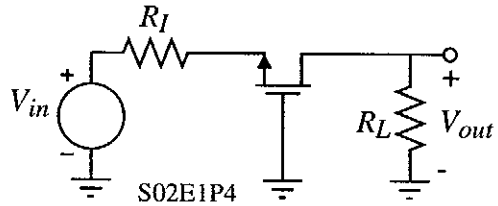
Homework Assignment No. 4 - Solutions

Problem 1 – (10 points)

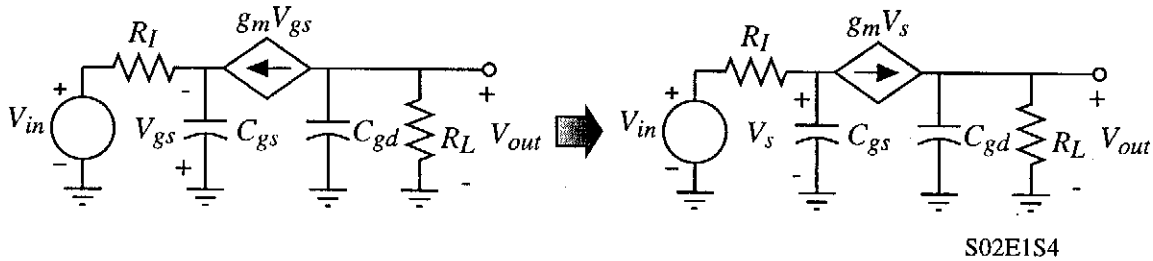
Find the midband voltage gain and the exact value of the two poles of the voltage transfer function for the circuit shown. Assume that $R_I = 1\text{k}\Omega$, $R_L = 10\text{K}\Omega$, $g_m = 1\text{mS}$, $C_{gs} = 5\text{pF}$ and $C_{gd} = 1\text{pF}$. Ignore r_{ds}.



Solution

The best approach to this problem is a direct analysis.

Small-signal model:



$V_{out} = g_m Z_L V_s$ where $Z_L = \dfrac{1}{sR_L C_{gd}+1}$ and $\dfrac{V_{in}-V_s}{R_I} = g_m V_s + sC_{gs}V_s$

Solving for V_s from the second equation gives,

$$V_s = \frac{V_{in}}{1+g_m R_I + sC_{gs}R_I}$$

Substituting V_s in the first equation gives,

$$V_{out} = g_m Z_L \frac{V_{in}}{1+g_m R_I + sC_{gs}R_I} \rightarrow \frac{V_{out}}{V_{in}} = g_m\left(\frac{1}{sR_L C_{gd}+1}\right)\left(\frac{1}{1+g_m R_I + sC_{gs}R_I}\right)$$

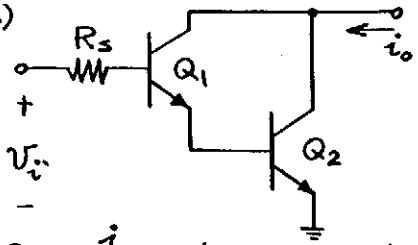
$$= \left(\frac{g_m R_L}{1+g_m R_I}\right)\left(\frac{1}{sR_L C_{gd}+1}\right)\left(\frac{1}{\frac{sC_{gd}R_I}{1+g_m R_I}+1}\right) = \text{MBG}\left(\frac{1}{1-\frac{s}{p_1}}\right)\left(\frac{1}{1-\frac{s}{p_2}}\right)$$

$$\therefore \text{MBG} = \left(\frac{g_m R_L}{1+g_m R_I}\right) = \left(\frac{1\cdot 10}{1+1\cdot 1}\right) = \underline{\underline{5\text{V/V}}}$$

$$p_1 = -\frac{1}{R_L C_{gd}} = -\frac{1}{10\cdot 1\text{ns}} = \underline{\underline{-10^8\text{ rad/s}}} \text{ and } p_2 = -\frac{1+g_m R_I}{R_I C_{gs}} = -\frac{1+1}{1\cdot 5\text{ns}} = \underline{\underline{-4\text{x}10^8\text{ rad/s}}}$$

7.11

(a)



$$G_m = \frac{i_o}{v_i} \simeq \frac{1}{2} g_{m2} = \frac{1}{2}\frac{1}{26} = \frac{1}{52}\ A/V \quad \text{— both circuits}$$

$$R_i \simeq r_{\pi 1}(1 + g_{m1} r_{\pi 2}) = 2 r_{\pi 1} = 2\frac{\beta}{g_{m1}} = 2 \times 100 \times 2.6k = 520k\Omega \quad \text{— both Circuits}$$

$$\therefore \frac{v_o}{v_i} = -\frac{R_i}{R_i + R_s} G_m R_L = -\frac{520}{620} \times \frac{1}{52} \times 3000 = -48.4 \quad \text{— both circuits}$$

(b) Darlington

$R_{cso} = R_L = 3k\Omega$ for Q_1 and Q_2

$\therefore R_{cso}(C_{cs1} + C_{cs2}) = 3 \times 2 = 6$ ns

$$R_{\pi o1} = r_{\pi 1} \| \frac{R_s + R_E}{1 + g_{m1} R_E} = r_{\pi 1} \| \frac{R_s + r_{\pi 2}}{1 + g_{m1} r_{\pi 2}}$$

$$= 260k \| \frac{102.6K}{2} = 42.9k\Omega$$

$$C_\pi + C_\mu = \frac{g_m}{2\pi f_T} = \frac{1}{26}\frac{1}{2\pi \times 500 \times 10^6} = 12.2\ pF \quad \text{at } I_C = 1mA$$

