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ICTP-UNU-Microprocessor Laboratory
Fifth Course on Basic VLSI Design Techniques

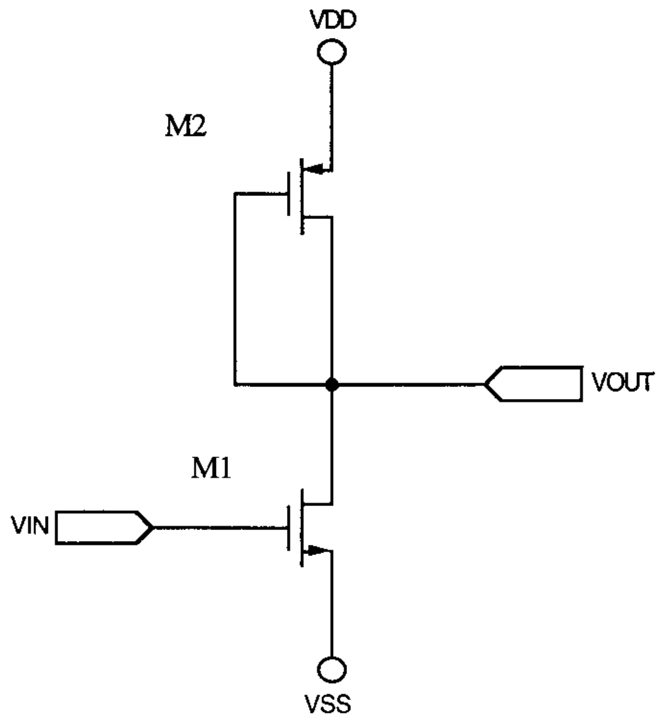
9 November - 4 December 1998

ANALOGUE VLSI DESIGN
Part 9

Sandro CENTRO
Dipartimento di Fisica "G. Galilei"
Universita' degli Studi di Padova
via Marzolo, 8
35131 Padova
Italy

9. SIMPLE AMPLIFIERS

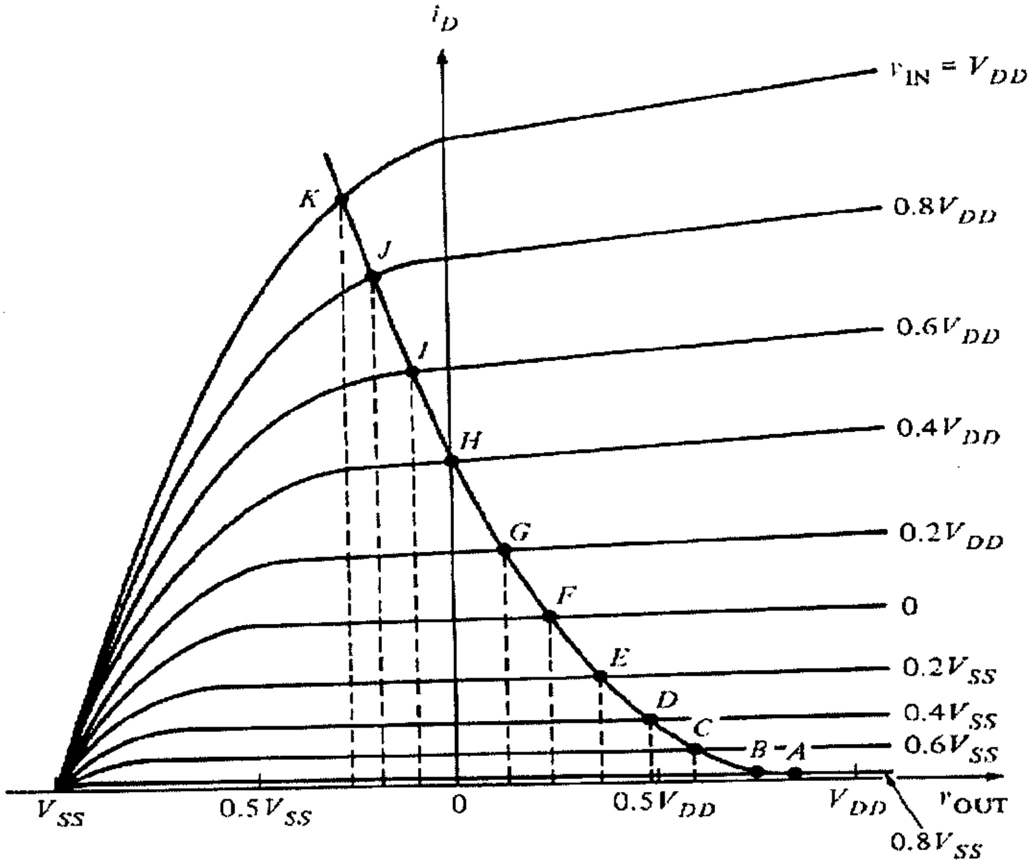
•The inverter is the basic gain stage of CMOS circuits. Typically the inverter uses the common source configuration with either a resistor for a load or a current sink/source as an active load.
A very common circuit is given in the following figure.



•The current through M2 is found from (5.5) assuming that

$$v_{DS}=v_{GS}-V_T$$

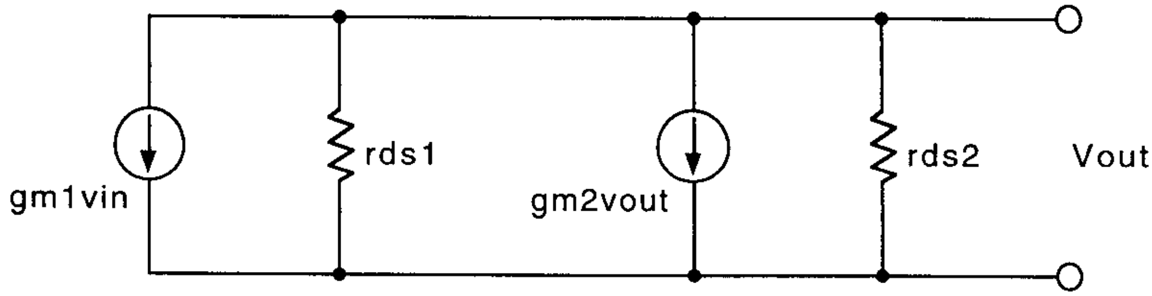
In the graph the working point is given as the intersection between the **M1** characteristic and **M2** load curve.



