Homework Assignment No. 7 -Solutions

Problem 1 - (10 points)

Find the low frequency PSRR and all roots of the positive and negative power supply rejection ratio performance for the two-stage op amp of Fig. P6.3-9.

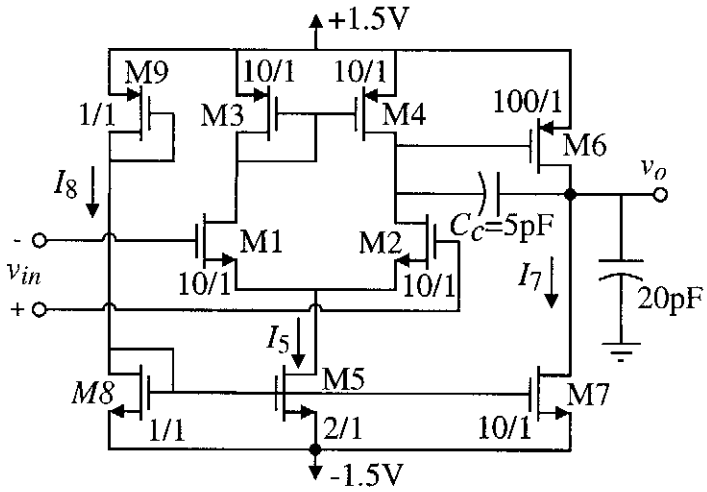


Figure P6.3-10

Solution

Referring to the figure

$$V_{DD} - V_{SS} = V_{T8} + V_{T9} + \sqrt{\frac{2I_8}{K_N (W/L)_8}} + \sqrt{\frac{2I_8}{K_P (W/L)_9}}$$

or, $I_8 = 60 \ \mu A$

Now,

$$g_{m1} = 363.3 \ \mu S \ , \ g_{ds2} = 2.4 \ \mu S \ , \ g_{ds4} = 3 \ \mu S \ , \ g_{m6} = 774.6 \ \mu S \ , \ g_{ds6} = 30 \ \mu S$$

and $g_{ds7} = 24 \ \mu S$

$\therefore$ $A_{v1} = 67.3$ and $A_{v2} = 14.3$

For the positive PSRR, the low frequency PSRR is

$$PSRR^+ = \frac{A_v(0)G_{II}}{g_{ds6}} = 1737$$

and poles and zeros are

$$p_1 = \frac{(GB)g_{ds6}}{A_v(0)G_{II}} = 6.66 \text{ KHz}, \ z_1 = GB = 11.6 \text{ MHz. and } z_2 = p_2 = 6.2 \text{ MHz.}$$

For the negative PSRR, the low frequency PSRR is given by

$$PSRR^- = \frac{A_v(0)G_{II}}{g_{ds7}} = 2171$$

and the poles and zeros are

$$p_1 = \frac{(GB)G_I}{g_{m1}} = 172.4 \text{ KHz}, \ z_1 = GB = 11.6 \text{ MHz and } z_2 = p_2 = 6.2 \text{ MHz.}$$

Problem 2 – (10 points)

A CMOS op amp that uses a 5V power supply is shown. All transistor lengths are 1μm and 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) = 4V, V_{out}(min) = 1V, V_{ic}(min) = 1.5V, V_{ic}(max) = 4V and GB = 10MHz.

Your design should meet or exceed these specifications. Ignore bulk effects and summarize your W values to the nearest micron, the bias current, I_5(μA), the power dissipation, the differential voltage gain, A_{vd}, and V_{BP} and V_{BN} in the table shown.

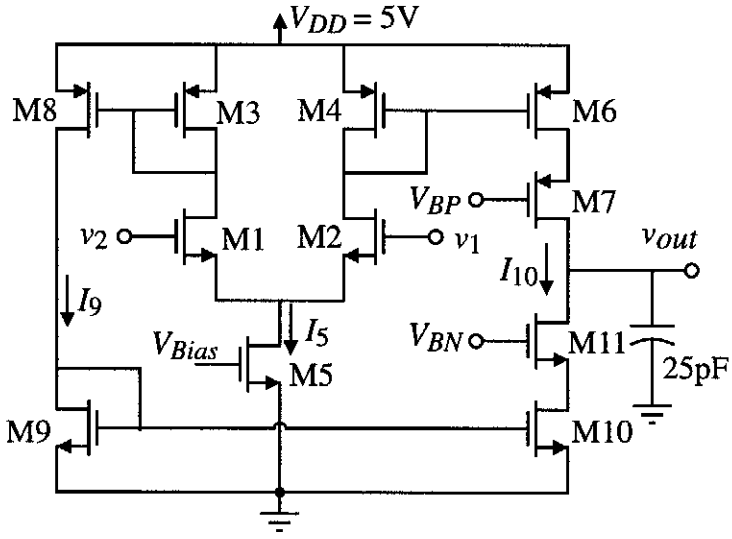


Figure P6.5-13

Solution

1.) $I_5 = C_L \cdot SR = 250\mu A$

2.) $g_{m1} = GB \cdot C_L = 20\pi \times 106 \cdot 25pF = 1{,}570.8\mu S \quad \Rightarrow \frac{W_1}{L_1} = \frac{(1.570 \times 10^{-3})^2}{2 \cdot 110 \cdot 125 \times 10^{-6}} = 90$

3.) $W3=W4=W6=W7=W8 = \frac{2I_D}{K'(V_{DS}(sat))^2} = \frac{2 \cdot 250}{50 \cdot 0.25} = 40$ (assumed I_D of 250μA worst case)

4.) $W9=W10=W11 = \frac{2I_D}{K'(V_{DS}(sat))^2} = \frac{2 \cdot 250}{110 \cdot 0.25} = 18$ (assumed I_D of 250μA worst case)

5.) $V_{icm}(min) = V_{DS5}(sat) + V_{GS1} \rightarrow V_{DS5}(sat) = 1.5 - (0.159+0.7) = 0.6411V$

$$\therefore W5 = \frac{2I_D}{K'(V_{DS}(sat))^2} = \frac{2 \cdot 250}{110 \cdot 0.6411^2} = 11$$