$\therefore C_\pi = 11.8$ pF at $I_C = 1$mA

$C_b = 9.8$ pF

$\therefore C_{b1} = 0.1$ pF, $\therefore C_{\pi 1} = 2.1$ pF

$\therefore C_{\pi 1} R_{\pi o1} = 2.1 \times 42.9 = 90.1$ ns

$R_{\mu o1} = R_x + R_L + G_m R_x R_L$

$R_x = R_i \| R_S = 520k \| 100k = 83.9k\Omega$

$\therefore R_{\mu o1} = 83.9 + 3 + \frac{1}{52} \times 3000 \times 83.9 = 4.93\ M\Omega$

$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 4.93 \times 10^3 = 1972$ ns

$C_{\pi 2} = 11.8$ pF

$$R_{\pi o2} = r_{\pi 2} \| \left(\frac{1}{g_{m1}} + \frac{R_s}{\beta_1}\right) = 2.6k \| (2.6k + \frac{100k}{100}) = 2.6k \| 3.6k = 1.51\ k\Omega$$

$\therefore C_{\pi 2} R_{\pi o2} = 17.8$ ns

$$R_{\mu o} = R_{\pi o2} + R_L + g_{m2} R_L R_{\pi o2} = 1.51 + 3 + \frac{3000}{26} \times 1.51 = 179\ k\Omega$$

$\therefore C_{\mu 2} R_{\mu o2} = 0.4 \times 179 = 71$ ns

$\therefore \Sigma T_o = 6 + 90 + 1972 + 18 + 71 = 2157$ ns

$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 73.8$ kHz

Common-collector-Common emitter

$R_{cso} C_{cs2} = 3$ ns

$R_{cso} C_{cs1} = 0$

$C_{\pi 1} R_{\pi o1} = 90.1$ ns

$C_{\pi 2} R_{\pi o2} = 17.8$ ns

$C_{\mu 2} R_{\mu o2} = 71$ ns

$R_{\mu o1} = R_i \| R_s = 83.9\ k\Omega$

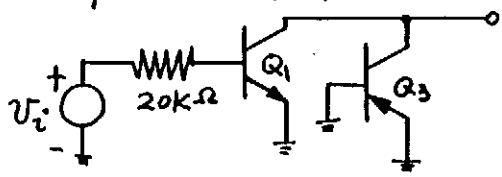
$\therefore C_{\mu 1} R_{\mu o1} = 0.4 \times 83.9 = 33.6$ ns

$\therefore \Sigma T_o = 3 + 90.1 + 17.8 + 71 + 33.6 = 215.5$ ns

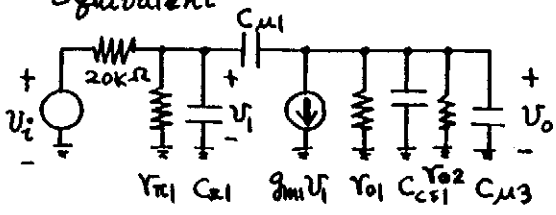
$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 738$ kHz

7.15

Half-circuits (ac)



Equivalent



$I_{C6} = \frac{9.4}{20} = 470\ \mu A$

$I_{C5} = \frac{V_T}{R_E} \ln \frac{I_{C6}}{I_{C5}} = 2.6 \ln \frac{470}{I_{C5}}\ \mu A$

$= 10\ \mu A$

$\therefore I_{C1} = I_{C3} = I_{C5}/2 = 5\mu A$

Q1

$r_{o1} = \frac{V_A}{I_{C1}} = \frac{120}{5} = 24\ M\Omega$

$r_{\pi 1} = \frac{\beta}{g_{m1}} = 200 \times \frac{26}{0.005} = 1.04\ M\Omega$

$C_{\mu 1} = \frac{0.7}{\sqrt{1 + \frac{5}{0.55}}} = 0.22\ pF$

$C_{cs1} = \frac{2}{\sqrt{1 + \frac{15}{0.55}}} = 0.38\ pF$

$C_{\pi 1} + C_{\mu 1} = \frac{g_m}{2\pi f_T} = \frac{1}{2\pi \times 26 \times 500 \times 10^6}$

$= 12.2pF$ at $1mA$

$\therefore C_{\pi 1} = 12\ pF$ at $1mA$

$C_{b1} = 9\ pF$ at $1mA$

$\simeq 0$ at $5\mu A$

$\therefore C_{\pi 1} = 3\ pF$ at $5\mu A$

Q3

$r_{o3} = \frac{50}{5} = 10 M\Omega$

$C_{\mu 3} = \frac{1}{\sqrt{1 + \frac{4.4}{0.55}}} = 0.33\ pF$

$\frac{v_o}{v_i} = -\frac{r_{\pi 1}}{r_{\pi 1} + R_S} g_{m1} r_o$

$r_o = r_{o1} \| r_{o3} = 24 \| 10 = 7.06\ M\Omega$

$\frac{v_o}{v_i} = -\frac{1.04}{1.06} \times \frac{0.005}{26} \times 7.06 \times 10^6$

