Homework Assignment No. 8 - Solutions

Problem 1 - (10 points)

This problem deals with the op amp shown in Fig. P6.5-15. All device lengths are 1μm, the slew rate is ±10V/μs, the GB is 10MHz, the maximum output voltage is +2V, the minimum output voltage is -2V, and the input common mode range is from -1V to +2V. Design all W values of all transistors in this op amp. Your design must meet or exceed the specifications. When calculating the maximum or minimum output voltages, divide the voltage drop across series transistors equally. Ignore bulk effects in this problem. When you have completed your design, find the value of the small signal differential voltage gain, $A_{vd} = v_{out}/v_{id}$, where $v_{id} = v_1 - v_2$ and the small signal output resistance, R_{out}.

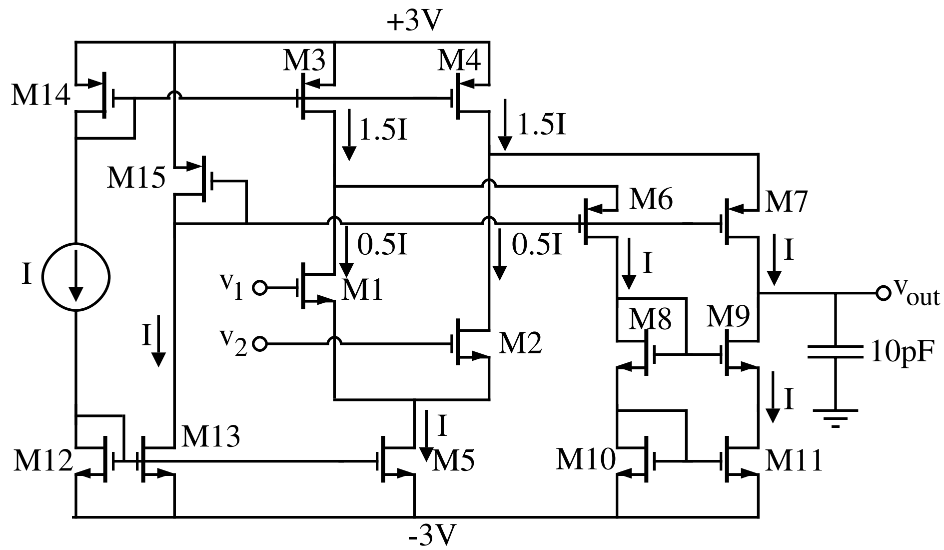


Figure P6.5-15

Solution

1.) The slew rate will specify I. $\quad\therefore\quad I = C\cdot SR = 10^{-11}\cdot 10^{7} = 10^{-4} = 100\mu A$.

2.) Use GB to define W_1 and W_2.

$$GB = \frac{g_{m1}}{C} \quad\rightarrow\quad g_{m1} = GB\cdot C = 2\pi x 10^{7}\cdot 10^{-11} = 628\mu S$$

$$\therefore\ W_1 = \frac{g_{m1}^2}{2K_N(0.5I)} = \frac{(628)^2}{2\cdot 110\cdot 50} = 35.85 \quad\Rightarrow\quad \underline{\underline{W_1 = W_2 = 36\mu m}}$$

3.) Design W_{15} to give $V_T + 2V_{ON}$ bias for M6 and M7. $V_{ON} = 0.5V$ will meet the desired maximum output voltage specification. Therefore,

$$V_{SG15} = V_{ON15} + |V_T| = 2(0.5V) + |V_T| \quad\rightarrow V_{ON15} = 1V = \sqrt{\frac{2I}{K_P W_{15}}}$$

$$\therefore\ W_{15} = \frac{2I}{K_P V_{ON15}^2} = \frac{2\cdot 100}{50\cdot 1^2} = 4\mu m \quad\Rightarrow\quad \underline{\underline{W_{15} = 4\mu m}}$$

4.) Design W_3, W_4, W_6 and W_7 to have a saturation voltage of 0.5V with 1.5I current.