6.) $A_{vd} = g_{m1}R_{out}$ $g_{mN} = 704\mu S$, $r_{dsN} = 0.2M\Omega$, $g_{mP} = 707\mu S$, $r_{dsN} = 0.16M\Omega$

$R_{out} \approx g_{mN} \cdot r_{dsN}^2 || g_{mP} \cdot r_{dsP}^2 = 28.14M\Omega || 18.1M\Omega = 11M\Omega$

$\therefore$ $A_{vd} = 1.57mS \cdot 11M\Omega = 17{,}329V/V$

7.) $V_{BP} = 5 - V_{DSP}(sat) + V_{GSP}(sat) = 5-0.5+0.5+0.7 = 3.3V$

$V_{BN} = V_{DSP}(sat) + V_{GSP}(sat) = 0.5+0.5+0.7 = 1.7V$

8.) $P_{diss} = 5(250\mu A + 250\mu A) = 2.5mW$

W1=W2	W3=W4=W6 =W7=W8	W9=W10 =W11	W5	I_5(μA)	A_{vd}	V_{BP}	V_{BN}	P_{diss}
90μm	40μm	18μm	11μm	250μA	17,329 V/V	3.3V	1.7V	2.5mW

Problem 3 – (10 points)

6.15

$200\,\mu A = |I_{D_8}| = |I_{D_5}| = |I_{D_7}| = I_{D_6}$

$100\,\mu A = I_{D_1} = I_{D_2} = I_{D_3} = I_{D_4}$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.9\,(8.85\times10^{-14}\ F/cm)}{80\ \text{Å}}$$

$$= 431\ nF/cm^2$$

$$\mu_n C_{ox} = 450\ \frac{cm^2}{V\cdot s}\ 431\ \frac{nF}{cm^2}$$

$$= 194\ \mu A/V^2$$

$$k_n' = 194\ \mu A/V^2$$

$$k_p' = 64.7\ \mu A/V^2$$

$$\frac{v_o}{v_i} = -g_{m_2}(r_{o2} \| r_{o4})\, g_{m_6}(r_{o6} \| r_{o7})$$

$$\frac{1}{r_{o2}} = \frac{I_{D_2}}{L_{eff}}\frac{dX_d}{dV_{DS}} = \frac{100\,\mu A}{0.72\,\mu m}(0.04\,\mu) = 5.56\,\mu$$

$r_{o2} = 180\,k\Omega = r_{o4}$

$r_{o6} = 90\,k\Omega = r_{o7}$

$$L_{eff} = L - X_d - 2L_d$$

$$= 1 - 0.1 - 2(0.09)$$

$$= 0.72\,\mu m$$

$$g_{m_2} = \sqrt{2k_p'\frac{W}{L_{eff}}I_{D_2}}$$

$$= \sqrt{2(64.7\,\mu)\left(\frac{150}{0.72}\right)(100\,\mu)}$$

$$= 1640\ \mu A/V$$

$$g_{m_6} = \sqrt{2(194\,\mu)\left(\frac{100}{0.72}\right)(200\,\mu)}$$

$$= 3280\ \mu A/V$$

$$\frac{v_o}{v_i} = -(1.64\,m)(90\,k)(3.28\,m)(45\,k)$$

$$= -2.18\times10^4$$

common mode range:

From (6.75),

$$V_{IC} > V_{t_1} + V_{t_3} + V_{OV_3} - V_{SS}$$

$$V_{OV_3} = \sqrt{\frac{2(100)}{194\,(50/0.72)}} = 0.12\ V$$

$$V_{IC} > -0.8 + 0.6 + 0.12 - 1.5$$

$$V_{IC} > -1.58\ V$$

From (6.77),

$$V_{IC} < V_{t_1} + V_{OV_1} + V_{OV_5} + V_{DD}$$

$$V_{OV_5} = -\sqrt{\frac{2(200)}{64.7\,(150/0.72)}} = -0.17\ V$$

$$V_{OV_1} = -\sqrt{\frac{2(100)}{64.7\,(150/0.72)}} = -0.12\ V$$

$$V_{IC} < -0.8 - 0.12 - 0.17 + 1.5$$

$$V_{IC} < 0.41\ V$$

From (6.86),

$$\frac{v_o}{v_{dd}} \cong 0$$

From (6.87),

$$\frac{v_o}{v_{ss}} = \frac{r_{o7}}{r_{o6} + r_{o7}} = 0.5$$

Problem 3 – Continued

```
TWO-STAGE CMOS AMPLIFIER
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.6U
VI2   6  2  0
VIC   2  0  0
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1P RELTOL=1U
.OP
.TF   V(9) VI1
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:2       =   0.       0:3       = 5.024E-01 0:6       = 9.357E-01
+0:5       = 4.600E-06 0:6       =   0.       0:7       =-7.609E-01
+0:8       =-7.602E-01 0:9       = 3.026E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00

SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:PMOS     0:PMOS     0:NMOS     0:NMOS
 ID      -9.772E-05 -9.772E-05  9.772E-05  9.772E-05
 IBS       0.         0.         0.         0.
 IBD       1.697E-14  1.696E-14 -7.391E-15 -7.398E-15
 VGS      -9.357E-01 -9.357E-01  7.391E-01  7.391E-01
 VDS      -1.696E+00 -1.695E+00  7.391E-01  7.398E-01
 VBS       0.         0.         0.         0.
 VTH      -8.000E-01 -8.000E-01  6.000E-01  6.000E-01
 VDSAT    -1.357E-01 -1.357E-01  1.391E-01  1.391E-01
 BETA      1.062E-02  1.062E-02  1.010E-02  1.010E-02
 GAM EFF   0.         0.         0.         0.
 GM        1.441E-03  1.441E-03  1.405E-03  1.405E-03
 GDS       4.957E-06  4.957E-06  5.210E-06  5.210E-06
 GMB       0.         0.         0.         0.

SUBCKT
ELEMENT  0:M5       0:M6       0:M7       0:M8
MODEL    0:PMOS     0:NMOS     0:PMOS     0:PMOS
 ID      -1.954E-04  2.053E-04 -2.053E-04 -2.000E-04
 IBS       0.         0.         0.         0.
 IBD       5.643E-15 -1.500E-14  1.500E-14  9.976E-15
 VGS      -9.976E-01  7.398E-01 -9.976E-01 -9.976E-01
 VDS      -5.643E-01  1.500E+00 -1.499E+00 -9.976E-01
 VBS       0.         0.         0.         0.
 VTH      -8.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT    -1.976E-01  1.398E-01 -1.976E-01 -1.976E-01
 BETA      1.061E-02  2.102E-02  1.051E-02  1.024E-02
 GAM EFF   0.         0.         0.         0.
 GM        1.978E-03  2.937E-03  2.078E-03  2.024E-03
 GDS       1.052E-05  1.052E-05  1.052E-05  1.052E-05
 GMB       0.         0.         0.         0.

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                                  = -1.975E+04
INPUT RESISTANCE AT         VI1           =  1.000E+20
OUTPUT RESISTANCE AT V(9)                 =  4.754E+04
```

```
TWO-STAGE CMOS AMPLIFIER (MAXIMUM COMMON-MODE INPUT VOLTAGE)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  13.7U
VI2   6  2  0
* THE MAXIMUM VALUE OF VIC IS ADJUSTED BY TRIAL AND ERROR
* UNTIL M5 BARELY OPERATES IN THE ACTIVE REGION
* (WHERE |VDS| > |VDSAT| FOR M5)
VIC   2  0  0.36
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1P RELTOL=1U
.OP
.TF   V(9) VI1
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:2       = 3.600E-01 0:3       = 5.024E-01 0:4       = 1.293E+00
+0:5       = 3.600E-01 0:6       = 3.600E-01 0:7       =-7.622E-01
+0:8       =-7.602E-01 0:9       = 1.329E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:PMOS     0:PMOS     0:NMOS     0:NMOS
 ID      -9.584E-05 -9.585E-05  9.584E-05  9.585E-05
 IBS       0.         0.         0.         0.
 IBD       2.055E-14  2.053E-14 -7.378E-15 -7.398E-15
 VGS      -9.331E-01 -9.332E-01  7.378E-01  7.376E-01
 VDS      -2.055E+00 -2.053E+00  7.378E-01  7.398E-01
 VBS       0.         0.         0.         0.
 VTH      -8.000E-01 -8.000E-01  6.000E-01  6.000E-01
 VDSAT    -1.331E-01 -1.332E-01  1.378E-01  1.378E-01
 BETA      1.081E-02  1.081E-02  1.010E-02  1.010E-02
 GAM EFF   0.         0.         0.         0.
 GM        1.440E-03  1.440E-03  1.391E-03  1.391E-03
 GDS       4.774E-06  4.775E-06  5.110E-06  5.110E-06
 GMB       0.         0.         0.         0.

SUBCKT
ELEMENT  0:M5       0:M6       0:M7       0:M8
MODEL    0:PMOS     0:NMOS     0:PMOS     0:PMOS
 ID      -1.917E-04  2.053E-04 -2.053E-04 -2.000E-04
 IBS       0.         0.         0.         0.
 IBD       2.068E-15 -1.500E-14  1.500E-14  9.976E-15
 VGS      -9.976E-01  7.398E-01 -9.976E-01 -9.976E-01
 VDS      -2.068E-01  1.500E+00 -1.499E+00 -9.976E-01
 VBS       0.         0.         0.         0.
 VTH      -8.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT    -1.976E-01  1.398E-01 -1.976E-01 -1.976E-01
 BETA      9.816E-03  2.102E-02  1.051E-02  1.024E-02
 GAM EFF   0.         0.         0.         0.
 GM        1.940E-03  2.937E-03  2.078E-03  2.024E-03
 GDS       1.052E-05  1.052E-05  1.052E-05  1.052E-05
 GMB       0.         0.         0.         0.

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                                  = -2.029E+04
INPUT RESISTANCE AT         VI1           =  1.000E+20
OUTPUT RESISTANCE AT V(9)                 =  4.753E+04
```