$= -1332$

$R_{\pi o1} = r_{\pi 1} \| R_S = 1M \| 20k = 19.6 K\Omega$

$\therefore C_{\pi 1} R_{\pi o1} = 3 \times 19.6 = 59\ ns$

$R_{\mu o1} = R_{\pi o1} + r_o + g_{m1} R_{\pi o1} r_o$

$R_{\mu o1} = 19.6K + 7.06M + \frac{0.005}{26} \times 19600 \times 7.06M$

$= 33.7 M\Omega$

$\therefore C_{\mu 1} R_{\mu o1} = 0.22 \times 33.7 = 7.41\ \mu s$

$(C_{cs1} + C_{\mu 3}) r_o = 0.71 \times 7.06 = 5.0\ \mu s$

$\therefore \Sigma T_o = 0.06 + 7.41 + 5 = 12.47\ \mu s$

$\therefore f_{-3dB} = \frac{1}{2\pi \Sigma T_o} = 12.8\ kHz$

7.21 (a)

$V_o = 2.5\ V\ dc$

$V_{GS_2} = 2.5\ V$

$V_{t_2} = V_{to} + \gamma\left(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right)$

$= 0.7 + 0.4\left(\sqrt{0.6 + 2.5} - \sqrt{0.6}\right)$

$= 1.09\ V$

$I_D = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)_2 (V_{GS_2} - V_{t_2})^2$

$= \frac{60\mu}{2} \frac{4}{1} (2.5 - 1.09)^2$

$= 237\ \mu A$

$\frac{V_o}{V_i} = \frac{-g_{m_1}}{g_{m_2} + g_{mb_2}} = \frac{-1.69m}{337\mu + 38.3\mu}$

$= -4.5$

$g_{m_1} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$

$= \sqrt{2(237\mu)(60\mu)(100)}$

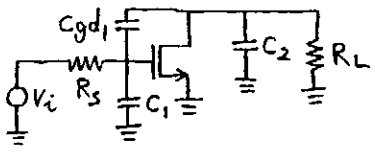
$= 1.69\ mA/V$

$g_{m_2} = \sqrt{2(237\mu)(60\mu)(4)}$

$= 337\ \mu A/V$

$g_{mb_2} = \frac{g_{m_2}\gamma}{2\sqrt{2\phi_f + V_{SB}}} = \frac{g_{m_2} 0.4}{2\sqrt{0.6 + 2.5}}$

$= 38.3\ \mu A/V$



$C_{ox} = 1.73\ \frac{fF}{\mu^2}$

$C_{gs1} = \frac{2}{3} WL C_{ox} + C_{o1} W$

$= 115\ fF + 30fF = 145fF$

$C_{gs2} = \frac{2}{3} WL C_{ox} + C_{o1} W$

$= 4.61\ fF + 1.2fF$

$= 5.8\ fF$

7.21- Continued

$$C_{db_1} = \frac{0.8\,(100)}{\sqrt{1+\frac{2.5}{0.6}}} = 35.2\text{ fF}$$

$$C_{gd_1} = C_{ol} W = 30\text{ fF}$$

$$C_{sb_2} = \frac{0.8\,(4)}{\sqrt{1+\frac{2.5}{0.6}}} = 1.41\text{ fF}$$

$$C_1 = C_{gs_1} = 145\text{ fF}$$

$$C_2 = C_{db_1} + C_{sb_2} + C_{gs_2} + C_L$$

$$= 142\text{ fF}$$

$$C_1 R_S = 145\text{ ps}$$

$$C_2 R_L = 142\text{ fF}(2665\,\Omega)$$

$$= 378\text{ ps}$$

$$C_{gd_1}(R_S + R_L + g_m R_S R_L)$$

$$= 30(1k + 2665 + 1.69m(1k)(2665))\text{ f}$$

$$= 245\text{ ps}$$

$$f_{-3dB} = \frac{1}{2\pi}\,\frac{10^{12}}{145+378+245}$$

$$= 207\text{ MHz}$$

(b)

