Homework Assignment No. 10 - Solutions

Problem 1 - (10 points)

Problem 8.13 of GHLM

Bias

$I_{C1}+I_{C2}=\frac{5.3}{5}=1.06\,mA$

$I_{C1}=\frac{V_{BE3}}{1.25}=\frac{0.7}{1.25}=0.56\,mA$

$\therefore I_{C2}=0.5\,mA$

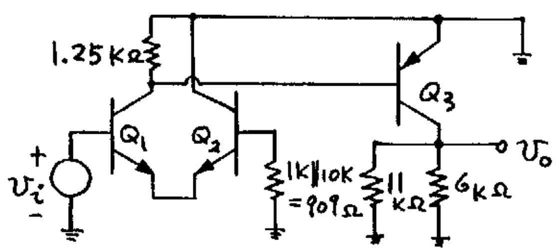
$I_{C3}=\frac{6V}{6k\Omega}=1mA$ for $v_o|_{dc}=0$

Assume $I_{C1}=I_{C2}=0.53\,mA$

Then $r_{\pi 1}=r_{\pi 2}=\frac{200\times 26}{0.53}=9.81\,k\Omega$

$r_{\pi 3}=2.6\,k\Omega$

Basic amplifier



$\frac{v_o}{v_i}=\frac{g_{m1}}{1+g_{m1}R_{E1}}R_1\,g_{m3}R_2$

$R_{E1}=\frac{1}{g_{m2}}+\frac{909}{\beta_2}=\frac{26}{0.53}+\frac{909}{200}$

$=54\,\Omega$

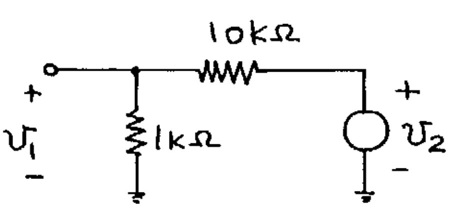
$R_1=1.25k\|r_{\pi 3}=844\,\Omega$

$R_2=6k\|11k=3.88\,k\Omega$

$\therefore \frac{v_o}{v_i}=\frac{0.53}{26}\frac{1}{1+\frac{0.53}{26}54}\,844\,\frac{3880}{26}$

$\therefore a=1222$

$f=h_{12f}=\frac{v_1}{v_2}=\frac{1}{11}$



$\therefore$ loop gain $=\frac{1222}{11}=111$

$\therefore$ with feedback gain

$\frac{v_o}{v_i}=\frac{1222}{1+111}=10.9$

For the basic amplifier

$r_{oa}=11k\|6K=3.88\,k\Omega$

$r_{ia}=r_{\pi 1}(1+g_{m1}R_{E1})$

$=9.81\left(1+\frac{0.53}{26}54\right)=20.6\,k\Omega$

With feedback

$R_o=\frac{3880}{112}=34.6\,\Omega$

$R_i=20.6\times 112=2.3\,M\Omega$

```
FEEDBACK AMP
VCC 1 0 6V
VEE 2 0 -6V
RL 1 3 1.25K
Q1 3 5 4 NPN
Q2 1 6 4 NPN
REE 4 2 5K
Q3 7 3 1 PNP
RBIAS 7 2 6K
RF 7 6 10K
RE 6 0 1K
.MODEL NPN NPN BF=200 IS=1E-15
.MODEL PNP PNP BF=100 IS=1E-15
VI 5 0 SIN 0 0.25 10K 0 0
.TRAN 4US 200US
.PLOT TRAN V(7)
.FOUR 10K V(7)
.DC VI -1 1 0.05
.PLOT DC V(7)
.TF V(7) VI
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
```

```
0****   DC TRANSFER CURVES
  VI         V(7)
              -5.0D+00    0.0D+00    5.0D+00    1.0D+01    1.5D+01
              ----------------------------------------------------
-6.000D-01 -3.884D+00 .  *
-5.500D-01 -3.884D+00 .  *
-5.000D-01 -3.884D+00 .  *
-4.500D-01 -3.884D+00 .  *
-4.000D-01 -3.884D+00 .  *
-3.500D-01 -3.818D+00 .  *
-3.000D-01 -3.318D+00 .   *
-2.500D-01 -2.779D+00 .    *
-2.000D-01 -2.234D+00 .     *
-1.500D-01 -1.686D+00 .      *
-1.000D-01 -1.137D+00 .       *
-5.000D-02 -5.862D-01 .        *
-4.441D-16 -3.500D-02 .          *
 5.000D-02  5.167D-01 .          *
 1.000D-01  1.069D+00 .           *
 1.500D-01  1.621D+00 .            *
 2.000D-01  2.173D+00 .             *
 2.500D-01  2.726D+00 .              *
 3.000D-01  3.279D+00 .               *
 3.500D-01  3.831D+00 .                *
 4.000D-01  4.384D+00 .                 *
 4.500D-01  4.937D+00 .                  *
 5.000D-01  5.490D+00 .                   *
 5.500D-01  5.918D+00 .                    *
 6.000D-01  5.947D+00 .                    *
 6.500D-01  5.950D+00 .                    *
 7.000D-01  5.951D+00 .                    *
 7.500D-01  5.952D+00 .                    *
              ----------------------------------------------------
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8.13 - Cont'd

