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.

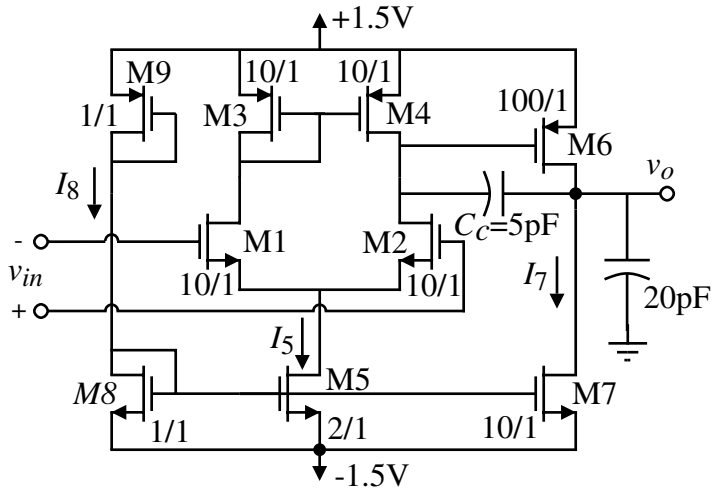


Figure P6.3-10

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.

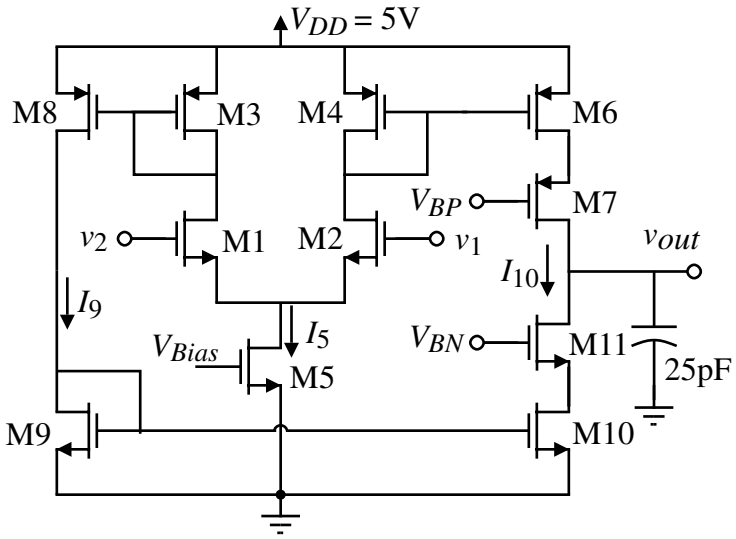


Figure P6.5-13

Solution

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

2.) $g_{m1} = GB \cdot C_L = 20\pi x106 \cdot 25pF = 1{,}570.8\mu S \quad \Rightarrow \frac{W_1}{L_1} = \frac{(1.570x10^{-3})^2}{2 \cdot 110 \cdot 125x10^{-6}} = 90$

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

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

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

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

$200\,\mu A = |I_{D8}| = |I_{D5}| = |I_{D7}| = I_{D6}$

$100\,\mu A = I_{D1} = I_{D2} = I_{D3} = I_{D4}$

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

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

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

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

$$\mathcal{K}_n' = 194\,\mu A/V^2$$

$$\mathcal{K}_p' = 64.7\,\mu A/V^2$$

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

$$\frac{1}{r_{o2}} = \frac{I_{D2}}{L_{eff}}\frac{dX_d}{dV_{DS}} = \frac{100\,\mu A}{0.72\,\mu m}(0.04\,\mu) = 5.56\,\mu$$