$$R_{SX} = \frac{1}{\mathcal{E}_c\, \mu C_{ox} W}$$

$$m1 \quad R_{SX} = \frac{1}{1.5M\;\; 60\mu\;\; 100\mu}$$

$$= 111\,\Omega$$

$$m2 \quad R_{SX} = \frac{1}{1.5M\; 60\mu\; 4\mu}$$

$$= 2.78\text{ k}$$

$$R_L' = R_{SX_2} + \frac{1}{g_{m2} + g_{mb2}}$$

$$= 2.78k + 2.66k$$

$$= 5.44\text{ k}$$

$$g_{m1}' = \frac{g_{m1}}{1 + g_{m1} R_{SX_1}}$$

$$= 1.42\text{ mA/V}$$

$$\frac{V_o}{V_i} = -g_{m1}' R_L' = -7.74$$

$$C_1 R_S = 145\text{ ps} \quad \text{unchanged}$$

$$C_2 R_L' = C_2 R_L \frac{R_L'}{R_L}$$

$$= 378\text{ ps}\,(2.04)$$

$$= 772\text{ ps}$$

$$C_{gd_1}(R_S + R_L' + g_{m1}' R_L' R_S)$$

$$= 30f(1k + 5.44k + 1.42m(5.44k)(1k))$$

$$= 425\text{ ps}$$

$$f_{-3dB} = \frac{1}{2\pi}\,\frac{10^{12}}{145+772+425}$$

$$= 119\text{ MHz}$$

```
NMOS AMP
VDD 1 0 5V
M2 1 1 2 0 NMOS2 W=4U L=1U
M1 2 3 0 0 NMOS W=100U L=1U
CLOAD 2 0 100FF
RS 4 3 1K
VI 4 0 0.981V AC
.PLOT AC VDB(2)
.PLOT AC VP(2)
.AC DEC 15 1MEG 2GIG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS2 NMOS KP=60U VTO=0.7 LAMBDA=0 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=3.2FF CBS=3.2FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
0****     SMALL SIGNAL BIAS SOLUTION
 NODE   VOLTAGE
( 1)  5.0000  ( 2)  2.5005  ( 3)  0.9810  ( 4)  0.9810
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```
0**** MOSFETS
0            M2         M1
0MODEL   NMOS2      NMOS
 ID      2.37E-04  2.37E-04
 VGS      2.499     0.981
 VDS      2.499     2.501
 VBS     -2.501     0.000
 VTH      1.094     0.700
 VDSAT    1.405     0.281
 GM      3.37E-04  1.69E-03
 GDS    -0.00E+00 -0.00E+00
 GMB     3.83E-05  4.35E-04
 CBD     1.19E-15  3.94E-14
 CBS     1.58E-15  8.00E-14
 CGSOVL  1.20E-15  3.00E-14
 CGDOVL  1.20E-15  3.00E-14
 CGBOVL  0.00E+00  0.00E+00
 CGS     4.60E-15  1.15E-13
 CGD     0.00E+00  0.00E+00
 CGB     0.00E+00  0.00E+00
```

```
0****     AC ANALYSIS
  FREQ      VDB(2)
                 -2.0D+01   -1.0D+01    0.0D+00    1.0D+01  2.0D+01
                   ------------------------------------------
1.000D+06  1.304D+01 .          .          .          . *      .
1.166D+06  1.304D+01 .          .          .          . *      .
1.359D+06  1.304D+01 .          .          .          . *      .
1.585D+06  1.304D+01 .          .          .          . *      .
1.848D+06  1.304D+01 .          .          .          . *      .
2.154D+06  1.304D+01 .          .          .          . *      .
2.512D+06  1.304D+01 .          .          .          . *      .
2.929D+06  1.304D+01 .          .          .          . *      .
3.415D+06  1.304D+01 .          .          .          . *      .
3.981D+06  1.304D+01 .          .          .          . *      .
4.642D+06  1.304D+01 .          .          .          . *      .
5.412D+06  1.304D+01 .          .          .          . *      .
6.310D+06  1.304D+01 .          .          .          . *      .
7.356D+06  1.304D+01 .          .          .          . *      .
8.577D+06  1.304D+01 .          .          .          . *      .
1.000D+07  1.304D+01 .          .          .          . *      .
1.166D+07  1.303D+01 .          .          .          . *      .
1.359D+07  1.303D+01 .          .          .          . *      .
1.585D+07  1.303D+01 .          .          .          . *      .
1.848D+07  1.302D+01 .          .          .          . *      .
2.154D+07  1.301D+01 .          .          .          . *      .
2.512D+07  1.300D+01 .          .          .          . *      .
2.929D+07  1.298D+01 .          .          .          . *      .
3.415D+07  1.296D+01 .          .          .          . *      .
3.981D+07  1.292D+01 .          .          .          . *      .
4.642D+07  1.288D+01 .          .          .          . *      .
5.412D+07  1.282D+01 .          .          .          . *      .
6.310D+07  1.275D+01 .          .          .          . *      .
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7.21 - Continued

```
7.356D+07  1.265D+01 .
8.577D+07  1.251D+01 .
1.000D+08  1.233D+01 .
1.166D+08  1.210D+01 .
1.359D+08  1.180D+01 .
1.585D+08  1.143D+01 .
1.848D+08  1.096D+01 .
2.154D+08  1.039D+01 .
2.512D+08  9.706D+00 .
2.929D+08  8.909D+00 .
3.415D+08  7.995D+00 .
3.981D+08  6.967D+00 .
4.642D+08  5.827D+00 .
5.412D+08  4.579D+00 .
6.310D+08  3.225D+00 .
7.356D+08  1.764D+00 .
8.577D+08  1.959D-01 .
1.000D+09 -1.482D+00 .
1.166D+09 -3.272D+00 .
1.359D+09 -5.172D+00 .
1.585D+09 -7.176D+00 .
1.848D+09 -9.276D+00 .
2.154D+09 -1.146D+01 .
```

0**** AC ANALYSIS