Problem 3 – Continued

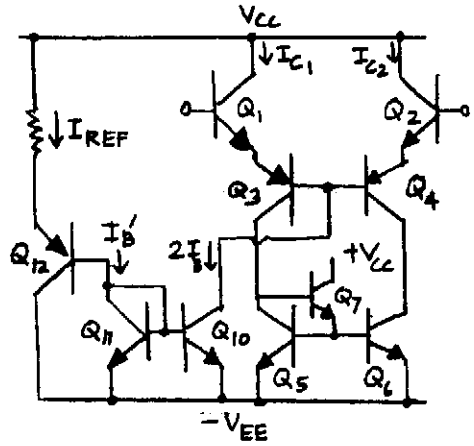
```
TWO-STAGE CMOS AMPLIFIER (MINIMUM COMMON-MODE INPUT VOLTAGE)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  -39.7U
VI2   6  2  0
* THE MINIMUM VALUE OF VIC IS ADJUSTED BY TRIAL AND ERROR
* UNTIL M1 BARELY OPERATES IN THE ACTIVE REGION
* (WHERE |VDS| > |VDSAT| FOR M1)
VIC   2  0  -1.55
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF   V(9) VI1
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:2       =-1.550E+00 0:3       = 5.024E-01 0:6       =-6.030E-01
+0:5       =-1.550E+00 0:6       =-1.550E+00 0:7       =-7.552E-01
+0:8       =-7.602E-01 0:9       = 5.068E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00

**** MOSFETS
SUBCKT
ELEMENT  0:M1       0:M2       0:M3       0:M4
MODEL    0:PMOS     0:PMOS     0:NMOS     0:NMOS
 ID      -1.058E-04 -1.058E-04  1.058E-04  1.058E-04
 IBS       0.         0.         0.         0.
 IBD       1.523E-15  1.572E-15 -7.448E-15 -7.398E-15
 VGS      -9.471E-01 -9.470E-01  7.448E-01  7.448E-01
 VDS      -1.523E-01 -1.572E-01  7.448E-01  7.398E-01
 VBS       0.         0.         0.         0.
 VTH      -8.000E-01 -8.000E-01  6.000E-01  6.000E-01
 VDSAT    -1.471E-01 -1.470E-01  1.448E-01  1.448E-01
 BETA      9.787E-03  9.790E-03  1.010E-02  1.010E-02
 GAM EFF   0.         0.         0.         0.
 GM        1.439E-03  1.439E-03  1.452E-03  1.452E-03
 GDS       5.824E-06  5.821E-06  5.640E-06  5.640E-06
 GMB       0.         0.         0.         0.

SUBCKT
ELEMENT  0:M5       0:M6       0:M7       0:M8
MODEL    0:PMOS     0:NMOS     0:PMOS     0:PMOS
 ID      -2.116E-04  2.053E-04 -2.053E-04 -2.000E-04
 IBS       0.         0.         0.         0.
 IBD       2.103E-14 -1.501E-14  1.499E-14  9.976E-15
 VGS      -9.976E-01  7.398E-01 -9.976E-01 -9.976E-01
 VDS      -2.103E+00  1.500E+00 -1.499E+00 -9.976E-01
 VBS       0.         0.         0.         0.
 VTH      -8.000E-01  6.000E-01 -8.000E-01 -8.000E-01
 VDSAT    -1.976E-01  1.398E-01 -1.976E-01 -1.976E-01
 BETA      1.084E-02  2.102E-02  1.051E-02  1.024E-02
 GAM EFF   0.         0.         0.         0.
 GM        2.142E-03  2.937E-03  2.077E-03  2.024E-03
 GDS       1.052E-05  1.052E-05  1.052E-05  1.052E-05
 GMB       0.         0.         0.         0.

****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                              = -1.750E+04
INPUT RESISTANCE AT         VI1       =  1.000E+20
OUTPUT RESISTANCE AT V(9)             =  4.754E+04
```

```
TWO-STAGE CMOS AMPLIFIER (GAIN FROM VDD)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.6U
VI2   6  2  0
VIC   2  0  0
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF   V(9) VDD
.END
 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:2       =  0.         0:3       = 5.024E-01 0:4       = 9.357E-01
+0:5       = 4.600E-06 0:6       =  0.         0:7       =-7.609E-01
+0:8       =-7.602E-01 0:9       = 3.026E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(9)/VDD                              = -1.647E-02
INPUT RESISTANCE AT         VDD       =  4.723E+04
OUTPUT RESISTANCE AT V(9)             =  4.754E+04
```

```
TWO-STAGE CMOS AMPLIFIER (GAIN FROM VSS)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5    4   4   PMOS W=150U  L=1U
M2    8  6    4   4   PMOS W=150U  L=1U
M3    7  7    200 200 NMOS W=50U   L=1U
M4    8  7    200 200 NMOS W=50U   L=1U
M5    4  3    100 100 PMOS W=150U  L=1U
M6    9  8    200 200 NMOS W=100U  L=1U
M7    9  3    100 100 PMOS W=150U  L=1U
M8    3  3    100 100 PMOS W=150U  L=1U
IBIAS 3  200  200U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.6U
VI2   6  2  0
VIC   2  0  0
*LEFF = LDRAWN - 2LD -XD = 1 - 2(0.09) - 0.1 = 0.72 UM
*LAMBDA=(DXD/DVDS)/LEFF = 0.04U/0.72U = 0.0555
.MODEL NMOS NMOS LEVEL=1 KP=194U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=64.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1F RELTOL=1U
.OP
.TF   V(9) VSS
.END
 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:2       =  0.         0:3       = 5.024E-01 0:4       = 9.357E-01
+0:5       = 4.600E-06 0:6       =  0.         0:7       =-7.609E-01
+0:8       =-7.602E-01 0:9       = 3.026E-04 0:100     = 1.500E+00
+0:200     =-1.500E+00
****     SMALL-SIGNAL TRANSFER CHARACTERISTICS
V(9)/VSS                              =  5.063E-01
INPUT RESISTANCE AT         VSS       =  1.865E+05
OUTPUT RESISTANCE AT V(9)             =  4.754E+04
```

Problem 4 – (10 points)

6.26 (a)

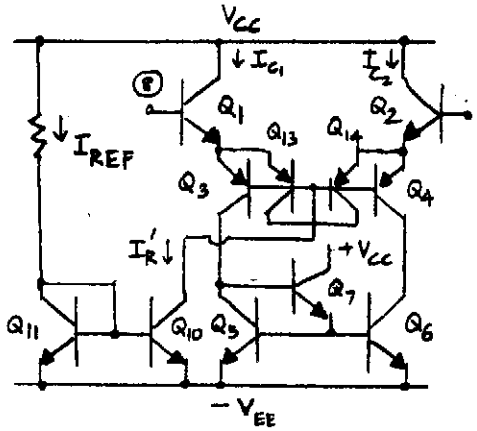


$I_{C_1} = I_{C_2} = 10\,\mu A \quad \beta_{pnp} = 50$

$I_B = \frac{I_{C_1}}{1+\beta_{pnp}} \quad \therefore\ 2I_B = 0.39\,\mu A \simeq I_B'$

$\therefore\ I_{REF} = (1+\beta_{pnp})\, I_B' = 20\,\mu A$

(b)



$I_{C_1} = I_{C_2} = 10\,\mu A$

$I_{E_3} = I_{E_{13}} = I_{E_{14}} = I_{E_4} \simeq \frac{I_{C_1}}{2} = 5\,\mu A$

$I_R' = 2|I_{C_3}| + 4|I_{B_{13}}|$

$= 2\left(\frac{5\,\mu A}{1+50}\right)\cdot 50 + 4\cdot\left(\frac{5\,\mu A}{1+50}\right)$

