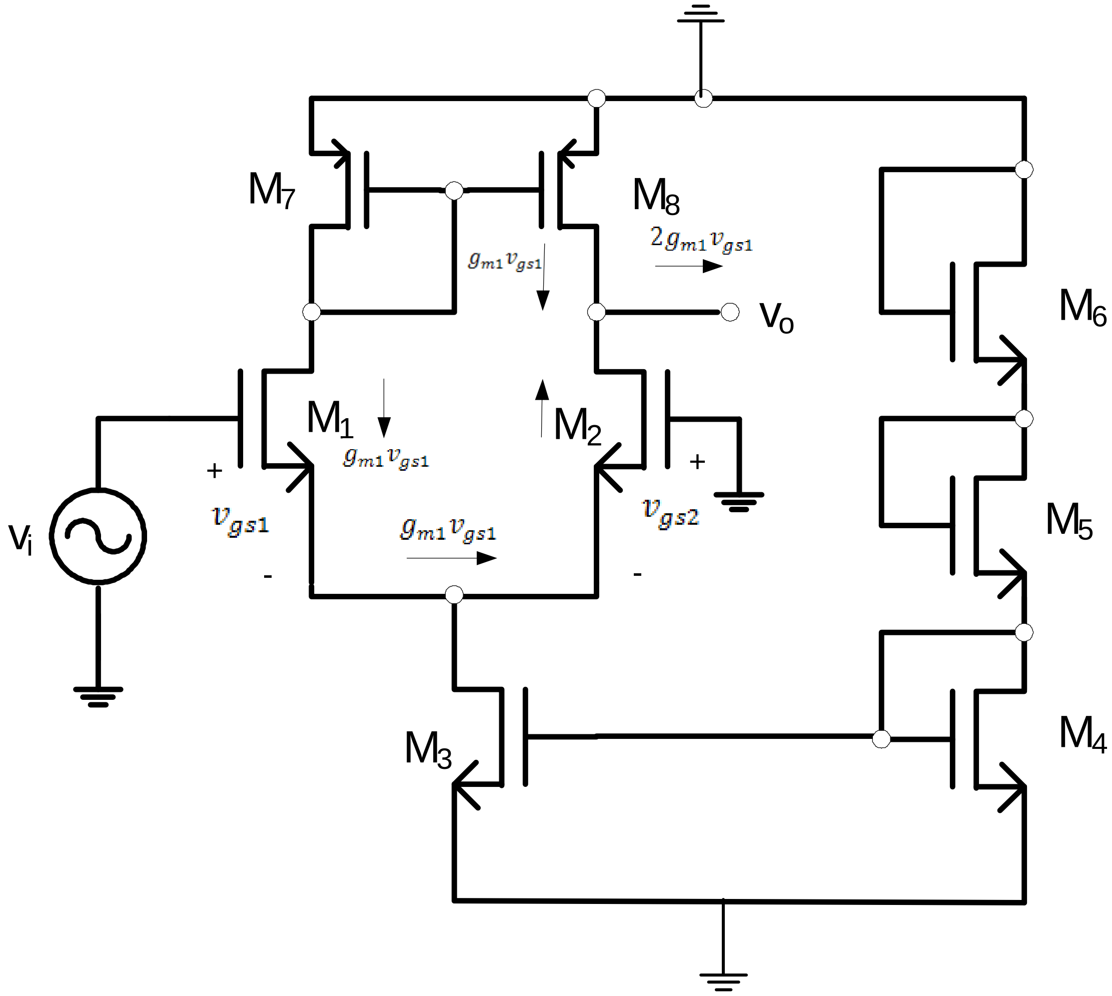
$$10 = V_{GS6} + V_{GS5} + V_{GS4} = 3V_{GS}$$

$$\therefore V_{GS} = \frac{10}{3}\ V$$

$$V_{TN} = V_{GS} - \sqrt{\frac{2I_D}{k}} = 2.626\ V$$

$$\therefore V_{TP} = -V_{TN} = -2.626\ V$$

To get the aspect ratio for M1, M2, M7 and M8 we will make AC analysis and equate the gain with 60 to find the required



$$v_{out} = 2g_{m1}v_{gs1}R_{out}$$

$$v_{in} = v_{gs1} - v_{gs2}$$

$$v_{gs1} = -v_{gs2}$$

$$\therefore v_{gs1} = \frac{v_{in}}{2}$$

$$\frac{v_{out}}{v_{in}} = g_{m1}R_{out}$$

$$R_{out} = r_{ds8}//\left[r_{ds2} + (1 + g_{m2}r_{ds2}) \times \left(r_{ds3}//\frac{1}{g_{m1}}\right)\right]$$