```
   FREQ     VP(2)
            0.0D+00    5.0D+01    1.0D+02    1.5D+02  2.0D+02
1.000D+06  1.797D+02 .
1.166D+06  1.797D+02 .
1.359D+06  1.796D+02 .
1.585D+06  1.795D+02 .
1.848D+06  1.795D+02 .
2.154D+06  1.794D+02 .
2.512D+06  1.793D+02 .
2.929D+06  1.792D+02 .
3.415D+06  1.790D+02 .
3.981D+06  1.789D+02 .
4.642D+06  1.787D+02 .
5.412D+06  1.784D+02 .
6.310D+06  1.782D+02 .
7.356D+06  1.779D+02 .
8.577D+06  1.775D+02 .
1.000D+07  1.771D+02 .
1.166D+07  1.767D+02 .
1.359D+07  1.761D+02 .
1.585D+07  1.755D+02 .
1.848D+07  1.747D+02 .
2.154D+07  1.738D+02 .
2.512D+07  1.728D+02 .
2.929D+07  1.716D+02 .
3.415D+07  1.702D+02 .
3.981D+07  1.686D+02 .
4.642D+07  1.668D+02 .
5.412D+07  1.647D+02 .
6.310D+07  1.622D+02 .
7.356D+07  1.594D+02 .
8.577D+07  1.562D+02 .
1.000D+08  1.525D+02 .
1.166D+08  1.484D+02 .
1.359D+08  1.438D+02 .
1.585D+08  1.388D+02 .
1.848D+08  1.334D+02 .
2.154D+08  1.275D+02 .
2.512D+08  1.214D+02 .
2.929D+08  1.150D+02 .
3.415D+08  1.085D+02 .
3.981D+08  1.018D+02 .
4.642D+08  9.501D+01 .
5.412D+08  8.815D+01 .
6.310D+08  8.120D+01 .
7.356D+08  7.417D+01 .
8.577D+08  6.705D+01 .
1.000D+09  5.986D+01 .
1.166D+09  5.262D+01 .
1.359D+09  4.539D+01 .
1.585D+09  3.821D+01 .
1.848D+09  3.112D+01 .
2.154D+09  2.417D+01 .
```

* DOMINANT POLE @ (DC PHASE - 45 DEGREES) = 135 DEGREES
* DOMINANT POLE = 185 MEGAHERTZ
* SECOND POLE @ (DC PHASE - 135 DEGREES) = 45 DEGREES
* SECOND POLE = 1.36 GIGAHERTZ

NMOS AMP, EXAMINE SMALL SIGNAL BANDWIDTH AS DC VIN VARIES

VI 4 0 0.5V AC

0**** AC ANALYSIS

```
   FREQ     VDB(2)
            -3.0D+01   -2.5D+01   -2.0D+01   -1.5D+01 -1.0D+01
3.981D+07 -1.510D+01 .
4.642D+07 -1.511D+01 .
5.412D+07 -1.511D+01 .
6.310D+07 -1.511D+01 .
7.356D+07 -1.512D+01 .
8.577D+07 -1.513D+01 .
1.000D+08 -1.514D+01 .
1.166D+08 -1.515D+01 .
1.359D+08 -1.517D+01 .
1.585D+08 -1.519D+01 .
1.848D+08 -1.523D+01 .
2.154D+08 -1.527D+01 .
2.512D+08 -1.534D+01 .
2.929D+08 -1.542D+01 .
3.415D+08 -1.553D+01 .
3.981D+08 -1.567D+01 .
4.642D+08 -1.586D+01 .
5.412D+08 -1.611D+01 .
6.310D+08 -1.642D+01 .
7.356D+08 -1.681D+01 .
8.577D+08 -1.730D+01 .
1.000D+09 -1.788D+01 .
1.166D+09 -1.856D+01 .
```

VI 4 0 1.5V AC

0**** AC ANALYSIS

```
   FREQ     VDB(2)
            -1.5D+01   -1.0D+01   -5.0D+00    0.0D+00 5.0D+00
2.929D+06  2.273D-01 .
3.415D+06  2.273D-01 .
3.981D+06  2.272D-01 .
4.642D+06  2.271D-01 .
5.412D+06  2.269D-01 .
6.310D+06  2.267D-01 .
7.356D+06  2.264D-01 .
8.577D+06  2.260D-01 .
1.000D+07  2.254D-01 .
1.166D+07  2.247D-01 .
1.359D+07  2.236D-01 .
1.585D+07  2.223D-01 .
1.848D+07  2.204D-01 .
2.154D+07  2.178D-01 .
2.512D+07  2.143D-01 .
2.929D+07  2.096D-01 .
3.415D+07  2.031D-01 .
3.981D+07  1.944D-01 .
4.642D+07  1.825D-01 .
5.412D+07  1.665D-01 .
6.310D+07  1.447D-01 .
7.356D+07  1.153D-01 .
8.577D+07  7.570D-02 .
1.000D+08  2.238D-02 .
1.166D+08 -4.909D-02 .
1.359D+08 -1.445D-01 .
1.585D+08 -2.709D-01 .
1.848D+08 -4.372D-01 .
2.154D+08 -6.539D-01 .
2.512D+08 -9.325D-01 .
2.929D+08 -1.286D+00 .
```

7.21 - Continued

```
3.415D+08 -1.725D+00 .
3.981D+08 -2.261D+00 .
4.642D+08 -2.901D+00 .
```

VI 4 0 2V AC
0**** AC ANALYSIS
FREQ VDB(2)