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

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

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

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

$$= 0.72\,\mu m$$

$$g_{m_2} = \sqrt{2\,\mathcal{K}_p'\frac{W}{L_{eff}}I_{D2}}$$

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

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

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

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

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

$$= -2.18\times10^4$$

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  20U
* 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) 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 0:4         = 9.357E-01
+0:5         = 4.600E-06 0:6         =   0.       0:7         =-7.600E-01
+0:8         =-7.602E-01 0:9         = 1.024E-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      1.457E-14  1.456E-14 -7.391E-15 -7.390E-15
 VGS     -9.357E-01 -9.357E-01  7.391E-01  7.391E-01
 VDS     -1.696E+00 -1.696E+00  7.391E-01  7.390E-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      4.997E-06  4.997E-06  5.310E-06  5.310E-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-05
 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     1.001E-02  2.102E-02  1.051E-02  1.024E-02
 GAM EFF    0.         0.         0.         0.
 GM       1.976E-03  2.937E-03  2.078E-03  2.026E-03
 GDS      1.052E-05  1.051E-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  20U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  19.7U
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=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         = 3.600E-01 0:3         = 5.024E-01 0:4         = 1.253E+00
+0:5         = 3.600E-01 0:6         = 3.600E-01 0:7         =-7.622E-01
+0:8         =-7.602E-01 0:9         = 1.128E-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  7.378E-01
 VDS     -2.015E+00 -2.013E+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  2.057E-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     -2.468E-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     9.819E-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  2.026E-03
 GDS      1.052E-05  1.052E-05  1.051E-05  1.052E-05
 GMB        0.         0.         0.         0.

 ****     SMALL-SIGNAL TRANSFER CHARACTERISTICS

V(9)/VI1                                      = -2.025E+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=15U0   L=1U
M2    8  6     4    4    PMOS W=15U0   L=1U
M3    7  7     200 200 NMOS W=5U0    L=1U
M4    8  7     200 200 NMOS W=5U0    L=1U
M5    4  3     100 100 PMOS W=15U0   L=1U
M6    9  8     200 200 NMOS W=100U   L=1U
M7    9  3     100 100 PMOS W=15U0   L=1U
M8    3  3     100 100 PMOS W=15U0   L=1U
IBIAS 3  200  20U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  -35.7U
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  -1.33
*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=134U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=44.7U 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        =-1.330E+00 0:3        = 5.024E-01 0:4        =-6.030E-01
+0:5        =-1.330E+00 0:6        =-1.331E+00 0:7        =-7.352E-01
+0:8        =-7.622E-01 0:9        = 6.068E-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      -1.050E-04 -1.050E-04  1.050E-04  1.050E-04
 IBS       0.          0.          0.          0.
 IBD      1.920E-15   1.972E-15 -7.448E-15 -7.398E-15
 VGS     -9.471E-01 -9.470E-01  7.448E-01  7.448E-01
 VDS     -1.920E-01 -1.972E-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     9.707E-03  9.700E-03  1.010E-03  1.010E-03
 GAM EFF   0.          0.          0.          0.
 GM       1.427E-03  1.428E-03  1.450E-03  1.450E-03
 GDS      5.826E-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  2.050E-04 -2.050E-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  2.930E-03  2.070E-03  2.024E-03
 GDS      1.152E-05  1.092E-05  1.092E-05  1.092E-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)                        =  4.751E+04
```

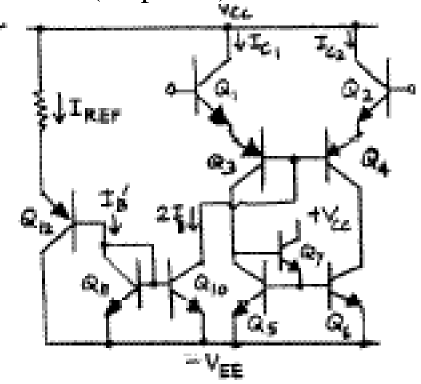
```
TWO-STAGE CMOS AMPLIFIER (GAIN FROM VDD)
******
VDD 100  0  1.5
VSS 200  0  -1.5
M1    7  5     4    4    PMOS W=15U0   L=1U
M2    8  6     4    4    PMOS W=15U0   L=1U
M3    7  7     200 200 NMOS W=5U0    L=1U
M4    8  7     200 200 NMOS W=5U0    L=1U
M5    4  3     100 100 PMOS W=15U0   L=1U
M6    9  8     200 200 NMOS W=100U   L=1U
M7    9  3     100 100 PMOS W=15U0   L=1U
M8    3  3     100 100 PMOS W=15U0   L=1U
IBIAS 3  200  20U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.0U
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=134U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=44.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1P 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        = 9.387E-01
+0:5        = 4.000E-06 0:6        =    0.      0:7        =-7.400E-01
+0:8        =-7.622E-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+06
OUTPUT RESISTANCE AT V(9)                  =  4.756E+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=15U0   L=1U
M2    8  6     4    4    PMOS W=15U0   L=1U
M3    7  7     200 200 NMOS W=5U0    L=1U
M4    8  7     200 200 NMOS W=5U0    L=1U
M5    4  3     100 100 PMOS W=15U0   L=1U
M6    9  8     200 200 NMOS W=100U   L=1U
M7    9  3     100 100 PMOS W=15U0   L=1U
M8    3  3     100 100 PMOS W=15U0   L=1U
IBIAS 3  200  20U
* THE DC OFFSET IS ADJUSTED BY TRIAL AND ERROR
* TO SET THE OUTPUT TO ZERO.
VI1   5  2  4.0U
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=134U  VTO=0.6  LAMBDA=0.0555
.MODEL PMOS PMOS LEVEL=1 KP=44.7U VTO=-0.8 LAMBDA=0.0555
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OPTIONS VNTOL=1N ABSTOL=1P 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        = 9.387E-01
+0:5        = 4.000E-06 0:6        =    0.      0:7        =-7.400E-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           =  1.665E+05
OUTPUT RESISTANCE AT V(9)                  =  4.756E+04
```

Problem 4 – (10 points)

6-26

(a)

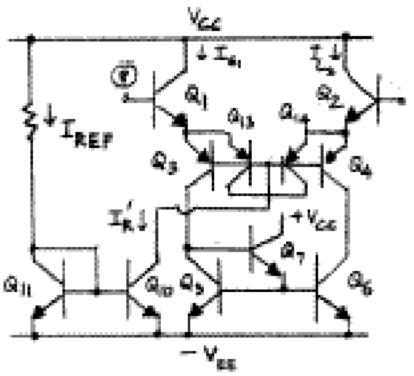


$I_{C_1} = I_{C_2} = 10\ \mu A \quad \beta_{pnp} = 50$

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

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

(b)



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

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

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

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

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