```
0****   SMALL SIGNAL BIAS SOLUTION
 NODE  VOLTAGE
( 1)  6.0000  ( 2)  -6.0000  ( 3)  5.2856  ( 4)  -0.7006
( 5)  -0.0000  ( 6)  -0.0053  ( 7)  -0.0350

0****   SMALL-SIGNAL CHARACTERISTICS
0   V(7)/VI                          = 1.103D+01
0   INPUT RESISTANCE AT VI               = 2.280D+06
0   OUTPUT RESISTANCE AT V(7)             = 3.505D+01

0**** BIPOLAR JUNCTION TRANSISTORS
0           Q1       Q2       Q3
0MODEL     NPN      NPN      PNP
 IB      2.91E-06 2.37E-06 -9.91E-06
 IC      5.82E-04 4.74E-04 -9.91E-04
 VBE       0.701    0.695   -0.714
 VBC      -5.286   -6.005    5.321
 VCE       5.986    6.701   -6.035
 BETADC  200.0    200.0    100.0

0****   TRANSIENT ANALYSIS
   TIME       V(7)
          -4.0D+00  -2.0D+00   0.0D+00   2.0D+00  4.0D+00
            - - - - - - - - - - - - - - - - - - - - - - - -
 0.000D+00 -3.498D-02 .
 4.000D-06 6.489D-01 .
 8.000D-06 1.287D+00 .
 1.200D-05 1.843D+00 .
 1.600D-05 2.281D+00 .
 2.000D-05 2.574D+00 .
 2.400D-05 2.703D+00 .
 2.800D-05 2.660D+00 .
 3.200D-05 2.447D+00 .
 3.600D-05 2.078D+00 .
 4.000D-05 1.576D+00 .
 4.400D-05 9.736D-01 .
 4.800D-05 3.079D-01 .
 5.200D-05 -3.788D-01 .
 5.600D-05 -1.043D+00 .
 6.000D-05 -1.643D+00 .
 6.400D-05 -2.140D+00 .
 6.800D-05 -2.505D+00 .
 7.200D-05 -2.714D+00 .
 7.600D-05 -2.757D+00 .
 8.000D-05 -2.630D+00 .
 8.400D-05 -2.340D+00 .
 8.800D-05 -1.906D+00 .
 9.200D-05 -1.352D+00 .
 9.600D-05 -7.152D-01 .
 1.000D-04 -3.427D-02 .
            - - - - - - - - - - - - - - - - - - - - - - - -

0****   FOURIER ANALYSIS

 FOURIER COMPONENTS OF TRANSIENT RESPONSE V(7)
 0DC COMPONENT =  -3.085D-02
 0HARMONIC  FREQUENCY  FOURIER   NORMALIZED  PHASE   NORM
   NO        (HZ)     COMPONENT  COMPONENT   (DEG)  PHASE (DEG)
   1     1.000D+04  2.739D+00   1.000000   -0.004     0.000
   2     2.000D+04  4.456D-03   0.001627 -103.114  -103.110
   3     3.000D+04  1.392D-03   0.000508    4.977     4.981

   TOTAL HARMONIC DISTORTION =     0.170784  PERCENT
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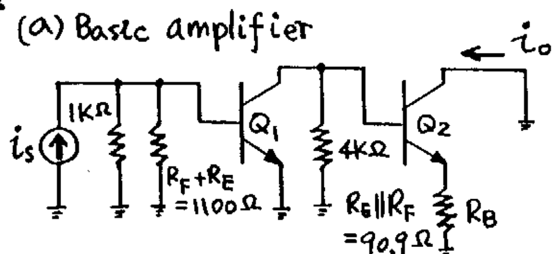
8.17

(a) Basic amplifier



Basic amplifier gain

$$\frac{i_o}{i_s} = -(1k \| 1.1k \| r_{\pi 1})\, g_{m1} R_1 \frac{g_{m2}}{1+g_{m2}R_B}$$

$$R_1 = 4k \| r_{\pi 2}(1+g_{m2}R_B) \| r_{o1}$$

$$= 4k \| 5.2\left(1+\frac{90.9}{26}\right)k \| 100k$$

$$= 3.30\ k\Omega$$

$$\therefore \frac{i_o}{i_s} = -476 \times \frac{3300}{26} \times \frac{1}{26} \times \frac{1}{4.5}$$