$$R_{out} \cong r_{ds8}//2r_{ds2}$$

$$R_{out} = \frac{r_{ds8} \times 2r_{ds2}}{r_{ds8} + 2r_{ds2}} = 2\,\frac{\frac{2}{\lambda_n I_{SS}} \times \frac{2}{\lambda_p I_{SS}}}{\frac{4}{\lambda_n I_{SS}} + \frac{2}{\lambda_p I_{SS}}}$$

$$R_{out} = \frac{4}{2\lambda_p I_{SS} + \lambda_n I_{SS}}$$

$$R_{out} = \frac{4}{0.04 I_{SS} + 0.01 I_{SS}} = \frac{4}{0.05 I_{SS}} = 8\ M\Omega$$

$$g_{m1} = \sqrt{\frac{2kI_{SS}}{2}} = \sqrt{10k}$$

$$\therefore \frac{v_{out}}{v_{in}} = g_{m1} R_{out} = 60$$

$$\sqrt{10 \times 10^{-6} k_n} = \frac{60}{8M} = 7.5 \times 10^{-6}$$

$$k_n = 5.625\ \mu A/V^2$$

$$k_n = \frac{\mu_n C_{ox} W}{L}$$

$$\frac{W}{L}_n = \frac{k_n}{\mu_n C_{ox}} = 0.28125$$

$$W_n = 10\mu \times 0.28125 = 2.8125\ \mu m$$

For the PMOS transistors ; assume $g_{mn} = g_{mp}$

$$k_p = 5.625\ \mu A/V^2$$

$$k_p = \frac{\mu_p C_{ox} W}{L}$$

$$\frac{W}{L}_p = \frac{k_p}{\mu_p C_{ox}} = 0.5625$$

$$W_p = 10\mu \times 0.5625 = 5.625\ \mu m$$

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b) L=5µm ; Calculate the new values for λ_n & λ_p

$$\lambda_n = \frac{0.01 \times \frac{1}{5}}{\frac{1}{10}} = 0.02\ V^{-1}$$

$$\lambda_p = \frac{0.02 \times \frac{1}{5}}{\frac{1}{10}} = 0.04\ V^{-1}$$

$$R_{out} = \frac{4}{2\lambda_p I_{SS} + \ \lambda_n I_{SS}}$$

$$R_{out} = \frac{4}{0.08 I_{SS} + \ 0.02 I_{SS}} = \frac{4}{0.1 I_{SS}} = 4\ M\Omega$$

$$\sqrt{10 \times 10^{-6} k_n} = \frac{60}{4M} = 15 \times 10^{-6}$$

$$k_n = 22.5 \mu A/V^2$$

$$k_n = \frac{\mu_n C_{ox} W}{L}$$

$$\frac{W}{L}_n = \frac{k_n}{\mu_n C_{ox}} = 1.125$$

$$W = 5\mu \times 1.125 = 5.625\ \mu m$$

For the PMOS transistors ; assume $g_{mn} = g_{mp}$

$$k_p = 22.5\ \mu A/V^2$$

$$k_p = \frac{\mu_p C_{ox} W}{L}$$

$$\frac{W}{L}_p = \frac{k_p}{\mu_p C_{ox}} = 2.25$$

$$W = 5\mu \times 2.25 = 11.25\ \mu m$$

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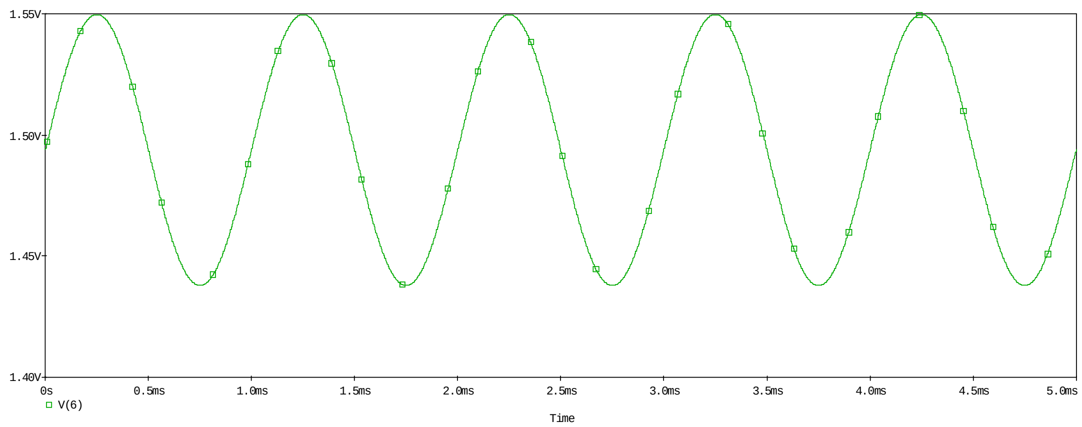
c) SPICE simulations