```
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,
* VCB10 = 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      1.4

.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 = 1.736E4/9.237E7 = 188E-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        =-1.385E+01 0:4        =-1.450E+01 0:6        =-1.378E+01
+0:8        =-1.260E+01 0:9        =-1.260E+01 0:10       =-1.320E+01
+0:11       =-1.320E+01 0:12       =-1.441E+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  -1.940E-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  -5.768E-01  -5.768E-01   5.532E-01
 VCE       2.815E+01   2.815E+01  -6.852E-01  -2.486E-01   9.813E-01
 VBC      -2.760E+01  -2.760E+01   1.083E-01  -3.304E-01  -4.282E-01
 VS       -1.500E+01  -1.500E+01   1.372E+01   1.372E+01   1.441E+01
 POWER     2.777E-04   2.777E-04   6.511E-06   2.502E-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   6.555E+05   1.332E+05   1.332E+05   6.660E+05
 RX        0.          0.          0.          0.          0.
 RO        5.530E+15   5.530E+15   1.641E+14   3.861E+07   8.563E+13
 BETAAC    2.500E+02   2.500E+02   5.000E+01   4.999E+01   2.500E+02
```

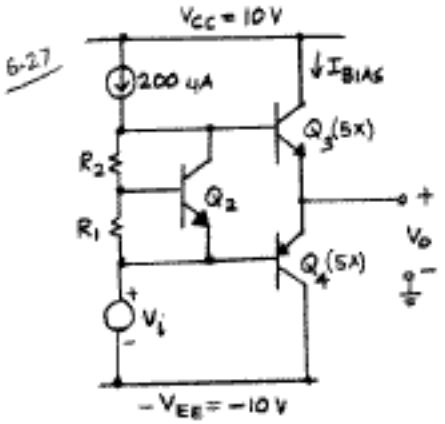
Problem 4 – Continued

```
SUBCKT
ELEMENT 0:Q6        0:Q7        0:Q10       0:Q11       0:Q12
MODEL   0:NPN       0:NPN       0:NPN       0:NPN       0:PNP
 IB     3.667E-08   3.094E-10   1.356E-09   1.356E-09  -3.933E-07
 IC     9.198E-06   7.732E-08   3.890E-07   3.890E-07  -1.961E-09
 VBE    5.932E-01   4.282E-01   4.699E-01   4.699E-01  -5.990E-01
 VCE    1.000E+00   2.944E-01   1.369E+00   4.699E-01  -1.365E+00
 VBC   -1.046E+00  -2.901E-01  -7.996E-01   0.          4.699E-01
 VS     1.346E+01  -1.500E+00   1.373E+01   1.453E+01   1.453E+01
 POWER  1.863E-05   2.273E-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   7.585E-04
 RPI    6.660E+05   8.358E+07   1.663E+07   1.663E+07   6.595E+04
 RX     0.          0.          0.          0.          0.
 RO     1.057E+14   1.003E+15   1.999E+14   5.172E+12   2.345E+14
 BETAAC 2.500E+02   2.500E+02   2.500E+02   2.500E+02   5.000E+01