$$W_3 = W_4 = W_6 = W_7 = \frac{2(1.5I)}{K_P V_{ON}^2} = \frac{2\cdot 150}{50\cdot 0.5^2} = 24\mu m \quad\Rightarrow \underline{\underline{W_3 = W_4 = W_6 = W_7 = 24\mu m}}$$

Problem 6.5-15 – Continued

5.) Next design W_8, W_9, W_{10} and W_{11} to meet the minimum output voltage specification. Note that we have not taken advantage of smallest minimum output voltage because a normal cascode current mirror is used which has a minimum voltage across it of $V_T + 2V_{ON}$. Therefore, setting $V_T + 2V_{ON} = 1\text{V}$ gives $V_{ON} = 0.15\text{V}$. Using worst case current, we choose $1.5I$. Therefore,

$$W_8 = W_9 = W_{10} = W_{11} = \frac{2(1.5I)}{K_N V_{ON}^2} = \frac{2\cdot 150}{110\cdot 0.15^2} = 121\mu\text{m} \Rightarrow \underline{\underline{W_8 = W_9 = W_{10} = W_{11} = 121\mu\text{m}}}$$

6.) Check the maximum ICM voltage.

$$V_{ic}(\text{max}) = V_{DD} + V_{SD3}(\text{sat}) + V_{TN} = 3\text{V} - 0.5 + 0.7 = 3.2\text{V} \quad \text{which exceeds spec.}$$

7.) Use the minimum ICM voltage to design W_5.

$$V_{ic}(\text{min}) = V_{SS} + V_{DS5}(\text{sat}) + V_{GS1} = -3 + V_{DS5}(\text{sat}) + \left(\sqrt{\frac{2\cdot 50}{110\cdot 36}} + 0.7\right) = -1\text{V}$$

$$\therefore \quad V_{DS5}(\text{sat}) = 1.141 \rightarrow W_5 = \frac{2I}{K_N\, V_{DS5}(\text{sat})^2} = 1.39\mu\text{m} = 1.4\mu\text{m}$$

Also, let $W_{12} = W_{13} = W_5 \quad \Rightarrow \quad \underline{\underline{W_{12} = W_{13} = W_5 = 1.4\mu\text{m}}}$

8.) W_{14} is designed as

$$W_{14} = W_3 \frac{I_{14}}{I_3} = 24\mu\text{m}\,\frac{I}{1.5I} = 16\mu\text{m} \quad \Rightarrow \quad \underline{\underline{W_{14} = 16\mu\text{m}}}$$

Now, calculate the op amp small-signal performance.

$$R_{out} \approx r_{ds11} g_{m9} r_{ds9} \| g_{m7} r_{ds7} (r_{ds2} \| r_{ds4})$$

$$g_{m9} = \sqrt{2K_N \cdot I \cdot W_9} = 1632\mu\text{S}, \quad r_{ds9} = r_{ds11} = \frac{25\text{V}}{100\mu\text{A}} = 0.25\text{M}\Omega,$$

$$g_{m7} = \sqrt{2K_P \cdot I \cdot W_7} = 490\mu\text{S}, \quad r_{ds7} = \frac{20\text{V}}{100\mu\text{A}} = 0.2\text{M}\Omega, \quad r_{d2} = \frac{25\text{V}}{50\mu\text{A}} = 0.5\text{M}\Omega$$

$$r_{ds4} = \frac{20\text{V}}{150\mu\text{A}} = 0.1333\text{M}\Omega \quad \therefore \quad \underline{\underline{R_{out} \approx 102\text{M}\Omega \| 10.31\text{M}\Omega = 9.3682\text{M}\Omega}}$$

$$A_{vd} = \left(\frac{2+\text{k}}{2+2\text{k}}\right) g_{m1} R_{out}, \quad \text{k} = \frac{102\text{M}\Omega}{(r_{ds2}\|r_{ds4}) g_{m7} r_{ds7}} = 9.888, \quad g_{m1} = \sqrt{K_N \cdot I \cdot W_1} = 629\mu\text{S}$$