Problem (1a)

```
Vdd 1 0 DC 5v
Vss 4 0 DC -5v

M1 8 7 5 5 nmos W=2.8U L=10U
M2 6 0 5 5 nmos W=2.8U L=10U

M3 5 3 4 4 nmos W=8U L=10U
M4 3 3 4 4 nmos W=20U L=10U
M5 2 2 3 3 nmos W=20U L=10U
M6 1 1 2 2 nmos W=20U L=10U

M7 8 8 1 1 pmos W=5.625U L=10U
M8 6 8 1 1 pmos W=5.625U L=10U

Vin 7 0 sin (0v 1mv 1kHz)
.TF V(6) VIN
.op
.probe
.tran 1ns 5ms 0S 1us

.MODEL NMOS NMOS (KP = 20U VTo= +2.262V LAMBDA=0.01)
.MODEL PMOS PMOS (KP = 10U VTo= -2.262V LAMBDA=0.02)

.end
```



Output file :

```
****     SMALL-SIGNAL CHARACTERISTICS

      V(6)/Vin =  5.599E+01

      INPUT RESISTANCE AT Vin =  1.000E+20

      OUTPUT RESISTANCE AT V(6) =  7.630E+06
```

Problem (1b):

```
Vdd 1 0 DC 5v
Vss 4 0 DC -5v

M1 8 7 5 5 nmos W=5.6U L=5U
M2 6 0 5 5 nmos W=5.6U L=5U

M3 5 3 4 4 nmos W=4.5U L=5U
M4 3 3 4 4 nmos W=10U L=5U
M5 2 2 3 3 nmos W=10U L=5U
M6 1 1 2 2 nmos W=10U L=5U

M7 8 8 1 1 pmos W=11.25U L=5U
M8 6 8 1 1 pmos W=11.25U L=5U

Vin 7 0 sin (0v 1mv 1kHz)
.TF V(6) VIN
.op
.probe
.tran 1ns 5ms 0S 1us

.MODEL NMOS NMOS (KP = 20U VTo= +2.262V LAMBDA=0.02)
.MODEL PMOS PMOS (KP = 10U VTo= -2.262V LAMBDA=0.04)

.end
```

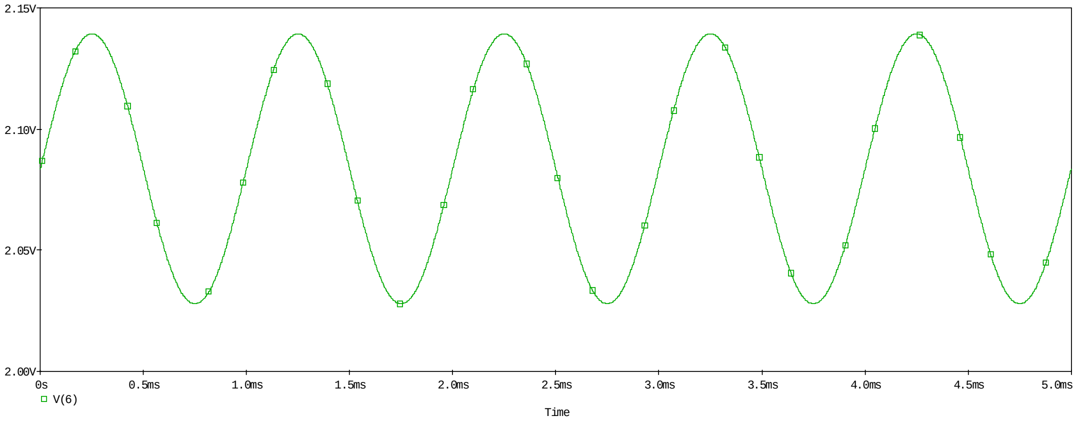
Output file:

**** SMALL-SIGNAL CHARACTERISTICS

V(6)/Vin = 5.572E+01

INPUT RESISTANCE AT Vin = 1.000E+20

OUTPUT RESISTANCE AT V(6) = 3.452E+06



<u>Problem 2:</u>

Given: PMOS parameters are VT =-3V, $V_{GS} = -6V$ at $I_D = 1mA$ $\mu_P C_{OX} = 10\frac{\mu A}{V^2}$; $\lambda_p = 0.1\ V^{-1}$ at L=2μm; BJT parameters are $\beta = 100, V_A = 40\ V, V_{DD} = -V_{EE} = 15V;$ $I_{SS} = 200\mu A$

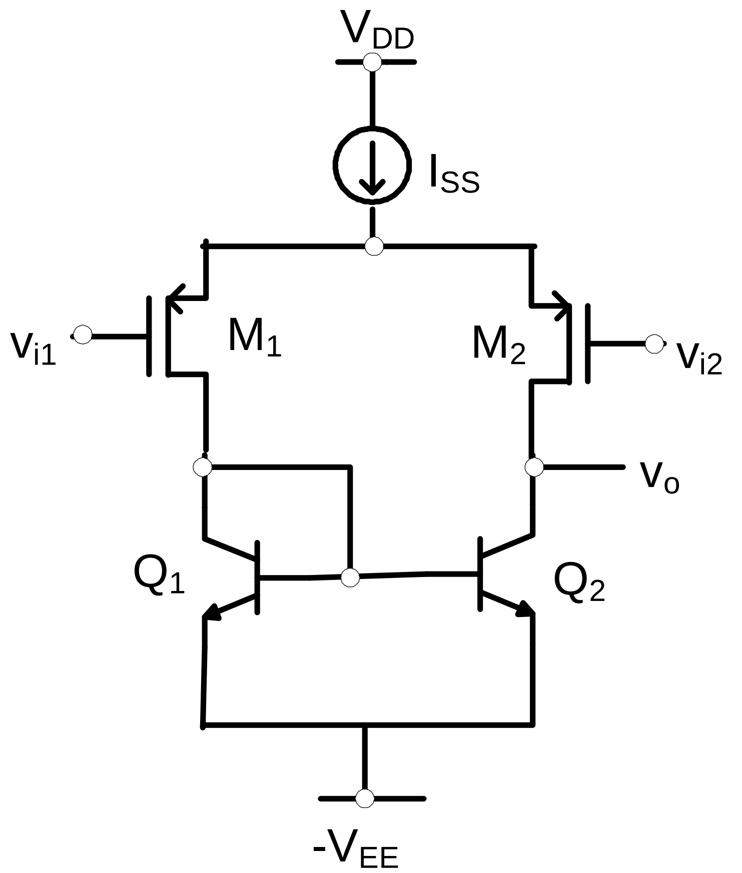


Fig.2

Required:

a) Calculate the aspect ratio of PMOS transistors, voltage gain vo/(vi1-vi2), the output resistance and the input resistance

b) Repeat (a) if ISS =100 μA, and 400 μA. Comment on the results

Solution:

a) For M1 and M2

$$g_{m1} = \frac{2I_D}{V_{SG} - |V_{TP}|} = \frac{2 \times 1mA}{6-3} = \frac{2}{3}\ mA/V$$

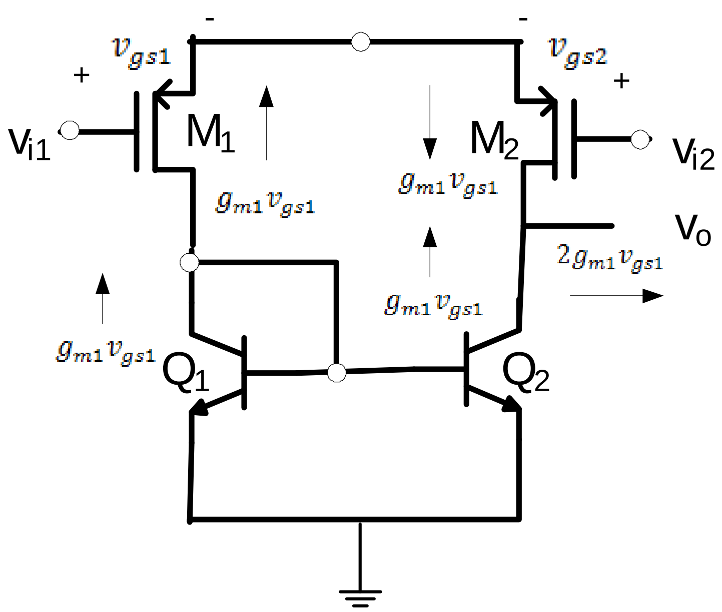
$$g_{m1} = \sqrt{2kI_D} = \sqrt{2k}$$

$$\therefore k = \frac{2}{9}\ mA/V^2$$

$$k = \frac{\mu_p C_{ox} W}{L}$$

$$\frac{W}{L} = \frac{k}{\mu_p C_{ox}} = \frac{2}{90}$$

AC analysis for the circuit given :