$= 10.2\,\mu A = I_{REF}$

```
741 INPUT BIAS SCHEME (A)
******
VCC     100     0       15
VEE     200     0       -15
IREF    100             3       20U
Q1      100     8       10      NPN
Q2      100     9       11      NPN
Q3      12      6       10      PNP
Q4      16      6       11      PNP
Q5      12      13      200     NPN
Q6      16      13      200     NPN
Q7      100     12      13      NPN
Q10     6       4       200     NPN
Q11     4       4       200     NPN
Q12     200     4       3       PNP

* WITH VIC = -12.6 V,
* VCE10 = VIC - VBE1 - |VBE3| - (-VEE)
*       = -12.6 - 0.6 - 0.6 + 15 = 1.2 V
* THIS IS ENOUGH TO OPERATE Q10 IN THE FORWARD-ACTIVE REGION.
VI1     8       0       -12.6
VI2     9       0       -12.6 AC   1

.MODEL NPN    NPN  BF=250 IS=5E-15
.MODEL PNP    PNP  BF=50  IS=2E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP

* VOUT IS USED TO MEASURE THE AC SHORT CIRCUIT OUTPUT
* CURRENT TO FIND GM.
* THE DC VALUE OF VOUT WAS GIVEN IN THE PROBLEM STATEMENT.
VOUT    16      200     1.6

.AC DEC 1 1 10
.PRINT AC IM(VOUT) IP(VOUT)

* THE TRANSCONDUCTANCE CAN ALSO BE MEASURED BY ELIMINATING
* THE VOLTAGE SOURCE CONNECTED AT THE OUTPUT AND THE
* AC ANALYSIS ABOVE, FINDING THE VOLTAGE GAIN AND OUTPUT
* RESISTANCE WITH A .TF STATEMENT AS SHOWN BELOW,
* AND CALCULATING GM = (VOLTAGE GAIN)/(OUTPUT RESISTANCE)
* THE RESULT IS GM = 1.736E6/9.237E7 = 18E-6 A/V
*.TF V(16) VI2
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       =-1.393E+01 0:4       =-1.453E+01 0:5       =-1.373E+01
+0:8       =-1.260E+01 0:9       =-1.260E+01 0:10      =-1.315E+01
+0:11      =-1.315E+01 0:12      =-1.401E+01 0:13      =-1.444E+01
+0:16      =-1.340E+01 0:100     = 1.500E+01 0:200     =-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1        0:Q2        0:Q3        0:Q4        0:Q5
MODEL    0:NPN       0:NPN       0:PNP       0:PNP       0:NPN
 IB       3.945E-08   3.945E-08  -1.942E-07  -1.949E-07   3.883E-08
 IC       9.863E-06   9.863E-06  -9.708E-06  -9.707E-06   9.708E-06
 VBE      5.536E-01   5.536E-01  -5.769E-01  -5.769E-01   5.532E-01
 VCE      2.815E+01   2.815E+01  -8.651E-01  -2.464E-01   9.813E-01
 VBC     -2.760E+01  -2.760E+01   2.883E-01  -3.304E-01  -4.282E-01
 VS      -1.500E+01  -1.500E+01   1.373E+01   1.373E+01   1.401E+01
 POWER    2.777E-04   2.777E-04   8.511E-05   2.505E-06   9.548E-06
 BETAD    2.500E+02   2.500E+02   5.000E+01   4.981E+01   2.500E+02
 GM       3.813E-04   3.813E-04   3.754E-04   3.753E-04   3.753E-04
 RPI      6.555E+05   6.556E+05   1.332E+05   1.332E+05   6.660E+05
 RX       0.          0.          0.          0.          0.
 RO       5.520E+15   5.520E+15   1.441E+14   3.661E+07   8.563E+13
 BETAAC   2.500E+02   2.500E+02   5.000E+01   4.999E+01   2.500E+02
```