```
                -2.5D+01   -2.0D+01   -1.5D+01   -1.0D+01   -5.0D+00
2.512D+07 -1.312D+01 .
2.929D+07 -1.312D+01 .
3.415D+07 -1.313D+01 .
3.981D+07 -1.313D+01 .
4.642D+07 -1.314D+01 .
5.412D+07 -1.315D+01 .
6.310D+07 -1.316D+01 .
7.356D+07 -1.318D+01 .
8.577D+07 -1.320D+01 .
1.000D+08 -1.323D+01 .
1.166D+08 -1.327D+01 .
1.359D+08 -1.332D+01 .
1.585D+08 -1.340D+01 .
1.848D+08 -1.349D+01 .
2.154D+08 -1.362D+01 .
2.512D+08 -1.379D+01 .
2.929D+08 -1.400D+01 .
3.415D+08 -1.427D+01 .
3.981D+08 -1.462D+01 .
4.642D+08 -1.504D+01 .
5.412D+08 -1.555D+01 .
6.310D+08 -1.614D+01 .
7.356D+08 -1.681D+01 .
```

VI 4 0 3V AC
0**** AC ANALYSIS
FREQ VDB(2)

```
                -3.5D+01   -3.0D+01   -2.5D+01   -2.0D+01   -1.5D+01
4.642D+07 -2.380D+01 .
5.412D+07 -2.381D+01 .
6.310D+07 -2.382D+01 .
7.356D+07 -2.383D+01 .
8.577D+07 -2.384D+01 .
1.000D+08 -2.386D+01 .
1.166D+08 -2.389D+01 .
1.359D+08 -2.392D+01 .
1.585D+08 -2.397D+01 .
1.848D+08 -2.403D+01 .
2.154D+08 -2.412D+01 .
2.512D+08 -2.423D+01 .
2.929D+08 -2.437D+01 .
3.415D+08 -2.455D+01 .
3.981D+08 -2.477D+01 .
4.642D+08 -2.504D+01 .
5.412D+08 -2.536D+01 .
6.310D+08 -2.573D+01 .
7.356D+08 -2.613D+01 .
8.577D+08 -2.657D+01 .
1.000D+09 -2.701D+01 .
```

VI 4 0 4V AC
0**** AC ANALYSIS
FREQ VDB(2)

```
                -3.6D+01   -3.4D+01   -3.2D+01   -3.0D+01   -2.8D+01
4.642D+07 -3.005D+01 .
5.412D+07 -3.006D+01 .
6.310D+07 -3.006D+01 .
7.356D+07 -3.007D+01 .
8.577D+07 -3.008D+01 .
1.000D+08 -3.009D+01 .
1.166D+08 -3.010D+01 .
1.359D+08 -3.012D+01 .
1.585D+08 -3.015D+01 .
1.848D+08 -3.018D+01 .
2.154D+08 -3.023D+01 .
2.512D+08 -3.029D+01 .
2.929D+08 -3.037D+01 .
3.415D+08 -3.046D+01 .
3.981D+08 -3.058D+01 .
4.642D+08 -3.072D+01 .
5.412D+08 -3.088D+01 .
6.310D+08 -3.106D+01 .
7.356D+08 -3.125D+01 .
8.577D+08 -3.144D+01 .
1.000D+09 -3.163D+01 .
1.166D+09 -3.181D+01 .
1.359D+09 -3.197D+01 .
1.585D+09 -3.211D+01 .
1.848D+09 -3.224D+01 .
2.154D+09 -3.235D+01 .
2.512D+09 -3.246D+01 .
2.929D+09 -3.256D+01 .
3.415D+09 -3.267D+01 .
3.981D+09 -3.279D+01 .
4.642D+09 -3.293D+01 .
5.412D+09 -3.310D+01 .
6.310D+09 -3.332D+01 .
7.356D+09 -3.359D+01 .
```

VI 4 0 5V AC
0**** AC ANALYSIS
FREQ VDB(2)