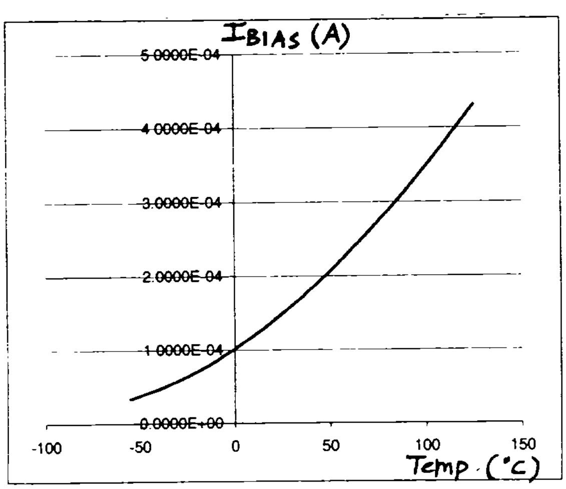
$$\therefore \quad A_{vd} = (0.5459)(629\mu\text{S})(9.3682\text{M}\Omega) = 3{,}217\text{V/V} \quad \Rightarrow \quad \underline{\underline{A_{vd} = 3{,}217\text{V/V}}}$$

```
****  OPERATING POINT INFORMATION      TNOM=  27.000 TEMP=  85.000
  NODE      =VOLTAGE        NODE      =VOLTAGE       NODE       =VOLTAGE
+0:3        = 4.739E-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        = 4.113E-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        =-1.242E-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



6-28

If the bias current level of 741 input stage is doubled, then from (6.134), $G_{m_1} = \frac{1}{2.7\,K\Omega}$

From (6.138),

$$R_{o1} = R_{OUT}|_{Q_4} \,||\, R_{OUT}|_{Q_6}$$

$$= 2\,r_{o4} \,||\, r_{o6}(1 + g_{m_6}(1K\Omega))$$

Using $\eta_{npn} = 2\times10^{-4}$, $\eta_{pnp} = 5\times10^{-4}$

and $|I_C| = 19\,\mu A$, we have

$$r_{o4} = \frac{1}{\eta g_m} = \frac{10^4}{5}\,\frac{26}{19\times10^{-3}} = 2.74\ M\Omega$$

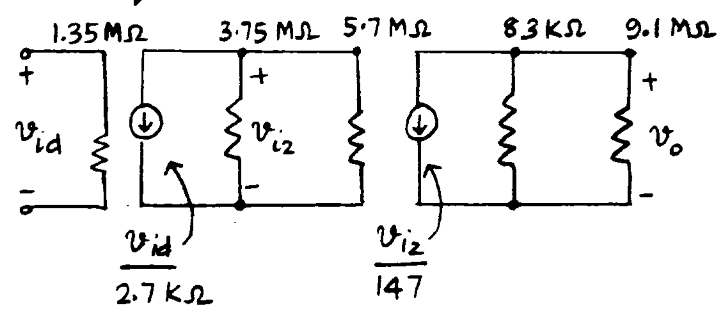
$$r_{o6} = \frac{10^4}{2}\,\frac{26}{19\times10^{-3}} = 6.84\ M\Omega$$

$$g_{m_6} \times 1K\Omega = 0.73$$

$$\therefore\ R_{o1} = (5.48)\,||\,(6.84\times1.73)\ M\Omega$$

$$= 3.75\ M\Omega$$

741 equivalent



$3.75 \,||\, 5.7 \quad 2.26\ M\Omega$; $83K \,||\, 9.1M \simeq 82K\Omega$

$$A_v = \frac{2260}{2.7}\cdot\frac{82}{0.147} = 838\times558$$

$$= 468{,}000$$

6.29

If the 100Ω emitter resistor of Q_{17} is removed, then in (6.142) we have,