$$\therefore a = -516$$

$$r_{ia} = 1k \| 1.1k \| r_{\pi 1} = 476\ \Omega$$

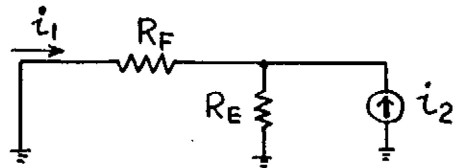
$$r_{oa} = r_{o2}\left(1+g_{m2}R_B \frac{r_{\pi 2}}{r_{\pi 2}+R_{s2}}\right)$$

$$R_{s2} = r_{o1} \| 4k = 3.85\ k\Omega$$

$$\therefore r_{oa} = 100\left(1+\frac{90.9}{26}\frac{5.2}{5.2+3.85}\right)k$$

$$= 300\ k\Omega$$

Feedback network



$$f = g_{12f} = \frac{i_1}{i_2} = -\frac{R_E}{R_E+R_F} = -\frac{100}{1100}$$

$$= -\frac{1}{11}$$

$$\therefore \text{loop gain} = \frac{516}{11} = 46.9 = af$$

∴ with feedback applied

$$\text{overall gain} = \frac{i_o}{i_i} = \frac{a}{1+af}$$

$$= \frac{-516}{47.9} = -10.8$$

Input resistance

$$R_i = \frac{r_{ia}}{1+T} = \frac{476}{47.9} = 9.94\ \Omega$$

Output resistance

$$R_o = r_{oa}(1+T) = 300 \times 47.9 = 14.4\ M\Omega$$

(b) f is unchanged

a increases by about 10 %

∴ change in overall gain is

$$\simeq \frac{10}{47.9} = 0.2\ \%$$

R_i changes by −10 % because

$$R_i = \frac{r_{ia}}{1+af}$$

8.20

(a) Assume high β

$$I_{Q8} = \frac{12-0.6}{11.4} = 1\ mA$$

$$\therefore I_{Q7} \simeq \frac{1400}{300} \times 1 = 4.7\ mA$$

$$\therefore I_{Q1} = I_{Q2} = \frac{1}{2} \times 4.7 = 2.3\ mA$$

$$I_{Q9} = 4.7\ mA$$

$$\therefore I_{Q3} = I_{Q4} = 2.3\ mA$$

$$I_{Q10} = I_{Q11} = \frac{1400}{400} \times 1 = 3.5\ mA$$

$$V_{C3} = V_{C4} = 6 - 1.1 \times 2.3 = 3.5\ V$$

$\therefore$ DC output voltage

$$= 3.5 - 0.6 = 2.9\ V$$

Sum currents at collector of Q_1

$$I_{Q1} = \frac{6 - V_{C1}}{2.4} + \frac{2.9 - V_{C1}}{7}$$

$$\therefore 2.3 = 2.5 - 0.42 V_{C1} + 0.41 - 0.14 V_{C1}$$

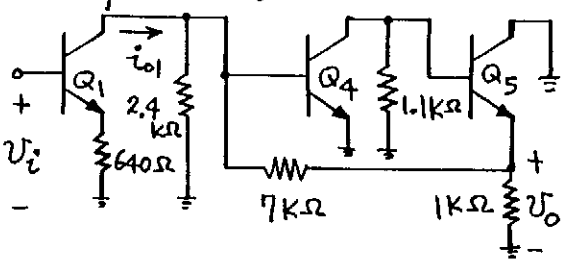
$$\therefore V_{C1} = 1\ V$$

$\therefore$ Current in $7k\Omega$ resistor

$$= \frac{2.9-1}{7} = 0.27\ mA$$

$$\therefore I_{Q5} = I_{Q6} = I_{Q10} + 0.27 = 3.8\ mA$$

(b) Half-circuit




```
733 AMP
VCC 1 0 6V
VEE 2 0 -6V
RC1 1 5 2.4K
RC2 1 6 2.4K
Q1 5 3 7 NPN
Q2 6 4 8 NPN
RE1 7 16 640
RE2 8 16 640
Q3 9 6 15 NPN
Q4 10 5 15 NPN
RC3 1 9 1.1K
RC4 1 10 1.1K
Q5 1 10 11 NPN
Q6 1 9 12 NPN
RF1 11 5 7K
RF2 12 6 7K
RL 11 12 2K
Q7 16 17 18 NPN
Q8 17 17 19 NPN
Q9 15 17 20 NPN
Q10 11 17 13 NPN
Q11 12 17 14 NPN
RQ7 18 2 300
RQ8 19 2 1.4K
RQ9 20 2 300
RQ10 13 2 400
RQ11 14 2 400
RBIAS 1 17 10K
.MODEL NPN NPN BF=100 IS=1E-13
VI1 3 0 0V
VI2 4 0 0V
.TF V(11,12) VI1
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
```

```
0****     SMALL SIGNAL BIAS SOLUTION
 NODE   VOLTAGE
( 1)   6.0000   ( 2)  -6.0000   ( 3)  -0.0000   ( 4)  -0.0000
( 5)   1.7678   ( 6)   1.7678   ( 7)  -0.6128   ( 8)  -0.6128
( 9)   3.8225   ( 10)  3.8225   ( 11)  3.1973   ( 12)  3.1973