```
                -5.0D+01   -4.5D+01   -4.0D+01   -3.5D+01   -3.0D+01
3.415D+08 -3.460D+01 .
3.981D+08 -3.461D+01 .
4.642D+08 -3.462D+01 .
5.412D+08 -3.463D+01 .
6.310D+08 -3.464D+01 .
7.356D+08 -3.465D+01 .
8.577D+08 -3.467D+01 .
1.000D+09 -3.468D+01 .
1.166D+09 -3.470D+01 .
1.359D+09 -3.471D+01 .
1.585D+09 -3.472D+01 .
1.848D+09 -3.474D+01 .
2.154D+09 -3.476D+01 .
2.512D+09 -3.479D+01 .
2.929D+09 -3.482D+01 .
3.415D+09 -3.486D+01 .
3.981D+09 -3.492D+01 .
4.642D+09 -3.500D+01 .
5.412D+09 -3.510D+01 .
6.310D+09 -3.523D+01 .
7.356D+09 -3.540D+01 .
8.577D+09 -3.563D+01 .
1.000D+10 -3.591D+01 .
1.166D+10 -3.627D+01 .
1.359D+10 -3.672D+01 .
1.585D+10 -3.727D+01 .
1.848D+10 -3.791D+01 .
2.154D+10 -3.865D+01 .
2.512D+10 -3.950D+01 .
```

7.22

m_3, m_4 $I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}(V_{GS}-V_t)^2$

$100\mu = 15\mu\ 50\ (V_{GS}-V_t)^2$

$V_{GS} = -1.065\ V$

m_2, m_6, m_7

$100\mu = 30\mu\ 50\ (V_{GS}-V_t)^2$

$V_{GS} = 0.958\ V$

$V_{GS5} = 5 - 1.065 - 0.958$

$= 2.977\ V$

$100\mu = 15\mu \frac{W}{L}(2.977-0.7)^2$

$m_5 \frac{W}{L} = 1.286 = \frac{2.57\mu}{2\mu}$

$2.5 = V_{GS_1} + V_{GS_2}$

$2.5 - 0.958 = 1.542\ V = V_{GS_1}$

$V_{t_1} = V_{t_0} + \gamma\left(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right)$

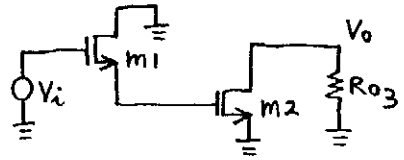
$= 0.7 + 0.4\left(\sqrt{0.6+0.958} - \sqrt{0.6}\right)$

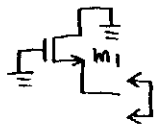
$= 0.89$

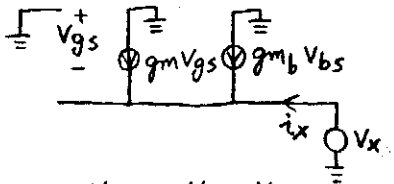
$I_{D_1} = 100\mu = 30\mu\left(\frac{W}{L}\right)_1 (1.542-0.89)^2$

$\left(\frac{W}{L}\right)_1 = 7.83 = \frac{15.7\mu}{2\mu}$

signal path







$V_{gs} = -V_x = V_{bs}$

$i_x = g_m V_x + g_{mb} V_x$

$R_{o_1} = \frac{V_x}{i_x} = \frac{1}{g_m + g_{mb}}$

$r_{o_2} = r_{o_3} = \frac{1}{0.03\,(100\mu)} = 333k$

$R_{o_3} = r_{o_2} \| r_{o_3} = 167k$

$g_{m_1} = \sqrt{2 I_D \mu C_{ox} \frac{W}{L}}$

$= \sqrt{200\mu\ 60\mu\ 7.83}$

$= 307\mu \frac{A}{V}$

$g_{mb_1} = g_{m_1} \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}}$

$= 307\mu \frac{0.4}{2\sqrt{0.6+0.958}}$

$= 49.2\mu \frac{A}{V}$

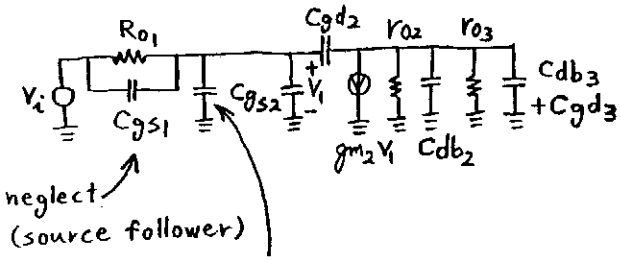
$R_{o_1} = 2811\ \Omega$

$g_{m_2} = \sqrt{200\mu\ 60\mu\ 50}$

$= 775\ \mu\frac{A}{V}$

Gain –

$\frac{V_o}{V_i} = -g_{m_1} R_{o_1} g_{m_2} R_{o_3} = -112\ V/V$



$C_{sb_1} + C_{db_7} + C_{gd_7}$

$C_{sb_1} = \frac{C_{sbo}}{\sqrt{1 + \frac{V_{SB}}{\psi_o}}}$

$= \frac{0.8\,f(7.83)}{\sqrt{1+\frac{0.958}{0.6}}} = 3.89\,fF$

$C_{db_7} = \frac{0.8\,f(100)}{\sqrt{1+\frac{0.958}{0.6}}} = 49.6fF$

$C_{gd_7} = 0.3(100\mu) = 30fF = C_{gd_2}$

$C_{gs_2} = \frac{2}{3} WL C_{ox} + 30fF$

$= 231 + 30$

$= 261\ fF$

$C_{db_2} = \frac{C_{sbo}}{\sqrt{1+\frac{V_{SB}}{\psi_o}}} = \frac{0.8f(100)}{\sqrt{1+\frac{2.5}{0.6}}} = 35.2fF$

$C_{db_3} = C_{db_2}$

7.22- Continued

$$R_{o_1}(C_{sb_1} + C_{db_7} + C_{gd_7} + C_{gs_2})$$
$$= 2811(3.89 + 49.6 + 30 + 261)f$$
$$= 0.968 ns$$

$$(r_{o_2} \| r_{o_3})(C_{db_2} + C_{db_3} + C_{gd_3})$$
$$= 167k\,(35.2 + 35.2 + 30)f$$
$$= 16.8 ns$$

$$C_{gd_2}(R_{o_1} + R_{o_3} + g_{m_2} R_{o_1} R_{o_3})$$
$$= 30f(2811 + 167k + 775\mu\, 167k\, 2811)$$
$$= 16 ns$$

$$f_{-3dB} = \frac{1}{2\pi}\frac{10^9}{0.968 + 16.8 + 16} = 4.71\ MHz$$