$$R_{eq_1} = r_{\pi_{17}} \pm \frac{\beta}{g_m} = 250 \times \frac{26}{0.55} = 11.8\ k\Omega$$

$$R_{i_2} = r_{\pi_{16}} + (1+\beta_o)(r_{\pi_{17}} \,\|\, 50\ k\Omega)$$

$$= 406\ k\Omega + 251 \times 9.55\ k\Omega$$

$$= 2.8\ M\Omega$$

From (6.146)

$$G_{m_2} \simeq g_{m_{17}} = \frac{0.55}{26} = \frac{1}{47.3\Omega}$$

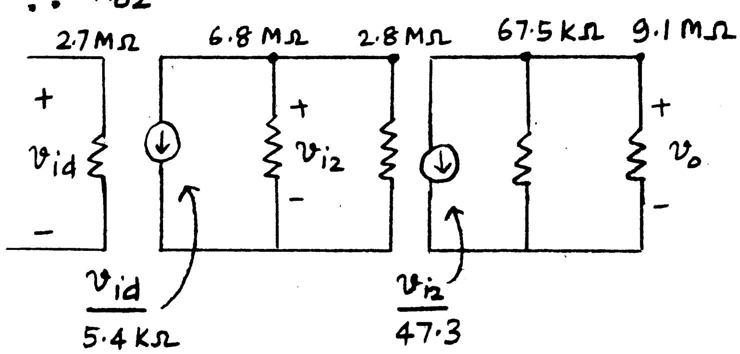
From (6.147)

$$R_{o2} = r_{o13_B} \,\|\, r_{o17}$$

$$r_{o13_B} = \frac{1}{\eta g_m} = \frac{10^4}{5}\,\frac{26}{0.55} = 94.5\ k\Omega$$

$$r_{o17} = \frac{1}{\eta g_m} = \frac{10^4}{2}\,\frac{26}{0.55} = 236\ k\Omega$$

$$\therefore R_{o2} = 67.5\ k\Omega$$



$$6.8 \,\|\, 2.8 = 1.98\ M\Omega$$

$$67.5k \,\|\, 9.1M = 67k$$

$$A_v = \frac{1980}{5.4} \times \frac{67}{0.047}$$

$$= 523{,}000$$

6.30

Minimum CM input voltage:

The circuit ceases to function correctly when Q_3 and Q_4 saturate.

Q_3 and Q_4 operate in the F.A.R. when,

$$V_{EC_3} > V_{CE(sat)}$$

$$V_{E_3} = V_{IC} - V_{BE_1}$$

$$V_{C_3} = -V_{EE} + V_{BE_5} + V_{BE_7} + \underbrace{I_{C_5}(1K)}_{\text{neglect}}$$

$$V_{EC_3} = V_{IC} - V_{BE_1} - (-V_{EE}) - V_{BE_5} - V_{BE_7} > V_{CE(sat)}$$

$$V_{IC} > -V_{EE} + V_{BE_1} + V_{BE_5} + V_{BE_7} + V_{CE(sat)}$$

Maximum CM input voltage:

Q_1 and Q_2 operate in the F.A.R. when

$$V_{CE_1} > V_{CE(sat)}$$

$$V_{C_1} = V_{CC} - |V_{BE_8}|$$

$$V_{E_1} = V_{IC} - V_{BE_1}$$

$$V_{CE_1} = V_{CC} - |V_{BE_8}| - V_{IC} + V_{BE_1} > V_{CE(sat)}$$

Assume $V_{BE_1} = |V_{BE_8}|$

Then $V_{IC} < V_{CC} - V_{CE(sat)}$