- From the following equivalent circuit one can obtain the small signal gain as

$$\frac{v_{OUT}}{v_{IN}} = \frac{-g_{m1}}{g_{ds1} + g_{ds2} + g_{m2}} \cong \frac{g_{m1}}{g_{m2}}$$

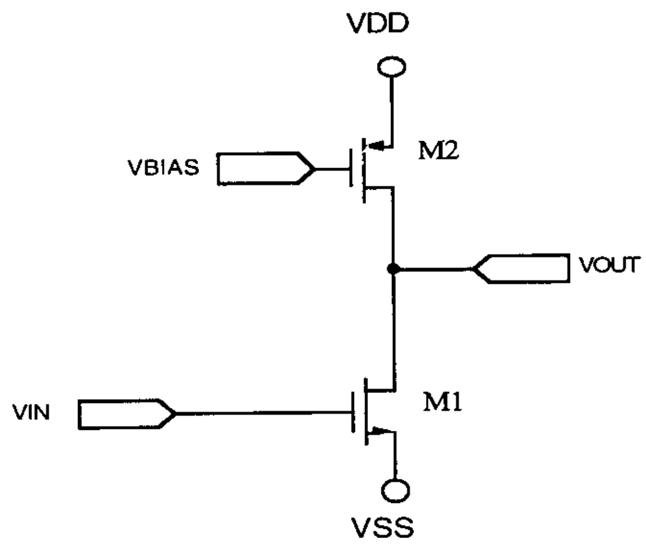
$$= -\frac{K'_N W_1 L_2}{K'_P W_2 L_1}$$

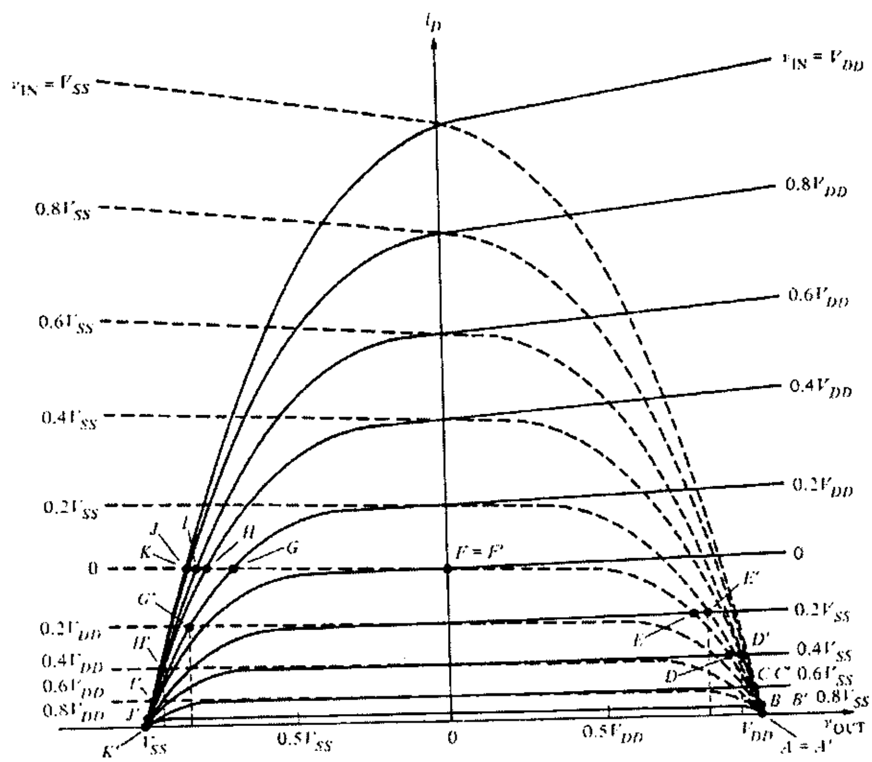


•A modified version of the inverter is shown in the following figure where the load is a current generator, that could mirror another current.
The small signal equivalent circuit misses now the second current generator and the small signal gain is obtained, using (6.1a) and (6.3a), as

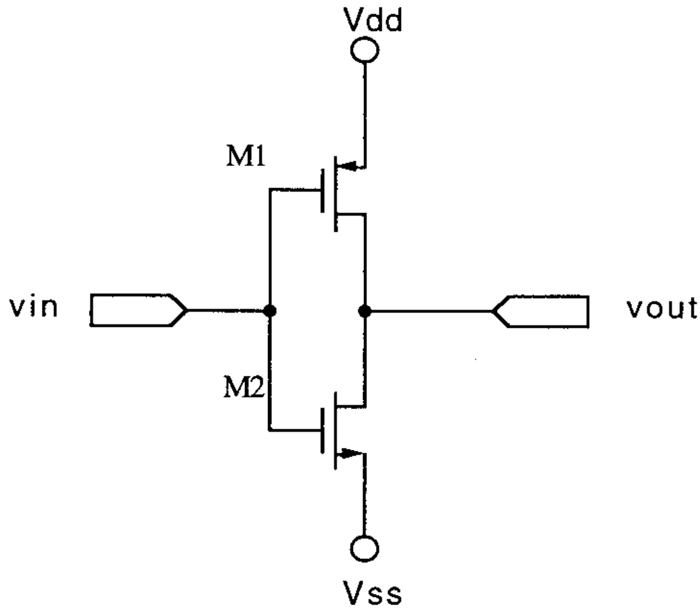
$$\frac{v_{OUT}}{v_{IN}} = \frac{-g_{m1}}{g_{ds1} + g_{ds2}} = \sqrt{\frac{2K_N' W_1}{L_1 I_D}} \left(\frac{-1}{\lambda_1 + \lambda_2} \right) \tag{9.1}$$

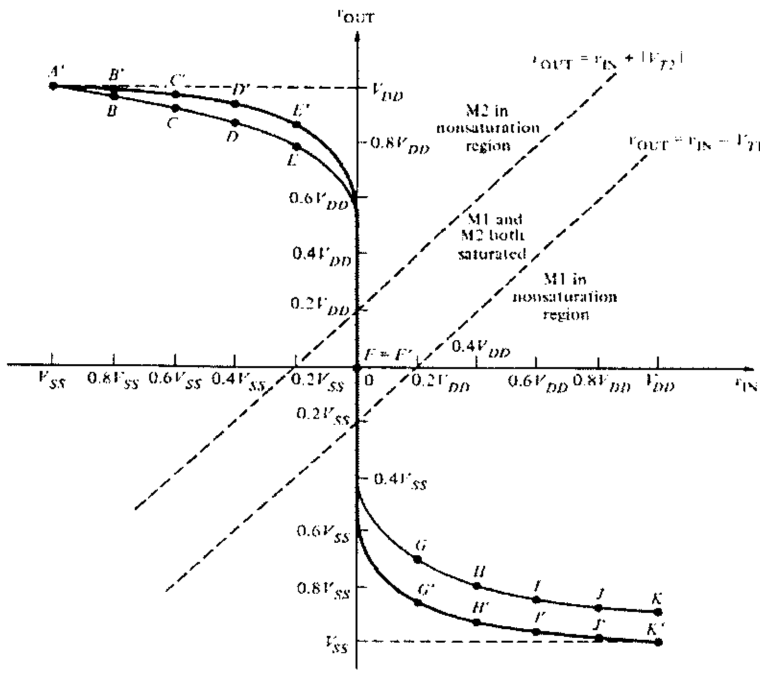
We see that the gain increases as the current I_D decreases. This holds true until the transistor work in the saturation region.
Gains of -500 and little more can be obtained by this stage.
The graph gives the transfer characteristic of this type of inverter.