```
CMOS AMP
VDD 1 0 5V
M1 2 8 6 0 NMOS1 W=15.7U L=2U
M2 7 6 0 0 NMOS W=100U L=2U
M3 7 2 1 1 PMOS W=100U L=2U
M4 2 2 1 1 PMOS W=100U L=2U
M5 5 5 2 2 PMOS5 W=2.57U L=2U
M6 5 5 0 0 NMOS W=100U L=2U
M7 6 5 0 0 NMOS W=100U L=2U
VI 8 0 2.5746V AC
.PLOT AC VDB(7)
.AC DEC 20 100K 100MEG
.MODEL NMOS NMOS KP=60U VTO=0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL NMOS1 NMOS KP=60U VTO=0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=12.6FF CBS=12.6FF
.MODEL PMOS PMOS KP=30U VTO=-0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=80FF CBS=80FF
.MODEL PMOS5 PMOS KP=30U VTO=-0.7 LAMBDA=0.03 LD=0 GAMMA=0.4
+ TOX=20NM CGSO=300PF CGDO=300PF CBD=2.06FF CBS=2.06FF
.OPTIONS NOPAGE NOMOD
.WIDTH OUT=80
.OP
.END
```

0**** SMALL SIGNAL BIAS SOLUTION

NODE VOLTAGE

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(1)	5.0000	(2)	3.8006	(5)	0.9504	(6)	1.0532
(7)	2.4930	(8)	2.5746				

0**** MOSFETS

0	M1	M2	M3	M4	M5	M6	M7
	NMOS1	NMOS	PMOS	PMOS	PMOS5	NMOS	NMOS
ID	9.70E-05	2.01E-04	-2.01E-04	-1.94E-04	-9.67E-05	9.67E-05	9.70E-05
VGS	1.521	1.053	-1.199	-1.199	-2.850	0.950	0.950
VDS	2.747	2.493	-2.507	-1.199	-2.850	0.950	1.053
VBS	-1.053	0.000	0.000	0.000	0.000	0.000	0.000
VTH	0.904	0.700	-0.700	-0.700	-0.700	0.700	0.700
VDSAT	0.617	0.353	-0.499	-0.499	-2.150	0.250	0.250
GM	3.15E-04	1.14E-03	8.05E-04	7.76E-04	9.00E-05	7.73E-04	7.75E-04
GDS	2.69E-06	5.61E-06	5.61E-06	5.61E-06	2.67E-06	2.82E-06	2.82E-06
GMB	4.89E-05	2.94E-04	2.08E-04	2.00E-04	2.32E-05	1.99E-04	2.00E-04
CBD	5.25E-15	3.94E-14	3.93E-14	5.06E-14	9.64E-16	5.41E-14	5.26E-14
CBS	8.28E-15	8.00E-14	8.00E-14	8.00E-14	2.06E-15	8.00E-14	8.00E-14
CGSOVL	4.71E-15	3.00E-14	3.00E-14	3.00E-14	7.71E-16	3.00E-14	3.00E-14
CGDOVL	4.71E-15	3.00E-14	3.00E-14	3.00E-14	7.71E-16	3.00E-14	3.00E-14
CGBOVL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.0E+00	0.0E+00	0.0E+00
CGS	3.61E-14	2.30E-13	2.30E-13	2.30E-13	5.92E-15	2.30E-13	2.30E-13
CGD	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
CGB	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

```
0****   AC ANALYSIS
  FREQ      VDB(7)
               1.0D+01   2.0D+01   3.0D+01   4.0D+01 5.0D+01
                 ------------------------------------------
 1.000D+05 3.873D+01
 1.122D+05 3.873D+01
 1.259D+05 3.872D+01
 1.413D+05 3.872D+01
 1.585D+05 3.872D+01
 1.778D+05 3.872D+01
 1.995D+05 3.872D+01
 2.239D+05 3.872D+01
 2.512D+05 3.872D+01
 2.818D+05 3.872D+01
 3.162D+05 3.872D+01
 3.548D+05 3.871D+01
 3.981D+05 3.871D+01
 4.467D+05 3.871D+01
 5.012D+05 3.870D+01
 5.623D+05 3.869D+01
 6.310D+05 3.869D+01
 7.079D+05 3.868D+01
 7.943D+05 3.866D+01
 8.913D+05 3.865D+01
 1.000D+06 3.863D+01
 1.122D+06 3.860D+01
 1.259D+06 3.857D+01
 1.413D+06 3.853D+01
 1.585D+06 3.848D+01
 1.778D+06 3.842D+01
 1.995D+06 3.834D+01
 2.239D+06 3.825D+01
 2.512D+06 3.813D+01
 2.818D+06 3.799D+01
 3.162D+06 3.782D+01
 3.548D+06 3.761D+01
 3.981D+06 3.736D+01
 4.467D+06 3.707D+01
 5.012D+06 3.673D+01
 5.623D+06 3.633D+01
 6.310D+06 3.588D+01
 7.079D+06 3.537D+01
 7.943D+06 3.480D+01
 8.913D+06 3.418D+01
 1.000D+07 3.350D+01
 1.122D+07 3.278D+01
 1.259D+07 3.200D+01
 1.413D+07 3.119D+01
 1.585D+07 3.035D+01
 1.778D+07 2.947D+01
 1.995D+07 2.857D+01
 2.239D+07 2.764D+01
 2.512D+07 2.669D+01
 2.818D+07 2.572D+01
 3.162D+07 2.474D+01
 3.548D+07 2.374D+01
 3.981D+07 2.272D+01
 4.467D+07 2.168D+01
 5.012D+07 2.062D+01
 5.623D+07 1.954D+01
 6.310D+07 1.844D+01
 7.079D+07 1.731D+01
 7.943D+07 1.614D+01
 8.913D+07 1.493D+01
 1.000D+08 1.368D+01
                 ------------------------------------------

-3DB FREQUENCY = 6.31 MEGAHERTZ
```