Problem 4 – Continued

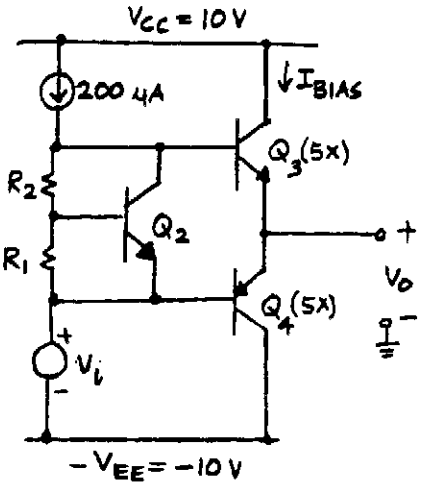
```
SUBCKT
ELEMENT  0:Q6       0:Q7       0:Q10      0:Q11      0:Q12
MODEL    0:NPN      0:NPN      0:NPN      0:NPN      0:PNP
 IB      3.883E-08  3.094E-10  1.556E-09  1.556E-09 -3.922E-07
 IC      9.708E-06  7.735E-08  3.890E-07  3.890E-07 -1.961E-05
 VBE     5.532E-01  4.282E-01  4.699E-01  4.699E-01 -5.950E-01
 VCE     1.600E+00  2.944E+01  1.269E+00  4.699E-01 -1.065E+00
 VBC    -1.046E+00 -2.901E+01 -7.996E-01   0.        4.699E-01
 VS      1.340E+01 -1.500E+01  1.373E+01  1.453E+01  1.453E+01
 POWER   1.555E-05  2.278E-06  4.947E-07  1.836E-07  2.112E-05
 BETAD   2.500E+02  2.500E+02  2.500E+02  2.500E+02  5.000E+01
 GM      3.753E-04  2.991E-06  1.504E-05  1.504E-05  7.581E-04
 RPI     6.660E+05  8.359E+07  1.662E+07  1.662E+07  6.595E+04
 RX      0.         0.         0.         0.         0.
 RO      2.093E+14  5.803E+15  1.599E+14  5.172E+12  2.349E+14
 BETAAC  2.500E+02  2.500E+02  2.500E+02  2.500E+02  5.000E+01


******  AC ANALYSIS            TEMP=  27.000 TEMP=  27.000
      FREQ     I MAG         I PHASE
                VOUT          VOUT
1.0000E+00    1.877E-04    4.174E-23
1.0000E+01    1.877E-04    4.174E-22
```

```
741 INPUT BIAS SCHEME (B)
******
VCC    100   0    15
VEE    200   0    -15
IREF   100     6        10.2U
Q1     100     8        10      NPN
Q2     100     9        11      NPN
Q3     12      6        10      PNP
Q4     16      6        11      PNP
Q5     12      13       200     NPN
Q6     16      13       200     NPN
Q7     100     12       13      NPN
Q10    6       4        200     NPN
Q11    4       4        200     NPN
* REMOVE Q12 FROM THE CIRCUIT.
*  IT WAS ONLY NEEDED FOR PART (A).
Q12    200     200      200     PNP
Q13    6       6        10      PNP
Q14    6       6        11      PNP

* WITH VIC = -12.6 V,
* VCE10 = VIC - VBE1 - |VBE3| - (-VEE)
        = -12.6 - 0.6 - 0.6 + 15 = 1.2 V
* THIS IS ENOUGH TO OPERATE Q10 IN THE FORWARD-ACTIVE REGION.
VI1    8       0        -12.6
VI2    9       0        -12.6 AC   1

.MODEL NPN   NPN  BF=250 IS=5E-15
.MODEL PNP   PNP  BF=50  IS=2E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP

* VOUT IS USED TO MEASURE THE AC SHORT CIRCUIT OUTPUT
* CURRENT TO FIND GM.
* THE DC VALUE OF VOUT WAS GIVEN IN THE PROBLEM STATEMENT.
VOUT   16      200      1.6

.AC DEC 1 1 10
.PRINT AC IM(VOUT) IP(VOUT)

* THE TRANSCONDUCTANCE CAN ALSO BE MEASURED BY ELIMINATING
* THE VOLTAGE SOURCE CONNECTED AT THE OUTPUT AND THE
* AC ANALYSIS ABOVE, FINDING THE VOLTAGE GAIN AND OUTPUT
* RESISTANCE WITH A .TF STATEMENT AS SHOWN BELOW,
* AND CALCULATING GM = (VOLTAGE GAIN)/(OUTPUT RESISTANCE)
* THE RESULT IS GM = 1.942E6/2.065E8 = 94E-6 A/V
* THE TRANSCONDUCTANCE IS REDUCED HERE COMPARED
* TO THE TRANSCONDUCTANCE IN PART (A) BECAUSE
* THE COLLECTOR CURRENT OF Q13 AND Q14 HERE FLOWS
* IN Q10 AND DOES NOT CONTRIBUTE TO THE STAGE OUTPUT.
*.TF V(16) VI2
.END
```

```
****  OPERATING POINT INFORMATION     TEMP=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       =   0.       0:4     =-1.444E+01 0:6     =-1.371E+01
+0:8       =-1.260E+01 0:9     =-1.260E+01 0:10    =-1.315E+01
+0:11      =-1.315E+01 0:12    =-1.405E+01 0:13    =-1.446E+01
+0:16      =-1.340E+01 0:100   = 1.500E+01 0:200   =-1.500E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1       0:Q2       0:Q3       0:Q4       0:Q5
MODEL    0:NPN      0:NPN      0:PNP      0:PNP      0:NPN
 IB      3.954E-08  3.954E-08 -9.729E-08 -9.765E-08  1.946E-08
 IC      9.884E-06  9.884E-06 -4.865E-06 -4.864E-06  4.865E-06
 VBE     5.536E-01  5.536E-01 -5.590E-01 -5.590E-01  5.353E-01
 VCE     2.815E+01  2.815E+01 -9.000E-01 -2.464E-01  9.456E-01
 VBC    -2.760E+01 -2.760E+01  3.418E-01 -3.126E-01 -4.103E-01
 VS     -1.500E+01 -1.500E+01  1.371E+01  1.371E+01  1.405E+01
 POWER   2.783E-06  2.783E-06  4.437E-06  1.253E-06  4.610E-06
 BETAD   2.500E+02  2.500E+02  5.000E+01  4.981E+01  2.500E+02
 GM      3.822E-04  3.822E-04  1.881E-04  1.881E-04  1.881E-04
 RPI     6.541E+05  6.541E+05  2.658E+05  2.658E+05  1.329E+06
 RX      0.         0.         0.         0.         0.
 RO      5.520E+15  5.520E+15  1.709E+14  7.290E+07  8.205E+13
 BETAAC  2.500E+02  2.500E+02  5.000E+01  4.959E+01  2.500E+02

SUBCKT
ELEMENT  0:Q6       0:Q7       0:Q10      0:Q11      0:Q12
MODEL    0:NPN      0:NPN      0:NPN      0:NPN      0:PNP
 IB      1.946E-08  1.550E-10  4.048E-08  4.048E-08  0.
 IC      4.865E-06  3.876E-08  1.012E-05  1.012E-05  0.
 VBE     5.353E-01  4.103E-01  5.542E-01  5.542E-01  0.
 VCE     1.600E+00  2.946E+01  1.287E+00  5.542E-01  0.
 VBC    -1.064E+00 -2.905E+01 -7.332E-01   0.        0.
 VS      1.340E+01 -1.500E+01  1.371E+01  1.444E+01  1.500E+01
 POWER   7.794E-06  1.162E-06  1.305E-05  5.631E-06  0.
 BETAD   2.500E+02  2.500E+02  2.500E+02  2.500E+02  0.
 GM      1.881E-04  1.499E-06  3.912E-04  3.912E-04  0.
 RPI     1.329E+06  1.668E+08  6.390E+05  6.390E+05  6.466E+14
 RX      0.         0.         0.         0.         0.
 RO      2.129E+14  5.810E+15  1.466E+14  5.172E+12  1.293E+13
 BETAAC  2.500E+02  2.500E+02  2.500E+02  2.500E+02  0.

SUBCKT
ELEMENT  0:Q13      0:Q14
MODEL    0:PNP      0:PNP
 IB     -9.729E-08 -9.730E-08
 IC     -4.865E-06 -4.865E-06
 VBE    -5.590E-01 -5.590E-01
 VCE    -5.590E-01 -5.590E-01
 VBC     0.         0.
 VS      1.371E+01  1.371E+01
 POWER   2.774E-06  2.774E-06
 BETAD   5.000E+01  5.000E+01
 GM      1.881E-04  1.881E-04
 RPI     2.658E+05  2.658E+05
 RX      0.         0.
 RO      1.293E+13  1.293E+13
 BETAAC  5.000E+01  5.000E+01

******  AC ANALYSIS            TEMP=  27.000 TEMP=  27.000
      FREQ     I MAG         I PHASE
                VOUT          VOUT
1.0000E+00    9.405E-05    8.873E-23
1.0000E+01    9.405E-05    8.873E-22
```