$$v_{out} = 2g_{m1}v_{gs1}R_{out}$$

$$v_{i1} - v_{i2} = v_{gs1} - v_{gs2}$$

$$v_{gs1} = -v_{gs2}$$

$$\therefore v_{gs1} = \frac{v_{i1} - v_{i2}}{2}$$

$$\frac{v_{out}}{v_{i1} - v_{i2}} = g_{m1} R_{out}$$

$$R_{out} = r_{o2} // \left[r_{ds2} + (1 + g_{m2} r_{ds2}) \times \frac{1}{g_{m1}} \right]$$

$$R_{out} \cong r_{o2} // 2r_{ds2}$$

$$g_{m1} = g_{m2} = \sqrt{2kI_D} = \sqrt{2 \times 100 \times 10^{-3} \times k} = 0.2108 \ mA/V$$

$$r_{o2} = \frac{V_A}{I_C} = \frac{2V_A}{I_{SS}} = 400 \ K\Omega$$

$$r_{ds2} = \frac{2}{\lambda_p \ I_{SS}} = 100 \ K\Omega$$

$$R_{out} = 400K // 200K = 133.33 \ K\Omega$$

$$R_{in} = \infty$$

$$\frac{v_{out}}{v_{i1} - v_{i2}} = g_{m1} R_{out} = 0.2108 \ \times 133.33 = 28.107$$

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b) At $I_{SS} = 400 \ \mu A$

$$g_{m1} = \sqrt{2kI_D} = \sqrt{2 \times 200 \times 10^{-3} \times k} = 0.2981 \ mA/V$$

$$r_{o2} = \frac{V_A}{I_C} = \frac{2V_A}{I_{SS}} = 200 \ K\Omega$$

$$r_{ds2} = \frac{2}{\lambda_p \ I_{SS}} = 50 \ K\Omega$$

$$R_{out} = 200K // 100K = 66.67 \ K\Omega$$

$$R_{in} = \infty$$

$$\frac{v_{out}}{v_{i1} - v_{i2}} = g_{m1}R_{out} = 0.2981 \times 66.67 = 19.873$$

At $I_{SS} = 100\ \mu A$

$$g_{m1} = \sqrt{2kI_D} = \sqrt{2 \times 50 \times 10^{-3} \times k} = 0.149mA/V$$

$$r_{o2} = \frac{V_A}{I_C} = \frac{2V_A}{I_{SS}} = 800\ K\Omega$$

$$r_{ds2} = \frac{2}{\lambda_p\ I_{SS}} = 200K\Omega$$

$$R_{out} = 800K//400K = 266.67\ K\Omega$$

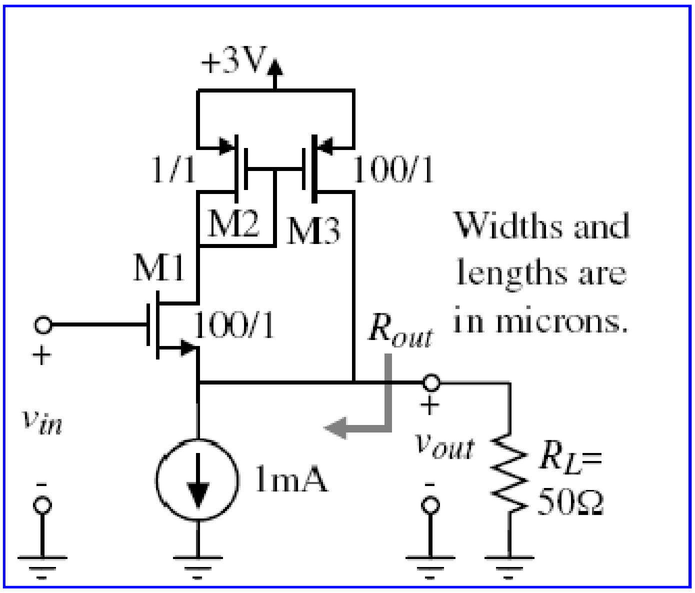
$$R_{in} = \infty$$

$$\frac{v_{out}}{v_{i1} - v_{i2}} = g_{m1}R_{out} = 39.73$$

As I_{SS}increases the gain decreases and vice versa.