•Another type of inverter is the push-pull inverter given in the figure.





Transfer characteristics of CMOS inverters ($V_{T1} = |V_{T2}| = 0.2\,V_{DD}$)

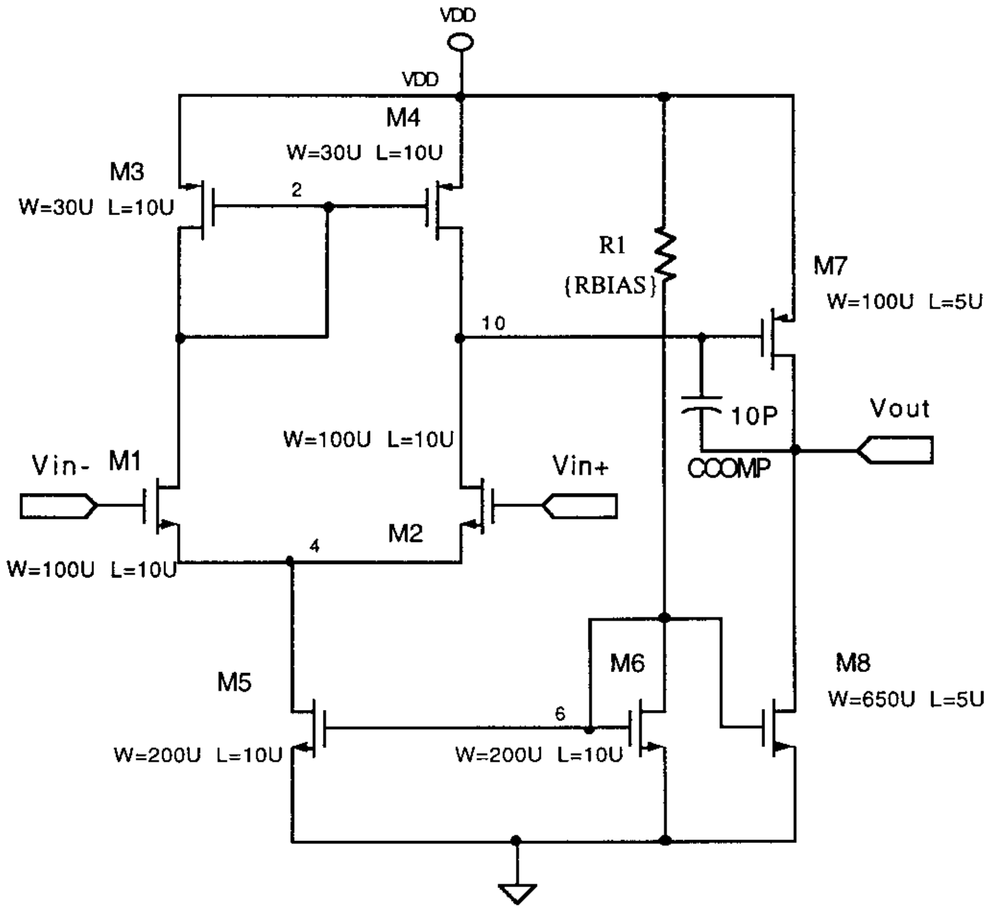
The gain, using the small signal equivalent circuit and the already used formulas, is given by

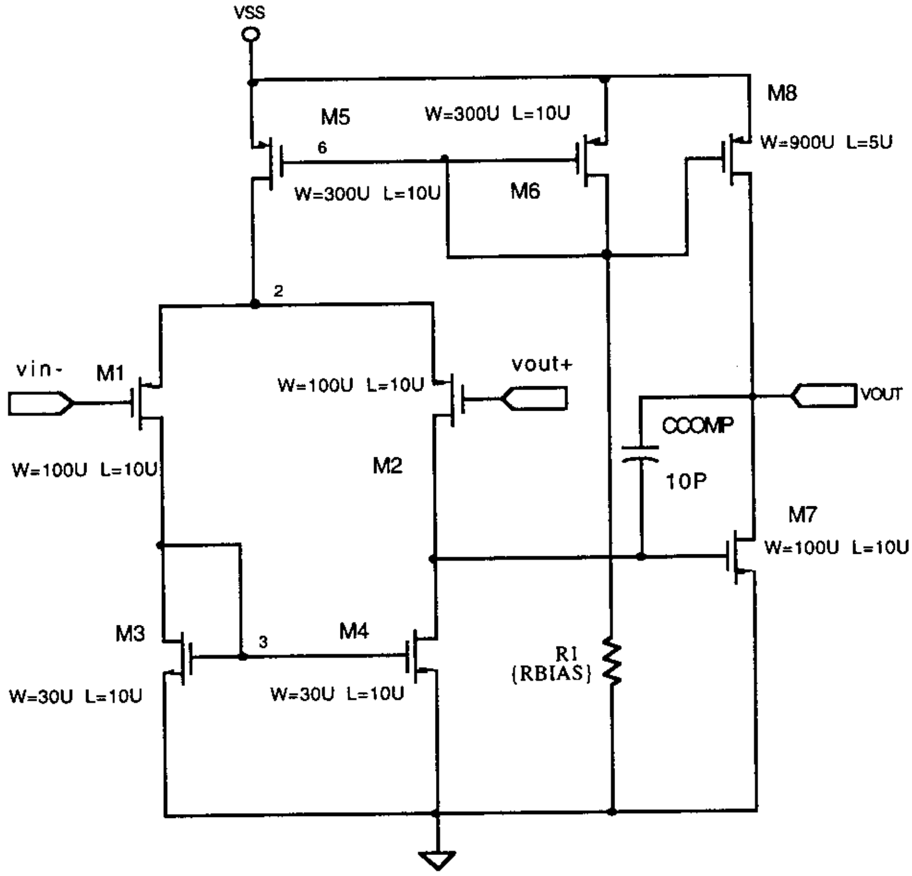
$$\frac{v_{OUT}}{v_{IN}} = \frac{-g_{m1} - g_{m2}}{g_{ds1} + g_{ds2}}$$

$$= \sqrt{2/I_D}\left(\sqrt{\frac{K_N' W_1}{L_1}} + \sqrt{\frac{K_P' W_2}{L_2}}\right)\left(\frac{-1}{\lambda_1 + \lambda_2}\right) \quad (9.2)$$

Gains in the order of -1000 can be easily obtained.