Problem 5 – (10 points)

6.27



Neglect current flow through R_1 and R_2 from 200 μA source.

$\therefore I_{C_2} = 200\,\mu A$, $V_{BE_2} = V_T \ln \frac{I_{C_2}}{I_{S_2}}$

$$V_{BE_4} + V_{BE_3} = V_{BE_2} + \frac{V_{BE_2}}{R_1} \times R_2$$

$$= \frac{V_T}{R_1}(R_1 + R_2) \ln \frac{I_{C_2}}{I_{S_2}}$$

$$= V_T \ln \left(\frac{I_{C_3} | I_{C_4}|}{I_{S_3} I_{S_4}} \right)$$

Areas of Q_3, Q_4 are 5 times of Q_1 and Q_2. Therefore,

$I_{S_1} = I_{S_2} = 10^{-15} A = I_S$

$I_{S_3} = I_{S_4} = 5 \times 10^{-15} A = 5 I_S$

$$V_T \ln \left(\frac{I_{BIAS}^2}{25 I_S^2} \right) = V_T \left(1 + \frac{R_2}{R_1}\right) \ln \left(\frac{I_{C_2}}{I_S} \right)$$

$$\therefore I_{BIAS} = 5 I_S \left(\frac{I_{C_2}}{I_S} \right)^{\frac{1}{2}\left(1 + \frac{R_2}{R_1}\right)}$$

$$= 5 \left(I_{C_2} \right)^{\frac{1}{2}\left(1 + \frac{R_2}{R_1}\right)} \left(I_S \right)^{\frac{1}{2}\left(1 - \frac{R_2}{R_1}\right)} \rightarrow (1)$$

$$\frac{R_2}{R_1} = \frac{2 \ln \left(\frac{I_{BIAS}}{5 I_S} \right)}{\ln \left(\frac{I_{C_2}}{I_S} \right)} - 1$$

$I_{BIAS} = 50\,\mu A$, $I_S = 10^{-15} A$, $I_{C_2} = 200\,\mu A$

$\therefore \frac{R_2}{R_1} = 0.77$

From (1), If we choose $\frac{R_2}{R_1} = 1$

then $I_{BIAS} = 5 (I_{C_2})^{\frac{1}{2}(1 + R_2/R_1)}$

$= 1000\,\mu A = 1\,mA$

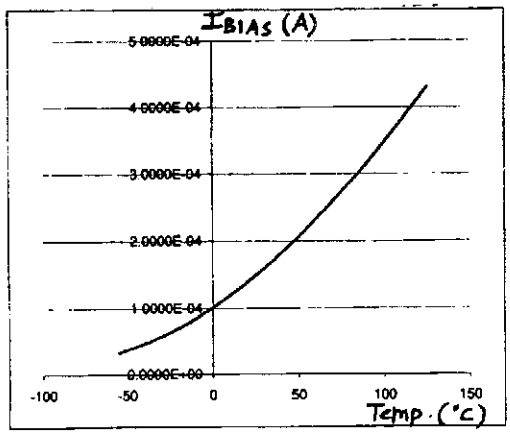
and I_{BIAS} is independent of temperature. In general, if $\frac{R_2}{R_1} \neq 1$ then I_{BIAS} is dependent on temperature because I_S depends on temperature.