```
741 AS A VOLTAGE FOLLOWER
******
* POWER SUPPLIES
VCC   100   0    15
VEE   200   0    -15

* INPUT STAGE
Q1    7     8      10    NPN
Q2    7     9      11    NPN
Q3    12    6      10    PNP
Q4    16    6      11    PNP
Q5    12    13     14    NPN
Q6    16    13     15    NPN
Q7    100   12     13    NPN
Q8    7     7      100   PNP
Q9    6     7      100   PNP
Q10   6     4      5     NPN
Q11   4     4      200   NPN
Q12   3     3      100   PNP
R1    14    200    1K
R2    15    200    1K
R3    13    200    50K
R5    3     4      39K
R4    5     200    5K

* DARLINGTON GAIN STAGE
Q13B  19    3      100   PNPB
Q16   100   16     17    NPN
Q17   19    17     18    NPN
R8    18    200    100
R9    17    200    50K

* OUTPUT STAGE
Q13A  20    3      100   PNPA
Q14   100   20     25    NPN  3
Q18   20    21     22    NPN
Q19   20    20     21    NPN
Q20   200   22     23    PNP  3
Q23   200   19     22    PNP
R6    25    9      27
R7    23    9      22
R10   21    22     40K

VI1   8      0      0
.MODEL NPN   NPN  BF=250  IS=5E-15    VAF=130
.MODEL PNP   PNP  BF=50   IS=2E-15    VAF=50
.MODEL PNPA  PNP  BF=50   IS=0.5E-15  VAF=50
.MODEL PNPB  PNP  BF=50   IS=1.5E-15  VAF=50
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.DC VI1 -15 15 0.5

* ASSUMING VCE(SAT) = 0.2 V AND VBE(ON) = 0.7 V,
* THE HAND CALCULATIONS PREDICT A COMMON-MODE RANGE OF
* -12.7 V < VIC < 14.8 V
* IN THE VOLTAGE-FOLLOWER CONFIGURATION, VO = VI = VIC
* AS LONG AS THE AMPLIFIER IS WORKING CORRECTLY.
* THE RESULTS OF THIS SIMULATION SHOW THAT
* VO = VI FOR THE FOLLOWING RANGE:
* -13 V < VI < 14.5 V
* THEREFORE, THIS SIMULATION SHOWS THAT THE
* COMMON MODE INPUT RANGE IS:
* -13 V < (VO = VI = VIC) < 14.5 V
* WHICH IS CLOSE TO THE RESULT
* PREDICTED BY HAND CALCULATIONS.