( 13) -4.8003   ( 14) -4.8003   ( 15)  1.1550   ( 16) -1.8721
( 17) -4.1766   ( 18) -4.8076   ( 19) -4.7686   ( 20) -4.8076
0**** BIPOLAR JUNCTION TRANSISTORS
0          Q1        Q2        Q3        Q4        Q5        Q6        Q7
0MODEL    NPN       NPN       NPN       NPN       NPN       NPN       NPN
 IB     1.95E-05  1.95E-05  1.95E-05  1.95E-05  3.14E-05  3.14E-05  3.94E-05
 IC     1.95E-03  1.95E-03  1.95E-03  1.95E-03  3.14E-03  3.14E-03  3.94E-03
 VBE      0.613     0.613     0.613     0.613     0.625     0.625     0.631
 VBC     -1.768    -1.768    -2.055    -2.055    -2.178    -2.178    -2.305
 VCE      2.381     2.381     2.667     2.667     2.803     2.803     2.936
 BETADC  100.00    100.00    100.00    100.00    100.00    100.00    100.00
 GM     7.53E-02  7.53E-02  7.53E-02  7.53E-02  1.22E-01  1.22E-01  1.52E-01
 RPI    1.33E+03  1.33E+03  1.33E+03  1.33E+03  8.23E+02  8.23E+02  6.57E+02
 RO     9.46E+11  9.46E+11  9.54E+11  9.54E+11  9.56E+11  9.56E+11  9.58E+11

           Q8        Q9        Q10       Q11
0MODEL    NPN       NPN       NPN       NPN
 IB     8.71E-06  3.94E-05  2.97E-05  2.97E-05
 IC     8.71E-04  3.94E-03  2.97E-03  2.97E-03
 VBE      0.592     0.631     0.624     0.624
 VBC      0.000    -5.332    -7.374    -7.374
 VCE      0.592     5.963     7.998     7.998
 BETADC  100.000   100.000   100.000   100.000
 GM     3.37E-02  1.52E-01  1.15E-01  1.15E-01
 RPI    2.97E+03  6.57E+02  8.71E+02  8.71E+02
 RO     2.05E+11  9.82E+11  9.87E+11  9.87E+11
##########################
HAND ANALYSIS STARTS WITH BIAS STRING: Q8 AND RESISTORS OF
10K AND 1.4K AND FINDS IC8=1MA.  BUT IT FAILS TO ACCOUNT FOR
BASE CURRENTS OF Q7, Q9, Q10, Q11.

USING SPICE, WE SEE THAT THIS 1MA IS DIVIDED AMONG THESE
TRANSISTORS: 1MA=IC8+IB7+IB9+IB10+IB11

SO THE SPICE DC BIAS CURRENTS OF TRANSISTORS ARE DIFFERENT
FROM THE VALUES OBTAINED BY HAND.
##########################
****     SMALL-SIGNAL CHARACTERISTICS
   V(11,12)/VI1                        =  9.531D+00
   INPUT RESISTANCE AT VI1                  =  1.319D+05
   OUTPUT RESISTANCE AT V(11,12)              =  3.793D+00
```

$$R_i = r_{\pi 1} + (1+\beta) R_{E1}$$

$$= \frac{100 \times 26}{2.3} + 101 \times 640 = 66\ k\Omega$$

— for the half circuit

$\therefore R_i = 132\ k\Omega$ — for the complete circuit

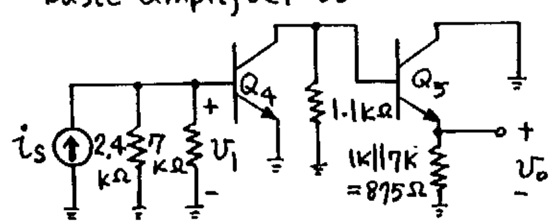
For the first stage

$$\frac{i_{o1}}{v_i} = -\frac{1}{640} \frac{1}{1 + \frac{1}{600}\left(\frac{26}{2.3} + \frac{640}{100}\right)}$$

$$= -1.52\ mA/V$$

Consider the shunt-shunt feedback stage.