Problem 5 – Continued

```
741 OUTPUT-STAGE BIAS SCHEME
* BF=LARGE TO CHECK HAND CALCULATIONS
******
VCC    100   0    10
VEE    200   0   -10
IREF   100     3       200U
Q2     3       4       5       MPN
Q3     100     3       6       MPN  5
Q4     200     5       6       PNP  5
R1     4       5       100K
R2     3       4       77K
VI     5       200     9.404
.MODEL MPN   MPN  BF=10000 IS=1E-15
.MODEL PNP   PNP  BF=10000 IS=1E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  27.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 5.952E-01 0:4       = 7.614E-02 0:5       =-5.960E-01
+0:6       =-4.124E-04 0:100     = 1.000E+01 0:200     =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       1.933E-08  5.008E-09 -5.008E-09
 IC       1.933E-04  5.008E-05 -5.008E-05
 VBE      6.721E-01  5.956E-01 -5.956E-01
 VCE      1.191E+00  1.000E+01 -9.999E+00
 BETAD    1.000E+04  1.000E+04  1.000E+04

741 OUTPUT-STAGE BIAS SCHEME
* SET BF TO NOMINAL VALUES AND RUN TEMPERATURE SWEEP
******
VCC    100   0    10
VEE    200   0   -10
IREF   100     3       200U
Q2     3       4       5       MPN
Q3     100     3       6       MPN  5
Q4     200     5       6       PNP  5
R1     4       5       100K
R2     3       4       77K
VI     5       200     9.404
.MODEL MPN   MPN  BF=250   IS=1E-15
.MODEL PNP   PNP  BF=50    IS=1E-15
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.TEMP -55 -35 -15 5 25 45 65 85 105 125
.END

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP= -55.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 8.957E-01 0:4       = 2.135E-01 0:5       =-5.960E-01
+0:6       = 1.497E-01 0:100     = 1.000E+01 0:200     =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.640E-07  1.301E-07 -6.403E-07
 IC       1.910E-04  3.253E-05 -3.202E-05
 VBE      8.095E-01  7.460E-01 -7.457E-01
 VCE      1.491E+00  9.850E+00 -1.015E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP= -35.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 8.375E-01 0:4       = 1.806E-01 0:5       =-5.960E-01
+0:6       = 1.206E-01 0:100     = 1.000E+01 0:200     =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.650E-07  2.086E-07 -1.027E-06
 IC       1.913E-04  5.215E-05 -5.134E-05
 VBE      7.766E-01  7.169E-01 -7.166E-01
 VCE      1.433E+00  9.879E+00 -1.012E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP= -15.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 7.786E-01 0:4       = 1.473E-01 0:5       =-5.960E-01
+0:6       = 9.110E-02 0:100     = 1.000E+01 0:200     =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.660E-07  3.116E-07 -1.533E-06
 IC       1.915E-04  7.790E-05 -7.667E-05
 VBE      7.433E-01  6.875E-01 -6.871E-01
 VCE      1.374E+00  9.908E+00 -1.009E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=   5.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 7.169E-01 0:4       = 1.135E-01 0:5       =-5.960E-01
+0:6       = 6.125E-02 0:100     = 1.000E+01 0:200     =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.668E-07  4.401E-07 -2.166E-06
 IC       1.917E-04  1.100E-04 -1.083E-04
 VBE      7.095E-01  6.576E-01 -6.573E-01
 VCE      1.314E+00  9.938E+00 -1.006E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  25.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 6.585E-01 0:4       = 7.939E-02 0:5       =-5.960E-01
+0:6       = 3.107E-02 0:100     = 1.000E+01 0:200     =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.675E-07  5.944E-07 -2.925E-06
 IC       1.919E-04  1.486E-04 -1.463E-04
 VBE      6.754E-01  6.275E-01 -6.271E-01
 VCE      1.254E+00  9.968E+00 -1.003E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  45.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 5.976E-01 0:4       = 4.492E-02 0:5       =-5.960E-01
+0:6       = 5.725E-04 0:100     = 1.000E+01 0:200     =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.682E-07  7.741E-07 -3.810E-06
 IC       1.920E-04  1.935E-04 -1.905E-04
 VBE      6.409E-01  5.970E-01 -5.966E-01
 VCE      1.193E+00  9.999E+00 -1.000E+01
 BETAD    2.500E+02  2.500E+02  5.000E+01

 ****  OPERATING POINT INFORMATION     TNOM=  27.000 TEMP=  65.000
   NODE    =VOLTAGE      NODE    =VOLTAGE      NODE    =VOLTAGE
+0:3       = 5.360E-01 0:4       = 1.012E-02 0:5       =-5.960E-01
+0:6       =-3.021E-02 0:100     = 1.000E+01 0:200     =-1.000E+01

**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2       0:Q3       0:Q4
MODEL    0:MPN      0:MPN      0:PNP
 IB       7.686E-07  9.782E-07 -4.814E-06
 IC       1.922E-04  2.446E-04 -2.407E-04
 VBE      6.061E-01  5.662E-01 -5.658E-01
 VCE      1.132E+00  1.003E+01 -9.969E+00
 BETAD    2.500E+02  2.500E+02  5.000E+01
```

Problem 5 – Continued

```
**** OPERATING POINT INFORMATION     TNOM= 27.000 TEMP= 85.000
   NODE    =VOLTAGE     NODE    =VOLTAGE     NODE    =VOLTAGE
+0:3       = 6.739E-01 0:4       =-2.498E-02 0:5       =-5.960E-01
+0:6       =-6.127E-02 0:100     = 1.000E+01 0:200     =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.693E-07  1.205E-06 -5.933E-06
 IC       1.923E-04  3.014E-04 -2.966E-04
 VBE      5.710E-01  5.352E-01 -5.347E-01
 VCE      1.069E+00  1.006E+01 -9.938E+00
 BETAD    2.500E+02  2.500E+02  5.000E+01

**** OPERATING POINT INFORMATION     TNOM= 27.000 TEMP= 105.000
   NODE    =VOLTAGE     NODE    =VOLTAGE     NODE    =VOLTAGE
+0:3       = 6.113E-01 0:4       =-6.037E-02 0:5       =-5.960E-01
+0:6       =-9.259E-02 0:100     = 1.000E+01 0:200     =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.697E-07  1.454E-06 -7.158E-06
 IC       1.924E-04  3.636E-04 -3.579E-04
 VBE      5.356E-01  5.039E-01 -5.034E-01
 VCE      1.007E+00  1.009E+01 -9.907E+00
 BETAD    2.500E+02  2.500E+02  5.000E+01

**** OPERATING POINT INFORMATION     TNOM= 27.000 TEMP= 125.000
   NODE    =VOLTAGE     NODE    =VOLTAGE     NODE    =VOLTAGE
+0:3       = 3.482E-01 0:4       =-9.604E-02 0:5       =-5.960E-01
+0:6       =-1.262E-01 0:100     = 1.000E+01 0:200     =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q2        0:Q3        0:Q4
MODEL    0:NPN       0:NPN       0:PNP
 IB       7.699E-07  1.723E-06 -8.480E-06
 IC       1.925E-04  4.308E-04 -4.240E-04
 VBE      5.000E-01  4.724E-01 -4.718E-01
 VCE      9.442E-01  1.012E+01 -9.875E+00
 BETAD    2.500E+02  2.500E+02  5.000E+01
```



TEMP (DEG C)	IC3 = IBIAS (A)	TEMP	IC3 = IBIAS (A)
-55	3.253E-05	45	1.935E-04
-35	5.215E-05	65	2.446E-04
-15	7.790E-05	85	3.014E-04
5	1.100E-04	105	3.636E-04
25	1.486E-04	125	4.308E-04