.PLOT DC V(9)
.END
```

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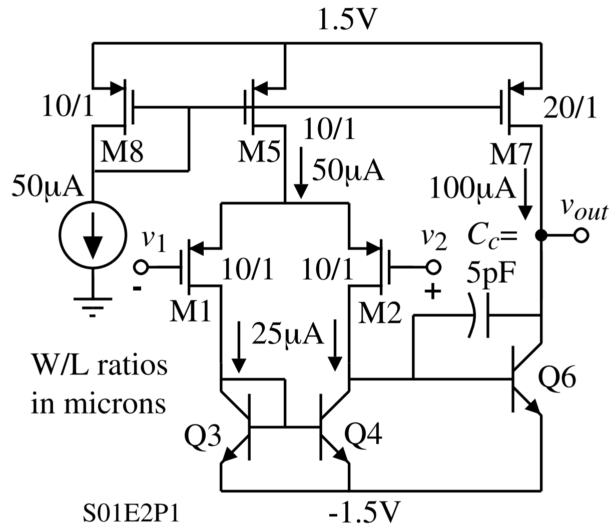
****** DC TRANSFER CURVES          TNOM=  27.000 TEMP=  27.000
    VOLT        V(9)
(A         )    -2.000E+01    -1.000E+01     0.           1.000E+01     2.000E+01
                     +             +             +             +             +
-1.500E+01 -1.31E+01-+------+--A---+------+------+------+------+------+------+-
-1.450E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.400E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.350E+01 -1.31E+01 +      +  A   +      +      +      +      +      +      +
-1.300E+01 -1.30E+01 +      +  A   +      +      +      +      +      +      +
-1.250E+01 -1.25E+01 +      +   A  +      +      +      +      +      +      +
-1.200E+01 -1.20E+01 +      +   A  +      +      +      +      +      +      +
-1.150E+01 -1.15E+01 +      +    A +      +      +      +      +      +      +
-1.100E+01 -1.10E+01 +      +     A+      +      +      +      +      +      +
-1.050E+01 -1.05E+01 +      +     A+      +      +      +      +      +      +
-1.000E+01 -9.99E+00-+------+------A------+------+------+------+------+------+-
-9.500E+00 -9.50E+00 +      +      +A     +      +      +      +      +      +
-9.000E+00 -9.00E+00 +      +      +A     +      +      +      +      +      +
-8.500E+00 -8.50E+00 +      +      + A    +      +      +      +      +      +
-8.000E+00 -8.00E+00 +      +      +  A   +      +      +      +      +      +
-7.500E+00 -7.50E+00 +      +      +   A  +      +      +      +      +      +
-7.000E+00 -7.00E+00 +      +      +   A  +      +      +      +      +      +
-6.500E+00 -6.50E+00 +      +      +    A +      +      +      +      +      +
-6.000E+00 -6.00E+00 +      +      +     A+      +      +      +      +      +
-5.500E+00 -5.50E+00 +      +      +     A+      +      +      +      +      +
-5.000E+00 -5.00E+00-+------+------+------A------+------+------+------+------+-
-4.500E+00 -4.50E+00 +      +      +      +A     +      +      +      +      +
-4.000E+00 -4.00E+00 +      +      +      +A     +      +      +      +      +
-3.500E+00 -3.50E+00 +      +      +      + A    +      +      +      +      +
-3.000E+00 -3.00E+00 +      +      +      +  A   +      +      +      +      +
-2.500E+00 -2.50E+00 +      +      +      +   A  +      +      +      +      +
-2.000E+00 -2.00E+00 +      +      +      +   A  +      +      +      +      +
-1.500E+00 -1.50E+00 +      +      +      +    A +      +      +      +      +
-1.000E+00 -1.00E-00 +      +      +      +     A+      +      +      +      +
-5.000E-01 -5.00E-01 +      +      +      +     A+      +      +      +      +
    0.      2.74E-04-+------+------+------+------A------+------+------+------+-
 5.000E-01  5.00E-01 +      +      +      +      +A     +      +      +      +
 1.000E+00  1.00E+00 +      +      +      +      +A     +      +      +      +
 1.500E+00  1.50E+00 +      +      +      +      + A    +      +      +      +
 2.000E+00  2.00E+00 +      +      +      +      +  A   +      +      +      +
 2.500E+00  2.50E+00 +      +      +      +      +   A  +      +      +      +
 3.000E+00  3.00E+00 +      +      +      +      +   A  +      +      +      +
 3.500E+00  3.50E+00 +      +      +      +      +    A +      +      +      +
 4.000E+00  4.00E+00 +      +      +      +      +     A+      +      +      +
 4.500E+00  4.50E+00 +      +      +      +      +     A+      +      +      +
 5.000E+00  5.00E+00-+------+------+------+------+------A------+------+------+-
 5.500E+00  5.50E+00 +      +      +      +      +      +A     +      +      +
 6.000E+00  6.00E+00 +      +      +      +      +      +A     +      +      +
 6.500E+00  6.50E+00 +      +      +      +      +      + A    +      +      +
 7.000E+00  7.00E+00 +      +      +      +      +      +  A   +      +      +
 7.500E+00  7.50E+00 +      +      +      +      +      +   A  +      +      +
 8.000E+00  8.00E+00 +      +      +      +      +      +   A  +      +      +
 8.500E+00  8.50E+00 +      +      +      +      +      +    A +      +      +
 9.000E+00  9.00E+00 +      +      +      +      +      +     A+      +      +
 9.500E+00  9.50E+00 +      +      +      +      +      +     A+      +      +
 1.000E+01  1.00E+01-+------+------+------+------+------+------A------+------+-
 1.050E+01  1.05E+01 +      +      +      +      +      +      +A     +      +
 1.100E+01  1.10E+01 +      +      +      +      +      +      +A     +      +
 1.150E+01  1.15E+01 +      +      +      +      +      +      + A    +      +
 1.200E+01  1.20E+01 +      +      +      +      +      +      +  A   +      +
 1.250E+01  1.25E+01 +      +      +      +      +      +      +   A  +      +
 1.300E+01  1.30E+01 +      +      +      +      +      +      +   A  +      +
 1.350E+01  1.35E+01 +      +      +      +      +      +      +    A +      +
 1.400E+01  1.40E+01 +      +      +      +      +      +      +     A+      +
 1.450E+01  1.45E+01 +      +      +      +      +      +      +     A+      +
 1.500E+01  1.46E+01-+------+------+------+------+------+------+------A------+-
                     +             +             +             +             +
```