Basic amplifier is



8.20-Cont'd

$v_i = i_s(2.4k \| 7k \| r_{\pi4})$
$= i_s \times 0.69k$

$R_{i5} = r_{\pi5} + (1+\beta) \times 875$
$= 684 + 88.4k = 89k\Omega$

$\therefore \frac{v_o}{i_s} = -0.69K \times g_{m4}[1.1k \| 89k]$
$= -0.69k \times \frac{2.3}{26} \times 1087$

$\therefore a = -66.3\ k\Omega$
$f = -\frac{1}{7k}$

$\therefore$ For the output stage with feedback applied

$\frac{v_o}{i_{o1}} = \frac{a}{1+af} = \frac{-281k}{1+9.47} = -6.33\ k\Omega$

$\therefore$ for the overall circuit

$\frac{v_o}{v_i} = 1.52 \times 10^{-3} \times 6.33 \times 10^3 = 9.6$

Loop gain of output stage
$T = af = 9.47$

Output impedance of half circuit
$= 875 \| [\frac{1}{g_{m5}} + \frac{1100}{\beta}]$
$= 875 \| [7 + 11] = 18\Omega$

$\therefore$ For the complete circuit
$r_{oa} = 36\Omega$, and with feedback applied, $R_o = \frac{36}{1+T} = 3.6\Omega$

8.23

$\frac{V_{DD} - V_{GS_2}}{10k} = I_{D_2} = \frac{30\mu}{2} 20 (V_{GS_2} - 0.8)^2$

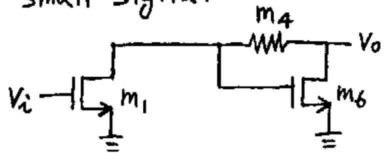
$5 - a = 3(a - 0.8)^2$
$= 3a^2 - 4.8a + 1.92$
$0 = 3a^2 - 3.8a - 3.08$

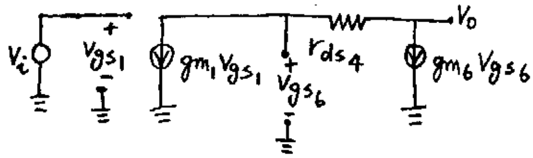
$a = \frac{+3.8 \pm \sqrt{3.8^2 - 4(3)(-3.08)}}{6}$

$V_{GS_2} = 1.83V$

$I_{D_2} = \frac{30\mu}{2} 20 (1.83 - 0.8)^2$
$= 317\mu A = I_{D_1} = I_{D_5} = I_{D_6}$

small signal





$V_o = V_{gs6} - g_{m6} V_{gs6} r_{ds4}$

$g_{m1} = g_{m6}$

$-g_{m1} V_{gs1} = g_{m6} V_{gs6}$

$-V_{gs1} = V_{gs6} = -V_i$

$V_o = -V_i + g_{m6} V_i r_{ds4}$

$\frac{V_o}{V_i} = -1 + g_{m6} r_{ds4}$

$g_{m6} = \sqrt{2(317\mu)(60\mu)(20)}$
$= 872\ \mu A/V$

$g_{ds4} = \mu_n C_{ox} \frac{W}{L}(V_{GS4} - V_{t4})$
$= 150\mu(V_c - 1.53 - 1.14)$
$= 150\mu(V_c - 2.67)$

$V_{t4} = V_{t_o} + \gamma(\sqrt{V_{SB_4} + 2\phi_f} - \sqrt{2\phi_f})$
$= 0.8 + 0.5(\sqrt{1.53+0.6} - \sqrt{0.6})$
$= 1.14V$

$V_{SB_4} = V_{GS6} = V_{t_6} + \sqrt{\frac{2 I_{D6}}{\mu C_{ox} \frac{W}{L}_6}}$
$= 0.8 + \sqrt{\frac{2(317\mu)}{60\mu(20)}}$
$= 1.53V$

$V_c = 3V$

$g_{ds4} = 150\mu(3 - 2.67)$
$= 49.5\mu$

$r_{ds4} = 20.2\ k$

$\frac{V_o}{V_i} = -1 + (872\mu)(20.2k) = 16.6$

8.23 - Cont'd

$V_c = 4\,V$

$$g_{ds_4} = 150\mu(4 - 2.67)$$
$$= 200\mu$$
$$r_{ds_4} = 5.01\,k$$
$$\frac{V_o}{V_i} = -1 + (872\mu)(5.01k)$$
$$= 3.37$$
$$R_o = \frac{1}{g_{m6}} = \frac{1}{872\mu} = 1.15\,k\Omega$$