•Differential amplifiers can be designed with CMOS technology. In the following figures two different structures are shown: one uses n-type input stage while the second uses the p-type input.





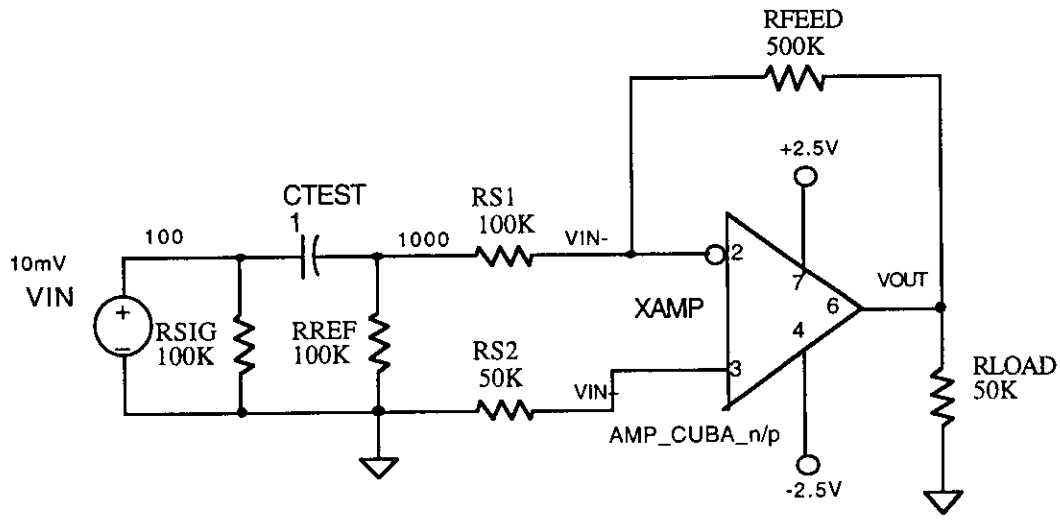
The two circuits have been simulated with models **LEVEL2** and the sub circuits given in the section 7.
The SPICE listing of the two amplifiers is given.
SUBCIRCUITS and MODELs have been written and put in a library CUBA.lib.

```
.SUBCKT AMP_CUBA_n VIN+ VIN- VDD VSS VOUT PARAMS: RBIAS=200K
X1 2 VIN- 4 VSS TN_2_CUBAQb PARAMS: WN=100U LN=10U
X2 10 VIN+ 4 VSS TN_2_CUBAQb PARAMS: WN=100U LN=10U
X3 2 2 VDD VDD TP_2_CUBAQb PARAMS: WP=30U LP=10U
X4 10 2 VDD VDD TP_2_CUBAQb PARAMS: WP=30U LP=10U
X5 4 6 VSS VSS TN_2_CUBAQb PARAMS: WN=200U LN=10U
X6 6 6 VSS VSS TN_2_CUBAQb PARAMS: WN=200U LN=10U
X7 VOUT 10 VDD VDD TP_2_CUBAQb PARAMS: WP=100U LP=10U
X8 VOUT 6 VSS VSS TN_2_CUBAQb PARAMS: WN=650U LN=5U
CCOMP VOUT 10 10PF
R1 VDD 6 {RBIAS}
.ENDS AMP_CUBA_n
* * * * * * * * * * * * * * * * * * * * * * * * *
.SUBCKT AMP_CUBA_p VIN+ VIN- VDD VSS VOUT PARAMS: RBIAS=200K
*
*
X1 3 VIN- 2 VDD TP_2_CUBAQb PARAMS:WP=100U LP=10U
X2 10 VIN+ 2 VDD TP_2_CUBAQb PARAMS: WP=100U LP=10U
X3 3 3 VSS VSS TN_2_CUBAQb PARAMS: WN=30U LN=10U
X4 10 3 VSS VSS TN_2_CUBAQb PARAMS: WN=30U LN=10U
X5 2 6 VDD VDD TP_2_CUBAQb PARAMS: WP=300U LP=10U
X6 6 6 VDD VDD TP_2_CUBAQb PARAMS: WP=300U LP=10U
X7 VOUT 10 VSS VSS TN_2_CUBAQb PARAMS: WN=100U LN=10U
X8 VOUT 6 VDD VDD TP_2_CUBAQb PARAMS: WP=900U LP=5U
CCOMP VOUT 10 10PF
R1 VSS 6 {RBIAS}
.ENDS AMP_CUBA_p
* * * * * * * * * * * * * * * * * * * * * * * * *

.SUBCKT TN_2_CUBAQb      D      G      S      BK     PARAMS:    WN=3U
        LN=2U
M1          D      G      S      BK    2_CUBAQN W={WN}   L={LN}
+AD={2U*WN}  AS={2U*WN}PD={2U+(2*WN)}PS={2U+(2*WN)}
+NRD={2U/WN} NRS={2U/WN}
.ENDS TN_2_CUBAQb
* * * * * * * * * * * * * * * * * * * * * * * * *
* PMOS_CAE
.SUBCKTTP_2_CUBAQb       D      G      S      BK     PARAMS:    WP=3U
        LP=2U
M1          D      G      S      BK    2_CUBAQP W={WP}   L={LP}
+AD={2U*WP}  AS={2U*WP}PD={2U+(2*WP)}PS={2U+(2*WP)}
+NRD={2U/WP} NRS={2U/WP}
.ENDS TP_2_CUBAQb
* * * * * * * * * *
*
*    2_CUBAQ 2um CMOS
* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
* typical parameters
*
.MODEL 2_CUBAQN NMOS LEVEL=2
+ CGSO  =0.560E-09  CGDO  =0.560E-09  CGBO  =0.165E-09
+ CJ    =0.400E-03  MJ    =0.500E+00  CJSW  =0.390E-09  MJSW  =0.060E+00
+ JS    =0.020E-03  PB    =0.860E+00  RSH   =30.00E+00  XQC   =1E+00
+ TOX   =31.10E-09  XJ    =0.054E-06  LD    =0.338E-06  WD    =0.644E-06
+ VTO   =0.770E+00  NSUB  =33.10E+15  NFS   =0.293E+12  NEFF  =3.560E+00
+ UO    =582.0E+00  UCRIT =20.90E+04  UEXP  =0.235E+00  UTRA  =0.000E+00
+ VMAX  =86.00E+03  DELTA =0E+00
*
.MODEL 2_CUBAQP PMOS LEVEL=2
+ CGSO  =0.560E-09  CGDO  =0.560E-09  CGBO  =0.165E-09
```

```
+ CJ     =0.360E-03  MJ     =0.500E+00  CJSW  =0.310E-09  MJSW  =0.010E+00
+ JS     =0.040E-03  PB     =0.790E+00  RSH   =81.00E+00  XQC   =1E+00
+ TOX    =31.10E-09  XJ     =0.021E-06  LD    =0.315E-06  WD    =0.731E-06
+ VTO    =-.804E+00  NSUB   =11.80E+15  NFS   =0.337E+12  NEFF  =2.030E+00
+ UO     =180.0E+00  UCRIT  =19.70E+04  UEXP  =0.219E+00  UTRA  =0.000E+00
+ VMAX   =41.20E+03  DELTA  =1.040E+00
***********************************************************************
```