****** AC ANALYSIS                TNOM=  27.000 TEMP=  27.000
       FREQ      I MAG         I PHASE
                 VOUT          VOUT
 1.0000E+00    1.877E-04     4.174E-21
 1.0000E+01    1.877E-04     4.174E-20
```

```
TEL INPUT BIAS SCHEME (B)
******
VCC     100   0     15
VEE     200   0     -15
IREF    100      4         10.0U
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     6        4         200    NPN
* REMOVE Q12 FROM THE CIRCUIT.
*  IT WAS ONLY NEEDED FOR PART (A).
Q12     100      100       100    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=1E-15
.MODEL PNP    PNP   BF=50  IS=1E-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 = 1.5428E4/2.0616E8 = 74E-6 A/V
* THE TRANSCONDUCTANCE IS REDUCED HERE COMPARED
* TO THE TRANSCONDUCTANCE IN PART (A) BECAUSE
* THE COLLECTOR CURRENT OF Q13 AND Q14 NOW FLOWS
* IN Q10 AND DOES NOT CONTRIBUTE TO THE STAGE OUTPUT.
*.TF V(16) VI2
.END
```

```
**** OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  27.000
 NODE      =VOLTAGE      NODE   =VOLTAGE      NODE   =VOLTAGE
+0:1       =  0.         0:4    =-1.444E+01   0:6    =-1.372E+01
+0:8       =-1.260E+01   0:9    =-1.260E+01   0:10   =-1.315E+01
+0:11      =-1.315E+01   0:12   =-1.400E+01   0:13   =-1.440E+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  -9.735E-08  -9.735E-08   1.546E-08
 IC     9.884E-06   9.884E-06  -4.865E-06  -4.864E-06   4.865E-06
 VBE    5.530E-01   5.530E-01  -5.590E-01  -5.590E-01   5.353E-01
 VCE    2.815E+01   2.815E+01  -9.880E-01  -1.466E+00   9.406E-01
 VBC   -2.760E+01  -2.760E+01   3.418E-01  -1.116E-01  -4.100E-01
 VS    -1.500E+01  -1.500E+01   1.371E+01   1.372E+01   1.405E+01
 POWER  2.782E-04   2.787E-04   4.437E-06   1.297E-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   2.648E+05   1.329E+06
 RX     0.          0.          0.          0.          0.
 RO     5.520E+15   5.520E+15   1.709E+14   7.259E+07   8.300E+13
 BETAAC 2.500E+02   2.500E+02   5.000E+01   4.998E+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     1.546E-08   1.585E-10   6.048E-08   4.048E-08   0.
 IC     4.865E-06   3.974E-08   1.512E-05   1.012E-05   0.
 VBE    5.353E-01   4.103E-01   5.542E-01   5.542E-01   0.
 VCE    1.000E+00   2.946E-01   1.387E+00   5.542E-01   0.
 VBC   -1.046E+00  -2.900E-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   1.142E-08   1.300E-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   5.812E-04   3.912E-04   0.
 RPI    1.329E+06   1.668E+08   6.390E+05   6.390E+05   6.450E+14
 RX     0.          0.          0.          0.          0.
 RO     2.128E+16   5.410E+16   1.666E+16   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    -9.730E-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                TNOM=  27.000 TEMP=  27.000
       FREQ       I MAG         I PHASE
                  VOUT          VOUT
 1.0000E+00     9.405E-05     8.473E-23
 1.0000E+01     9.405E-05     8.473E-22
```

Problem 5 – (10 points)



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       NPN
Q3    100      3        6       NPN  5
Q4    200      5        6       PNP  5
R1    4        5        100K
R2    3        4        77K
VI    5        100      0.604
.MODEL NPN   NPN  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        = 5.892E-01 0:4         = 7.654E-02 0:5         =-5.980E-01
+0:6        =-4.126E-06 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       1.553E-08  5.000E-09 -5.000E-09
 IC       1.553E-04  5.000E-05 -5.000E-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 NORMAL VALUES AND RUN TEMPERATURE SWEEP
******
VCC   100   0    10
VEE   200   0    -10
IREF  100      3        200U
Q2    3        4        5       NPN
Q3    100      3        6       NPN  5
Q4    200      5        6       PNP  5
R1    4        5        100K
R2    3        4        77K