8.24

$$I_{D_1} = I_{D_2} = \tfrac{1}{2} I_{D_6} = 100\mu A = I_{D_3}$$
$$I_{D_8} = 200\mu A$$
$$a = \tfrac{1}{2} g_{m_1}(2r_{o_2} \,||\, r_{o_3}) \frac{g_{m8}(21k)}{1 + g_{m8}(21k)}$$
$$= \tfrac{1}{2}(693\mu)(222k)(0.954)$$
$$= 73.4$$
$$g_{m_1} = \sqrt{2(100\mu)(60\mu)40}$$
$$= 693\mu A/V$$
$$r_{o_2} = r_{o_3} = \frac{1}{\lambda I_D} = \frac{1}{0.03(100\mu)}$$
$$= 333k$$
$$g_{m8} = \sqrt{2(200\mu)(60\mu)40}$$
$$= 980\mu A/V$$
$$f = \frac{1k}{1k + 20k} = \frac{1}{21}$$
$$T = af = 3.5$$
$$A = \frac{a}{1+T} = \frac{73.4}{4.5} = 16.3 = \frac{V_o}{V_i}$$
$$R_o = \frac{r_{out}}{1+T} = \frac{973}{4.5}$$
$$= 216\Omega$$
$$r_{out} = 21k \,||\, \frac{1}{g_{m8}}$$
$$= 21k \,||\, 1.02k$$
$$= 973\Omega$$

```
VARIABLE GAIN CMOS AMP
 VDD 1 0 5V
 M1 3 4 0 0 NMOS W=20U L=1U
 M2 2 2 1 1 PMOS W=20U L=1U
 R1 2 0 10K
 M3 3 2 1 1 PMOS W=20U L=1U
 M5 5 2 1 1 PMOS W=20U L=1U
 M6 5 3 0 0 NMOS W=20U L=1U
 M4 5 6 3 0 NMOS W=5U L=2U
 VC 6 0 3V
 VI 4 0 1.527V
 .DC VI 1.47 1.6 0.005
 .PLOT DC V(5)
 .TF V(5) VI
 .NODESET V(2)=3.17V V(3)=1.53V V(5)=1.53V
 .MODEL NMOS NMOS KP=60U VTO=0.8 GAMMA=0.5
 .MODEL PMOS PMOS KP=30U VTO=-0.8 GAMMA=0.5
 .OPTIONS NOPAGE NOMOD
 .WIDTH OUT=80
 .OP
 .END
0****     DC TRANSFER CURVES
  VI         V(5)
              1.0D+00  2.0D+00  3.0D+00  4.0D+00  5.0D+00
                  ------------------------------------
 1.470D+00  1.065D+00 .*      .       .       .       .
 1.475D+00  1.092D+00 .*      .       .       .       .
 1.480D+00  1.119D+00 . *     .       .       .       .
 1.485D+00  1.149D+00 . *     .       .       .       .
 1.490D+00  1.180D+00 .  *    .       .       .       .
 1.495D+00  1.213D+00 .  *    .       .       .       .
 1.500D+00  1.248D+00 .  *    .       .       .       .
 1.505D+00  1.287D+00 .   *   .       .       .       .
 1.510D+00  1.329D+00 .   *   .       .       .       .
 1.515D+00  1.376D+00 .    *  .       .       .       .
 1.520D+00  1.430D+00 .    *  .       .       .       .
 1.525D+00  1.495D+00 .     * .       .       .       .
 1.530D+00  1.580D+00 .     * .       .       .       .
 1.535D+00  1.707D+00 .      *.       .       .       .
 1.540D+00  4.292D+00 .       .       .       . *     .
 1.545D+00  4.463D+00 .       .       .       .  *    .
 1.550D+00  4.563D+00 .       .       .       .   *   .
 1.555D+00  4.632D+00 .       .       .       .    *  .
 1.560D+00  4.683D+00 .       .       .       .    *  .
 1.565D+00  4.722D+00 .       .       .       .     * .
 1.570D+00  4.753D+00 .       .       .       .     * .
 1.575D+00  4.777D+00 .       .       .       .     * .
 1.580D+00  4.796D+00 .       .       .       .     * .
 1.585D+00  4.811D+00 .       .       .       .      *.
 1.590D+00  4.822D+00 .       .       .       .      *.
 1.595D+00  4.830D+00 .       .       .       .      *.
 1.600D+00  4.836D+00 .       .       .       .      *.
                  ------------------------------------

0****     SMALL SIGNAL BIAS SOLUTION
 NODE   VOLTAGE
 ( 1)   5.0000   ( 2)   3.1718   ( 3)   1.5271   ( 4)   1.5270
 ( 5)   1.5259   ( 6)   3.0000

0**** MOSFETS
0            M1        M2        M3        M5        M6        M4
0MODEL     NMOS      PMOS      PMOS      PMOS      NMOS      NMOS
 ID     3.17E-04 -3.17E-04 -3.17E-04 -3.17E-04  3.17E-04 -5.96E-08
 VGS       1.527    -1.828    -1.828    -1.828     1.527     1.473
 VDS       1.527    -1.828    -3.473    -3.474     1.526    -0.001
 VBS       0.000     0.000     0.000     0.000     0.000    -1.527
 VTH       0.800    -0.800    -0.800    -0.800     0.800     1.142
 VDSAT     0.727    -1.028    -1.028    -1.028     0.727     0.332
 GM     8.72E-04  6.17E-04  6.17E-04  6.17E-04  8.73E-04  1.80E-07
 GDS    0.00E+0   0.00E+0   0.00E+0   0.00E+0   0.00E+0   4.97E-05
 GMB    2.82E-04  1.99E-04  1.99E-04  1.99E-04  2.82E-04  3.08E-08

0****     SMALL-SIGNAL CHARACTERISTICS
0    V(5)/VI                          =  1.649D+01
0    INPUT RESISTANCE AT VI                  =  1.000D+20
0    OUTPUT RESISTANCE AT V(5)                  =  1.141D+03
```