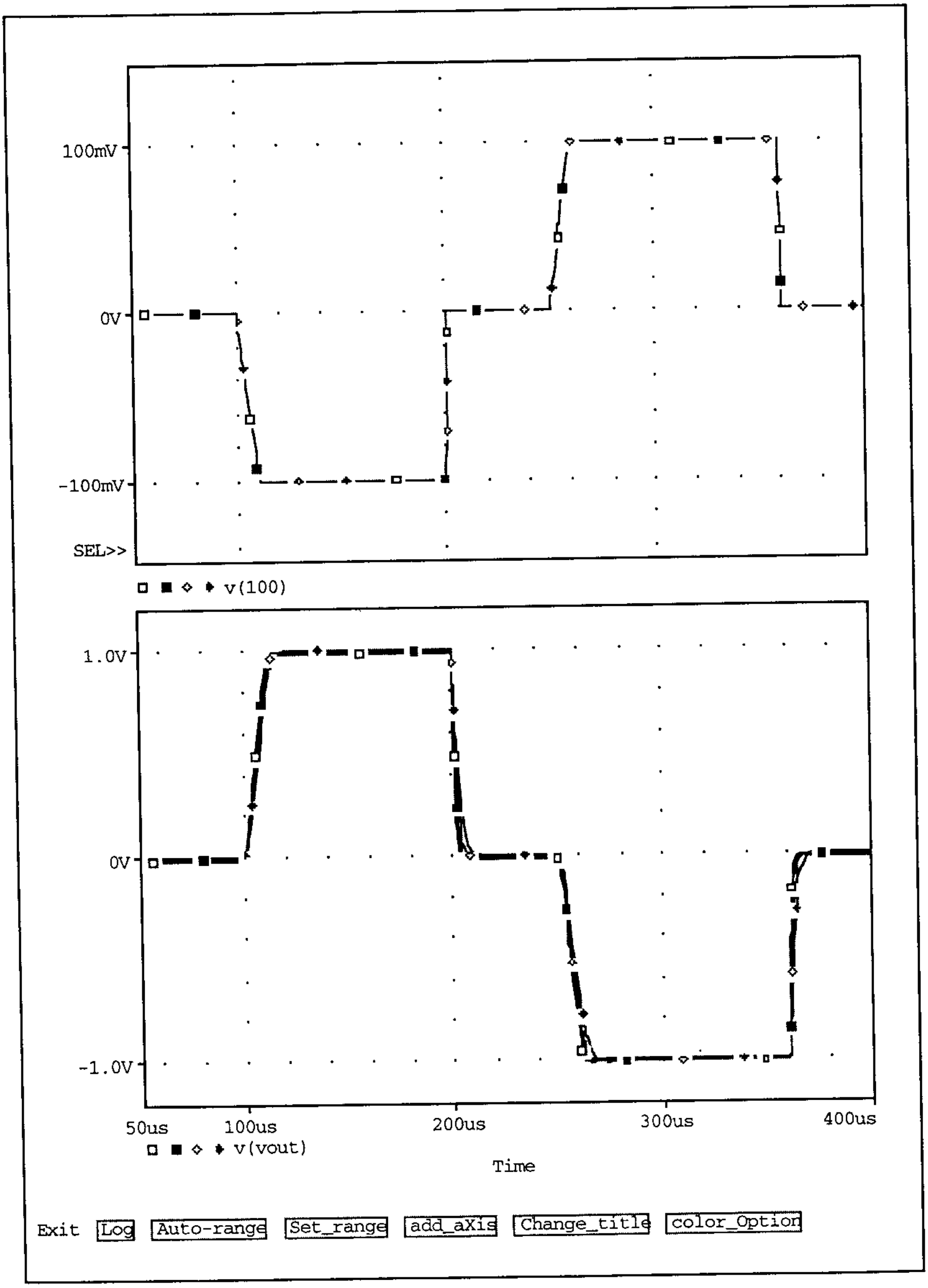
•Then the following circuit has been simulated both for the n-type and p-type to find the AC and TRAN responses.