**** OPERATING POINT INFORMATION   TNOM= 27.000 TEMP= 27.000

NODE	=VOLTAGE	NODE	=VOLTAGE	NODE	=VOLTAGE
+0:3	= 1.431E+01	0:4	=-1.433E+01	0:5	=-1.490E+01
+0:6	=-1.107E+00	0:7	= 1.441E+01	0:8	= 0.
+0:9	= 2.744E-04	0:10	=-5.439E-01	0:11	=-5.437E-01
+0:12	=-1.389E+01	0:13	=-1.444E+01	0:14	=-1.499E+01
+0:15	=-1.499E+01	0:16	=-1.370E+01	0:17	=-1.426E+01
+0:18	=-1.493E+01	0:19	=-1.260E+00	0:20	= 5.904E-01
+0:21	= 2.345E-02	0:22	=-6.088E-01	0:23	=-2.361E-03
+0:25	= 3.509E-03	0:100	= 1.500E+01	0:200	=-1.500E+01

Problem 5 – (10 points)

A two-stage, BiCMOS op amp is shown. For the PMOS transistors, the model parameters are K_P'=50μA/V^2, V_{TP} = -0.7V and λ_P = 0.05V^{-1}. For the NPN BJTs, the model parameters are β_F = 100, V_{CE}(sat) = 0.2V, V_A = 25V, V_t = 26mV, I_s = 10fA and n=1. (a.) Identify which input is positive and which input is negative. (b.) Find the numerical values of differential voltage gain magnitude, $|A_v(0)|$, GB (in Hertz), the slew rate, SR, and the location of the RHP zero. (c.) Find the numerical value of the maximum and minimum input common mode voltages.



S01E2P1

Solution

(a.) The plus and minus signs on the schematic show which input is positive and negative.

(b.) The differential voltage gain, $A_v(0)$, is given as

$$A_v(0) = \frac{g_{m1}}{g_{ds2}+g_{o4}+g_{\pi6}} \cdot \frac{g_{m6}}{g_{ds7}+g_{o6}} \qquad g_{m1} = g_{m2} = \sqrt{2\cdot50\cdot25\cdot10} = 158.1\mu S$$

$$r_{ds2} = \frac{1}{\lambda_P I_D} = \frac{20}{25\mu A} = 0.8M\Omega,\ r_{o4} = \frac{V_A}{I_C} = \frac{25V}{25\mu A} = 1M\Omega,\ g_{m6} = \frac{I_C}{V_t} = \frac{100\mu A}{26mV} = 3846\mu S$$

$$r_{\pi6} = \frac{\beta_F}{g_{m6}} = 26k\Omega, \quad r_{ds7} = \frac{1}{\lambda_P I_D} = \frac{20}{100\mu A} = 0.2M\Omega \text{ and } r_{o6} = \frac{V_A}{I_C} = \frac{25V}{100\mu A} = 0.25M\Omega$$

$\therefore$ $|A_v(0)|$ = [158.1(0.8||1||0.026)][3846(0.2||0.25)]= 3.888·427.36 = 1,659.6V/V

$$GB = \frac{g_{m1}}{C_c} = \frac{158.1\mu S}{5pF} = 31.62\text{x}10^6 \text{ rads/sec} \rightarrow GB = 5.0325MHz$$

$$SR = \frac{50\mu A}{5pF} = 10V/\mu s$$

$$\text{RHP zero} = \frac{g_{m6}}{C_c} = \frac{3.846mS}{5pF} = 769.24\text{x}10^6 \text{ rads/sec. (122MHz)}$$

(c.) The maximum input common mode voltage is given as

$$v_{icm}+ = V_{CC}-V_{DS5}(\text{sat}) - V_{SG1} = 1.5 - \sqrt{\frac{2\cdot50}{50\cdot10}} - 0.7 - \sqrt{\frac{2\cdot25}{50\cdot10}} = 0.8 - 0.447 - 0.316 =$$

$\therefore$ $v_{icm}+$ = 0.0367V

$$v_{icm}- = -1.5 + V_{BE3} - V_{T1} = -1.5 + V_t \ln\left(\frac{25\mu A}{10fA}\right) - 0.7 = -2.2 + 0.5626 = -1.6374V$$