8.24 - Cont'd

```
VARIABLE GAIN CMOS AMP
VDD 1 0 5V
M1 3 4 0 0 NMOS W=20U L=1U
M2 2 2 1 1 PMOS W=20U L=1U
R1 2 0 10K
M3 3 2 1 1 PMOS W=20U L=1U
M5 5 2 1 1 PMOS W=20U L=1U
M6 5 3 0 0 NMOS W=20U L=1U
M4 5 6 3 0 NMOS W=5U L=2U
VC 6 0 4V
VI 4 0 1.527V
.DC VI 1.0 1.8 0.05
.PLOT DC V(5)
.TF V(5) VI
.NODESET V(2)=3.17V V(3)=1.53V V(5)=1.53V
.MODEL NMOS NMOS KP=60U VTO=0.8 GAMMA=0.5
.MODEL PMOS PMOS KP=30U VTO=-0.8 GAMMA=0.5
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
0****    DC TRANSFER CURVES
  VI        V(5)
             0.0D+00    2.0D+00    4.0D+00    6.0D+00  8.0D+00
            - - - - - - - - - - - - - - - - - - - - - - - - - -
 1.000D+00  7.255D-01 .  *      .         .         .         .
 1.050D+00  7.496D-01 .  *      .         .         .         .
 1.100D+00  7.806D-01 .  *      .         .         .         .
 1.150D+00  8.197D-01 .   *     .         .         .         .
 1.200D+00  8.687D-01 .   *     .         .         .         .
 1.250D+00  9.299D-01 .    *    .         .         .         .
 1.300D+00  1.003D+00 .    *    .         .         .         .
 1.350D+00  1.089D+00 .     *   .         .         .         .
 1.400D+00  1.188D+00 .     *   .         .         .         .
 1.450D+00  1.303D+00 .      *  .         .         .         .
 1.500D+00  1.441D+00 .       * .         .         .         .
 1.550D+00  1.607D+00 .        *.         .         .         .
 1.600D+00  1.803D+00 .         *.        .         .         .
 1.650D+00  2.038D+00 .          *        .         .         .
 1.700D+00  2.339D+00 .         .*        .         .         .
 1.750D+00  4.054D+00 .         .         *         .         .
 1.800D+00  4.132D+00 .         .         .*        .         .
            - - - - - - - - - - - - - - - - - - - - - - - - - -

0****    SMALL SIGNAL BIAS SOLUTION
  NODE   VOLTAGE
 ( 1)   5.0000  ( 2)   3.1718  ( 3)   1.5271  ( 4)   1.5270
 ( 5)   1.5268  ( 6)   4.0000

0**** MOSFETS
```

0	M1	M2	M3	M5	M6	M4
0MODEL	NMOS	PMOS	PMOS	PMOS	NMOS	NMOS
ID	3.17E-04	-3.17E-04	-3.17E-04	-3.17E-04	3.17E-04	-5.96E-08
VGS	1.527	-1.828	-1.828	-1.828	1.527	2.473
VDS	1.527	-1.828	-3.473	-3.473	1.527	0.000
VBS	0.000	0.000	0.000	0.000	0.000	-1.527
VTH	0.800	-0.800	-0.800	-0.800	0.800	1.142
VDSAT	0.727	-1.028	-1.028	-1.028	0.727	1.331
GM	8.72E-04	6.17E-04	6.17E-04	6.17E-04	8.73E-04	4.48E-08
GDS	0.00E+0	0.00E+0	0.00E+0	0.00E+0	0.00E+0	2.00E-04
GMB	2.82E-04	1.99E-04	1.99E-04	1.99E-04	2.82E-04	7.68E-09

```
0****    SMALL-SIGNAL CHARACTERISTICS
0    V(5)/VI                      = 3.369D+00
0    INPUT RESISTANCE AT VI             = 1.000D+20
0    OUTPUT RESISTANCE AT V(5)            = 1.146D+03
```

```
CMOS FEEDBACK AMP
VDD 1 0 5V
VSS 9 0 -5V
M4 2 2 1 1 PMOS W=20U L=1U
I1 2 3 100UA
M5 3 3 9 9 NMOS W=20U L=1U
M6 6 3 9 9 NMOS W=40U L=1U
M1 1 4 6 9 NMOS W=40U L=1U
M2 5 7 6 9 NMOS W=40U L=1U
M3 5 2 1 1 PMOS W=20U L=1U
M8 1 5 8 9 NMOS W=40U L=1U
M7 8 3 9 9 NMOS W=40U L=1U
RF 8 7 20K
RE 7 0 1K
VI 4 0 0V
.TF V(8) VI
.MODEL NMOS NMOS KP=60U VTO=0.8 LAMBDA=0.03
.MODEL PMOS PMOS KP=30U VTO=-0.8 LAMBDA=0.03
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
0****    SMALL SIGNAL BIAS SOLUTION
  NODE   VOLTAGE
 ( 1)   5.0000  ( 2)   3.6341  ( 3)  -3.7989  ( 4)  -0.0000
 ( 5)   1.4134  ( 6)  -1.0776  ( 7)   0.0096  ( 8)   0.2016
 ( 9)  -5.0000

0**** MOSFETS
```