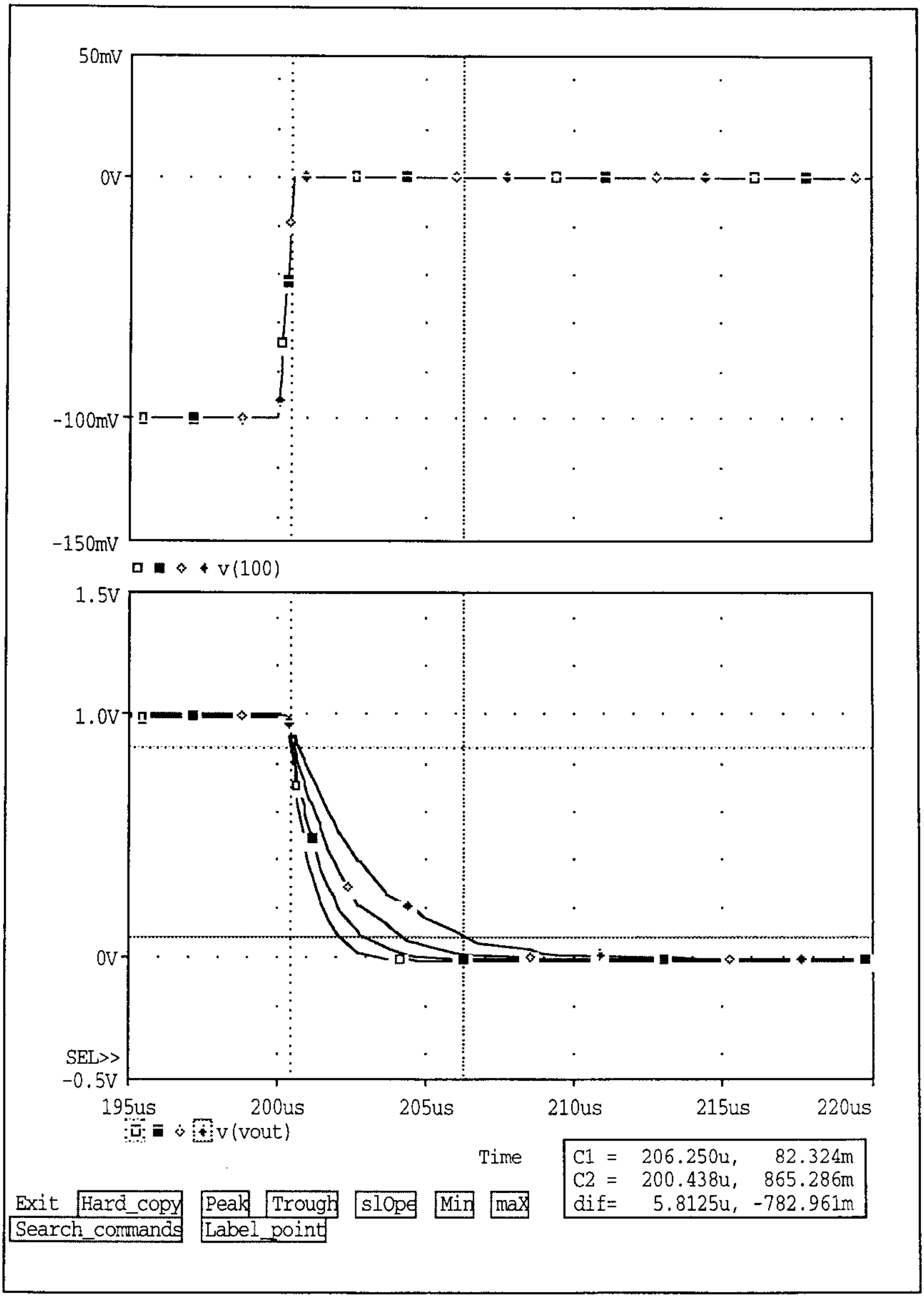


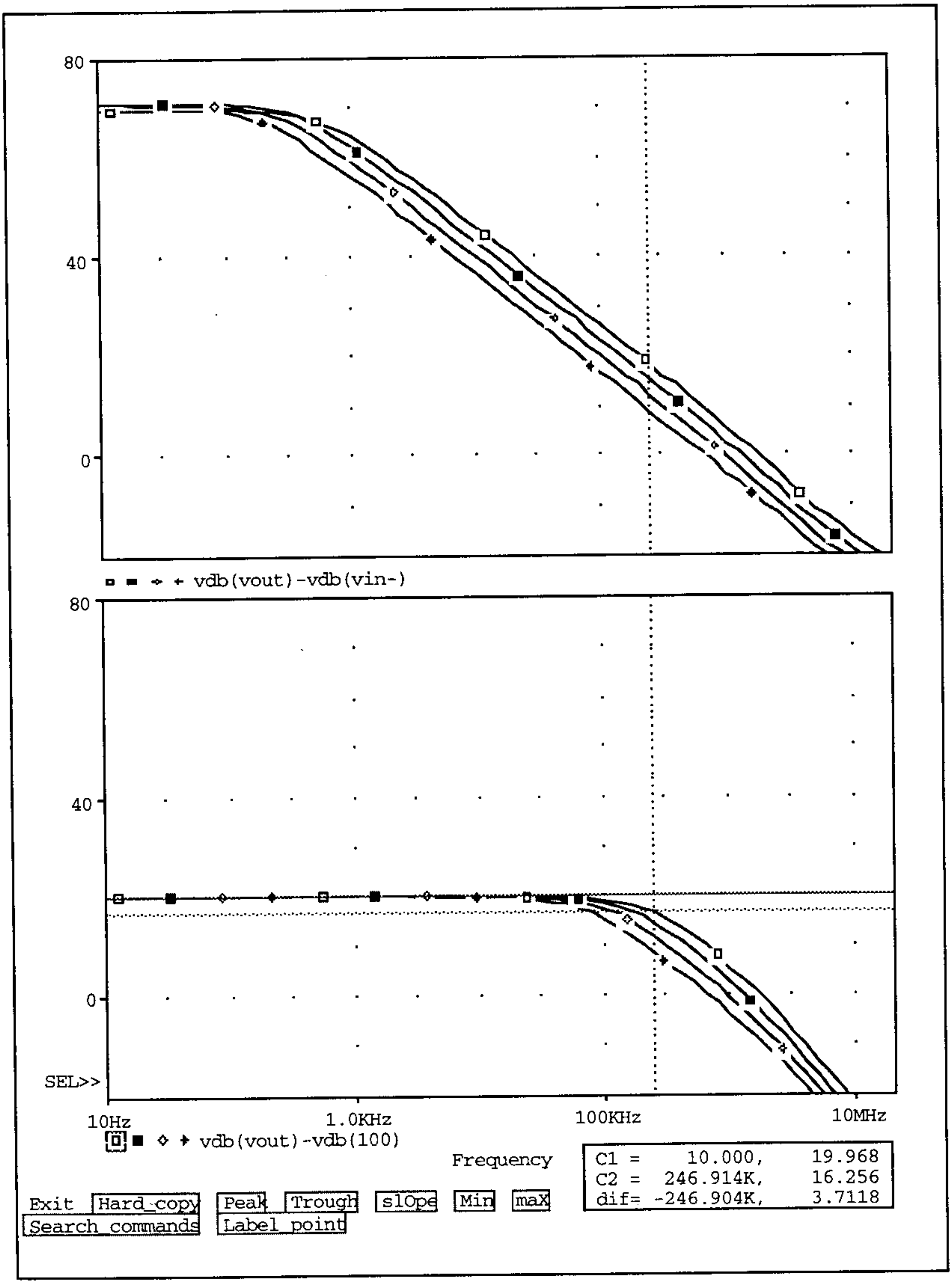
9.11

```
SPICE File_1
***************ANALISYS  OF  DIFF_AMP  N_TYPE
.lib CUBA.lib
.TRAN 1U 400u
.AC dec 10 10 20MEG
Vin 100 0 ac 10m pwl(0 0V 100u 0V 110u -100mV 200u -100mV 210u 0 250U 0V
+260U 100mV 360u 100mV 370u 0v 10m 0)
.PROBE
.OP
.TEMP 25
.PARAM RBIAS=400K
.STEP PARAM RBIAS LIST 100K, 200K,400K, 800K
*****************************************************************
*power supply (simmetrical)
V10 VDD 0 2.5V
V20 0 VSS 2.5V
*********************
XAMP VIN+ VIN- VDD VSS VOUT AMP_CUBA_n PARAMS: RBIAS={RBIAS}
*********************
*********************
*FEEDBACK & LOAD NETWORK
*********************
RFEED VOUT VIN- 500K
RS1 VIN+ 0 100K
RS2 VIN- 1000 50K
RLAOD VOUT 0 50K
*********************
*SIGNAL NETWORK
RSIG 100 0 100K
RREF 1000 0 100K
CTEST 100 1000 1
.END
SPICE File_2
.lib CUBA.lib
***************ANALISYS  OF  DIFF_AMP  P_TYPE
.TRAN 1U 400u
.AC dec 10 10 20MEG
Vin 100 0 ac 10m pwl(0 0V 100u 0V 110u -100mV 200u -100mV 210u 0 250U 0V
+260U 100mV 360u 100mV 370u 0v 10m 0)
.PROBE
.OP
.TEMP 25
.PARAM RBIAS=400K
.STEP PARAM RBIAS LIST 100K, 200K,400K, 800K
 *
*power supply (simmetrical)
V10 VDD 0 2.5V
V20 0 VSS 2.5V
*********************
XAMP VIN+ VIN- VDD VSS VOUT AMP_CUBA_p PARAMS: RBIAS={RBIAS}
*********************
*********************
*FEEDBACK & LOAD NETWORK
*********************
RFEED VOUT VIN- 500K
RS1 VIN+ 0 100K
RS2 VIN- 1000 50K
RLAOD VOUT 0 50K
*********************
*SIGNAL NETWORK
```

```
RSIG 100 0 100K
RREF 1000 0 100K
CTEST 100 1000 1
.END
```