VI    5        100      0.604
.MODEL NPN  NPN  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        = 6.957E-01 0:4         = 2.110E-01 0:5         =-5.980E-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:NPN      0:NPN      0:PNP
 IB       7.640E-07  1.301E-07 -6.463E-07
 IC       1.910E-04  3.253E-05 -3.232E-05
 VBE      8.089E-01  7.460E-01 -7.477E-01
 VCE      1.451E+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        = 6.375E-01 0:4         = 1.806E-01 0:5         =-5.980E-01
+0:6        = 1.255E-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       7.650E-07  2.068E-07 -1.027E-06
 IC       1.913E-04  5.213E-05 -5.136E-05
 VBE      7.760E-01  7.160E-01 -7.160E-01
 VCE      1.453E+00  9.875E+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         = 1.472E-01 0:5         =-5.980E-01
+0:6        = 9.118E-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       7.660E-07  3.116E-07 -1.553E-06
 IC       1.915E-04  7.790E-05 -7.667E-05
 VBE      7.457E-01  6.870E-01 -6.871E-01
 VCE      1.374E+00  9.909E+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        = 7.188E-01 0:4         = 1.135E-01 0:5         =-5.980E-01
+0:6        = 6.135E-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       7.668E-07  4.401E-07 -2.166E-06
 IC       1.917E-04  1.100E-04 -1.083E-04
 VBE      7.055E-01  6.576E-01 -6.573E-01
 VCE      1.316E+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         = 7.910E-02 0:5         =-5.980E-01
+0:6        = 3.237E-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       7.676E-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      1.256E+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         = 4.482E-02 0:5         =-5.980E-01
+0:6        = 3.721E-04 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       7.682E-07  7.761E-07 -3.816E-06
 IC       1.920E-04  1.939E-04 -1.908E-04
 VBE      6.428E-01  5.979E-01 -5.984E-01
 VCE      1.195E+00  9.998E+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         =-5.980E-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:NPN      0:NPN      0:PNP
 IB       7.688E-07  9.782E-07 -4.816E-06
 IC       1.922E-04  2.446E-04 -2.407E-04
 VBE      6.081E-01  5.662E-01 -5.678E-01
 VCE      1.132E+00  1.003E+01 -9.970E+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        = 6.735E-01 0:4          =-2.438E-02 0:5          =-5.968E-01
+0:6        =-6.127E-03 0:100        = 1.000E+01 0:200        =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1         0:Q2         0:Q4
MODEL    0:NPN        0:NPN        0:PNP
 IB      7.653E-07   1.205E-06  -5.832E-06
 IC      1.913E-04   3.014E-04  -2.916E-04
 VBE     5.718E-01   6.052E-01  -5.347E-01
 VCE     1.065E+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        = 6.513E-01 0:4          =-5.077E-02 0:5          =-5.968E-01
+0:6        =-9.259E-03 0:100        = 1.000E+01 0:200        =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1         0:Q3         0:Q4
MODEL    0:NPN        0:NPN        0:PNP
 IB      7.697E-07   1.454E-06  -7.150E-06
 IC      1.914E-04   3.636E-04  -3.575E-04
 VBE     5.384E-01   5.838E-01  -5.074E-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        = 3.412E-01 0:4          =-9.634E-02 0:5          =-5.968E-01
+0:6        =-1.342E-01 0:100        = 1.000E+01 0:200        =-1.000E+01
**** BIPOLAR JUNCTION TRANSISTORS
SUBCKT
ELEMENT  0:Q1         0:Q3         0:Q4
MODEL    0:NPN        0:NPN        0:PNP
 IB      7.690E-07   1.723E-06  -8.480E-06
 IC      1.925E-04   4.306E-04  -4.240E-04
 VBE     5.080E-01   4.734E-01  -4.718E-01
 VCE     8.442E-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	3.351E-05	45	1.935E-04
-35	5.315E-05	65	2.446E-04
-15	7.750E-05	85	3.014E-04
5	1.100E-04	105	3.636E-04
25	1.486E-04	125	4.306E-04