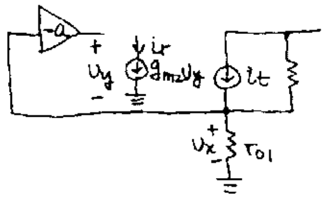
0	M4	M5	M6	M1	M2	M3	M8
0MODEL	PMOS	NMOS	NMOS	NMOS	NMOS	PMOS	NMOS
ID	-1.00E-04	1.00E-04	2.16E-04	1.09E-04	1.06E-04	-1.06E-04	2.33E-04
VGS	-1.366	1.201	1.201	1.078	1.087	-1.366	1.212
VDS	-1.366	1.201	3.922	6.078	2.491	-3.587	4.798
VBS	0.000	0.000	0.000	-3.922	-3.922	0.000	-5.202
VTH	-0.800	0.800	0.800	0.800	0.800	-0.800	0.800
VDSAT	-0.566	0.401	0.401	0.278	0.287	-0.566	0.412
GM	3.54E-04	4.99E-04	1.08E-03	7.88E-04	7.41E-04	3.76E-04	1.13E-03
GDS	2.88E-06	2.90E-06	5.79E-06	2.77E-06	2.97E-06	2.88E-06	6.10E-06

0	M7
0MODEL	NMOS
ID	2.23E-04
VGS	1.201
VDS	5.202
VBS	0.000
VTH	0.800
VDSAT	0.401
GM	1.11E-03
GDS	5.79E-06

```
0****    SMALL-SIGNAL CHARACTERISTICS
0    V(8)/VI                      = 1.662D+01
0    INPUT RESISTANCE AT VI             = 1.000D+20
0    OUTPUT RESISTANCE AT V(8)            = 1.707D+02
```

8.26

(a) g_{m2} is the controlled source.



$R_{out}(g_{m2}=0) = r_{o1}+r_{o2}$

$R(\text{short}) = (r_{o1}\|r_{o2})(a+1)g_{m2}$

$R(\text{open}) = 0$

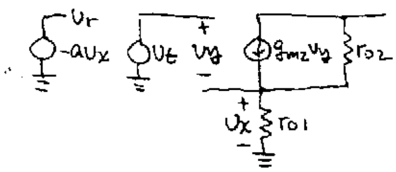
$R_{out} = R_{out}(g_{m2}=0)\dfrac{1+R(\text{short})}{1+R(\text{open})}$

$= (r_{o1}+r_{o2})\dfrac{1+(r_{o1}\|r_{o2})(a+1)g_{m2}}{1+0}$

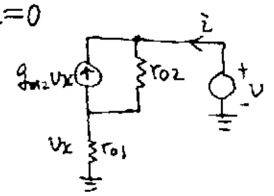
$= r_{o1}+r_{o2}+(a+1)g_{m2}r_{o1}r_{o2}$

$\approx a g_{m2} r_{o1} r_{o2}$

(b) a is the controlled source.



$a=0$



$\dfrac{v_x}{r_{o1}} = g_{m2}v_x + \dfrac{v_x - v}{r_{o2}}$

$R_{out}(a=0) = \dfrac{v}{i} = \dfrac{v}{v_x/r_{o1}}$

$= g_{m2}r_{o1}r_{o2} + r_{o1} - r_{o2}$

$\approx g_{m2}r_{o1}r_{o2}$

The output is short

$v_x = g_{m2}(v_t - v_x)(r_{o1}\|r_{o2})$

$v_x = \dfrac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}v_t$

$R(\text{short}) = a\dfrac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}$

$R(\text{open}) = 0$ ($v_x=0$ when the output is open)

$R_{out} = R_{out}(a=0)\dfrac{1+R(\text{short})}{1+R(\text{open})}$

$\approx g_{m2}r_{o1}r_{o2}\dfrac{1+a\dfrac{g_{m2}(r_{o1}\|r_{o2})}{1+g_{m2}(r_{o1}\|r_{o2})}}{1+0}$

$\approx a g_{m2} r_{o1} r_{o2}$

(c) The results are the same, as they should be, even though the terms $R_{out}(k=0)$, $R(\text{open})$, and $R(\text{short})$ differ in (a) and (b).