50mV
0V
-100mV
-150mV
v(100)
1.5V
1.0V
0V
SEL>>
-0.5V
195us
200us
205us
210us
215us
220us
v(vout)
Time
C1 = 206.250u, 82.324m
C2 = 200.438u, 865.286m
dif= 5.8125u, -782.961m
Exit
Hard_copy
Peak
Trough
slOpe
Min
maX
Search_commands
Label_point



80
40
0
vdb(vout)-vdb(vin-)
80
40
0
SEL>>
10Hz
1.0KHz
100KHz
10MHz
vdb(vout)-vdb(100)
Frequency
C1 = 10.000, 19.968
C2 = 246.914K, 16.256
dif= -246.904K, 3.7118
Exit
Hard_copy
Peak
Trough
slOpe
Min
maX
Search commands
Label point

```
****    MOSFET MODEL PARAMETERS

*************************************************************************
*************

              2_CUBAQP              2_CUBAQN
                PMOS                  NMOS
       LEVEL   2                        2
       L    100.000000E-06        100.000000E-06
       W    100.000000E-06        100.000000E-06
       LD   315.000000E-09        338.000000E-09
       WD   731.000000E-09        644.000000E-09
      VTO     -.804                  .77
       KP    19.986040E-06         64.621530E-06
    GAMMA      .563673               .944061
      PHI      .703995               .75735
      RSH    81                     30
       JS    40.000000E-06         20.000000E-06
       PB       .79                   .86
     PBSW       .79                   .86
       CJ   360.000000E-06        400.000000E-06
     CJSW   310.000000E-12        390.000000E-12
     MJSW       .01                   .06
     CGSO   560.000000E-12        560.000000E-12
     CGDO   560.000000E-12         560.000000E-12
     CGBO   165.000000E-12        165.000000E-12
     NSUB    11.800000E+15         33.100000E+15
      NFS   337.000000E+09        293.000000E+09
      TOX    31.100000E-09         31.100000E-09
       XJ    21.000000E-09         54.000000E-09
       UO   180                   582
    UCRIT   197.000000E+03        209.000000E+03
     UEXP      .219          .    235
     VMAX    41.200000E+03         86.000000E+03
     NEFF     2.03                  3.56
    DELTA     1.04

**** MOSFET MODEL PARAMETERS
NAME          VTO         PHI         PB          IS(JS)      KP          UO
 2_CUBAQP   -8.074E-01   7.078E-01   7.932E-01   2.934E-05   2.019E-05   1.818E+02
 2_CUBAQN    7.733E-01   7.608E-01   8.627E-01   1.467E-05   6.527E-05   5.879E+02

**** 01/21/96  19:25:38 ********* PSpice 6.0 (Jan 1994) ******** ID# 53788
****

SPICE File_1

****    SMALL SIGNAL BIAS SOLUTION      TEMPERATURE =  25.000 DEG C

****    CURRENT STEP                  PARAM RBIAS =  100.0000E+03
```

****

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(100)	0.0000	(VDD)	2.5000	(VSS)	-2.5000	(1000)	-.0021
(VIN+)	0.0000	(VIN-)	-.0032	(VOUT)	-.0137	(XAMP.2)	.7966
(XAMP.4)	-1.4707	(XAMP.6)	-1.4446	(XAMP.10)	-.2187		

**** MOSFETS

NAME	XAMP.X1.M1	XAMP.X2.M1	XAMP.X3.M1	XAMP.X4.M1	XAMP.X5.M1
MODEL	2_CUBAQN	2_CUBAQN	2_CUBAQP	2_CUBAQP	2_CUBAQN
ID	1.96E-05	1.98E-05	-1.96E-05	-1.98E-05	3.94E-05
VGS	1.47E+00	1.47E+00	-1.70E+00	-1.70E+00	1.06E+00
VDS	2.27E+00	1.25E+00	-1.70E+00	-2.72E+00	1.03E+00
VBS	-1.03E+00	-1.03E+00	0.00E+00	0.00E+00	0.00E+00
VTH	1.24E+00	1.24E+00	-8.51E-01	-8.50E-01	8.14E-01
VDSAT	2.03E-01	2.05E-01	-6.92E-01	-6.93E-01	1.92E-01
GM	1.44E-04	1.44E-04	4.39E-05	4.45E-05	2.72E-04
GDS	2.00E-07	2.62E-07	2.59E-07	1.91E-07	5.28E-07
GMB	4.82E-05	4.83E-05	1.21E-05	1.23E-05	1.36E-04
CBD	1.08E-13	1.15E-13	3.11E-14	2.92E-14	2.57E-13
CBS	1.29E-13	1.29E-13	4.08E-14	4.08E-14	3.16E-13
CGSOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGDOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGBOV	1.54E-15	1.54E-15	1.55E-15	1.55E-15	1.54E-15
CGS	6.81E-13	6.81E-13	1.98E-13	1.98E-13	1.37E-12
CGD	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