Problem 3:

Given: the bias current is 1mA $\mu_n C_{OX} = 100\frac{\mu A}{V^2}$ $V_{TN} = 0.7V$,
$\mu_p C_{OX} = 50\frac{\mu A}{V^2}$ $V_{TP} = -0.7V$

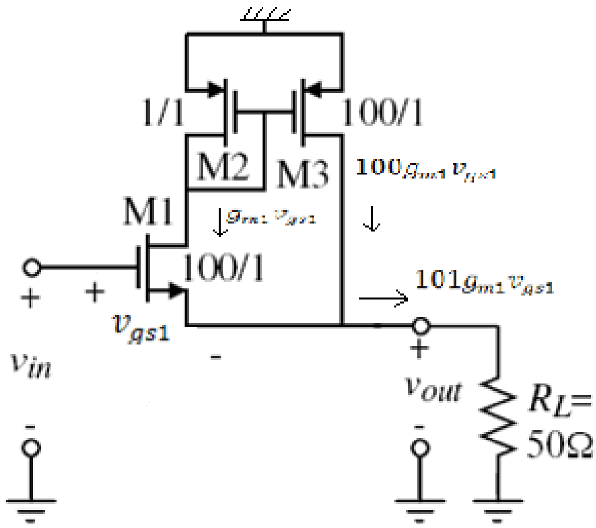


Required:

Find an algebraic expression for the voltage gain; *vout*/*vin*, and the output resistance, *Rout*, of the source follower shown in terms of the small signal model parameters, *gm* and *RL* (ignore *rds)*; find the numerical value of the voltage gain and the output resistance

Solution:

AC analysis:



$$v_{out} = 101g_{m1}v_{gs1}R_L$$

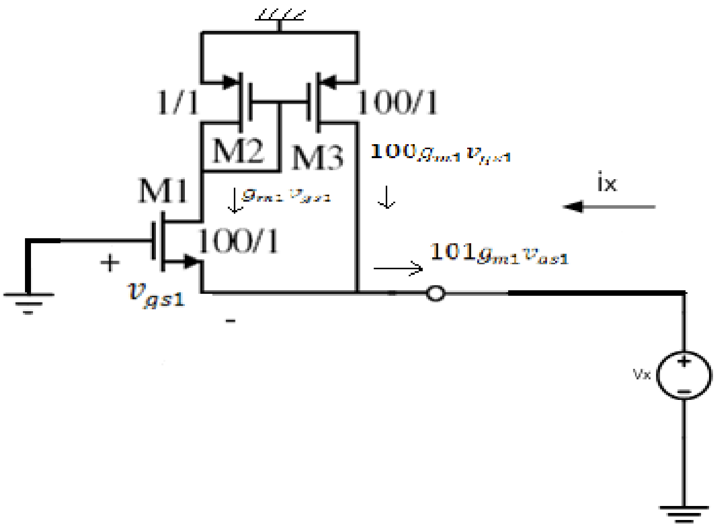
$$v_{gs1} = v_{in} - v_{out}$$

$$v_{gs1} = v_{in} - 101g_{m1}v_{gs1}R_L$$

$$v_{gs1}(1 + 101g_{m1}R_L) = v_{in}$$

$$\therefore \frac{v_{out}}{v_{in}} = \frac{101g_{m1}R_L}{(1 + 101g_{m1}R_L)}$$

To calculate the output resistance:



$$R_{out} = \frac{v_x}{i_x}$$

$$i_x = -g_{m1}v_{gs1} - 100g_{m1}v_{gs1} = -101g_{m1}v_{gs1}$$

$$v_x = -v_{gs1}$$

$$\therefore R_{out} = \frac{v_x}{i_x} = \frac{1}{101g_{m1}}$$

DC analysis:

$$I_{bias} = 101I_{DS1}$$

$$\therefore I_{DS1} = 9.9\ \mu A$$

$$g_{m1} = \sqrt{2kI_{DS1}} = \sqrt{2 \times 100 \times 100 \times 9.9} = 0.445mA/V$$

$$\therefore R_{out} = \frac{1}{101g_{m1}} = 22.25\ \Omega$$

$$\therefore \frac{v_{out}}{v_{in}} = \frac{101g_{m1}R_L}{(1 + 101g_{m1}R_L)} = 0.9996$$