NAME	XAMP.X6.M1	XAMP.X7.M1	XAMP.X8.M1
MODEL	2_CUBAQN	2_CUBAQP	2_CUBAQN
ID	3.94E-05	-3.13E-04	3.14E-04
VGS	1.06E+00	-2.72E+00	1.06E+00
VDS	1.06E+00	-2.51E+00	2.49E+00
VBS	0.00E+00	0.00E+00	0.00E+00
VTH	8.14E-01	-8.49E-01	8.00E-01
VDSAT	1.92E-01	-1.49E+00	2.01E-01
GM	2.72E-04	2.93E-04	2.07E-03
GDS	5.22E-07	3.93E-06	5.60E-06
GMB	1.36E-04	6.59E-05	1.01E-03
CBD	2.57E-13	9.69E-14	7.31E-13
CBS	3.16E-13	1.34E-13	1.03E-12
CGSOV	1.11E-13	5.52E-14	3.63E-13
CGDOV	1.11E-13	5.52E-14	3.63E-13
CGBOV	1.54E-15	1.55E-15	7.13E-16
CGS	1.37E-12	6.83E-13	2.08E-12
CGD	0.00E+00	0.00E+00	0.00E+00
CGB	0.00E+00	0.00E+00	0.00E+00

**** SMALL SIGNAL BIAS SOLUTION TEMPERATURE = 25.000 DEG C

**** CURRENT STEP PARAM RBIAS = 200.0000E+03

****
****

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(100)	0.0000	(VDD)	2.5000	(VSS)	-2.5000	(1000)	-.0012
(VIN+)	0.0000	(VIN-)	-.0019	(VOUT)	-.0080	(XAMP.2)	1.0497
(XAMP.4)	-1.4113	(XAMP.6)	-1.5274	(XAMP.10)	.3020		

**** MOSFETS

NAME	XAMP.X1.M1	XAMP.X2.M1	XAMP.X3.M1	XAMP.X4.M1	XAMP.X5.M1
MODEL	2_CUBAQN	2_CUBAQN	2_CUBAQP	2_CUBAQP	2_CUBAQN
ID	1.00E-05	1.01E-05	-1.00E-05	-1.01E-05	2.02E-05
VGS	1.41E+00	1.41E+00	-1.45E+00	-1.45E+00	9.73E-01
VDS	2.46E+00	1.71E+00	-1.45E+00	-2.20E+00	1.09E+00
VBS	-1.09E+00	-1.09E+00	0.00E+00	0.00E+00	0.00E+00
VTH	1.26E+00	1.26E+00	-8.51E-01	-8.50E-01	8.14E-01
VDSAT	1.46E-01	1.47E-01	-4.95E-01	-4.95E-01	1.37E-01
GM	1.03E-04	1.03E-04	3.13E-05	3.16E-05	1.94E-04
GDS	1.23E-07	1.44E-07	1.40E-07	1.09E-07	3.12E-07
GMB	3.42E-05	3.43E-05	9.02E-06	9.10E-06	9.89E-05
CBD	1.07E-13	1.11E-13	3.18E-14	3.01E-14	2.55E-13
CBS	1.28E-13	1.28E-13	4.08E-14	4.08E-14	3.16E-13
CGSOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGDOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGBOV	1.54E-15	1.54E-15	1.55E-15	1.55E-15	1.54E-15
CGS	6.81E-13	6.81E-13	1.98E-13	1.98E-13	1.37E-12
CGD	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

NAME	XAMP.X6.M1	XAMP.X7.M1	XAMP.X8.M1
MODEL	2_CUBAQN	2_CUBAQP	2_CUBAQN
ID	2.01E-05	-1.66E-04	1.66E-04
VGS	9.73E-01	-2.20E+00	9.73E-01
VDS	9.73E-01	-2.51E+00	2.49E+00
VBS	0.00E+00	0.00E+00	0.00E+00
VTH	8.14E-01	-8.49E-01	8.00E-01
VDSAT	1.37E-01	-1.08E+00	1.46E-01
GM	1.94E-04	2.40E-04	1.50E-03
GDS	3.29E-07	1.82E-06	3.51E-06
GMB	9.87E-05	6.09E-05	7.46E-04
CBD	2.59E-13	9.69E-14	7.31E-13
CBS	3.16E-13	1.34E-13	1.03E-12
CGSOV	1.11E-13	5.52E-14	3.63E-13
CGDOV	1.11E-13	5.52E-14	3.63E-13
CGBOV	1.54E-15	1.55E-15	7.13E-16

CGS	1.37E-12	6.83E-13	2.08E-12
CGD	0.00E+00	0.00E+00	0.00E+00
CGB	0.00E+00	0.00E+00	0.00E+00

**** SMALL SIGNAL BIAS SOLUTION TEMPERATURE = 25.000 DEG C

**** CURRENT STEP PARAM RBIAS = 400.0000E+03

****

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(100)	0.0000	(VDD)	2.5000	(VSS)	-2.5000	(1000)	-760.5E-06
(VIN+)	0.0000	(VIN-)	-.0011	(VOUT)	-.0049	(XAMP.2)	1.2334
(XAMP.4)	-1.3687	(XAMP.6)	-1.5872	(XAMP.10)	.6755		

**** MOSFETS

NAME	XAMP.X1.M1	XAMP.X2.M1	XAMP.X3.M1	XAMP.X4.M1	XAMP.X5.M1
MODEL	2_CUBAQN	2_CUBAQN	2_CUBAQP	2_CUBAQP	2_CUBAQN
ID	5.11E-06	5.15E-06	-5.11E-06	-5.15E-06	1.03E-05
VGS	1.37E+00	1.37E+00	-1.27E+00	-1.27E+00	9.13E-01
VDS	2.60E+00	2.04E+00	-1.27E+00	-1.82E+00	1.13E+00
VBS	-1.13E+00	-1.13E+00	0.00E+00	0.00E+00	0.00E+00
VTH	1.27E+00	1.27E+00	-8.51E-01	-8.51E-01	8.14E-01
VDSAT	1.04E-01	1.05E-01	-3.53E-01	-3.53E-01	9.79E-02
GM	7.34E-05	7.36E-05	2.22E-05	2.24E-05	1.38E-04
GDS	7.77E-08	8.65E-08	7.60E-08	6.19E-08	1.92E-07
GMB	2.43E-05	2.44E-05	6.64E-06	6.69E-06	7.12E-05
CBD	1.06E-13	1.09E-13	3.24E-14	3.09E-14	2.54E-13
CBS	1.27E-13	1.27E-13	4.08E-14	4.08E-14	3.16E-13
CGSOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGDOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGBOV	1.54E-15	1.54E-15	1.55E-15	1.55E-15	1.54E-15
CGS	6.81E-13	6.81E-13	1.98E-13	1.98E-13	1.37E-12
CGD	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

NAME	XAMP.X6.M1	XAMP.X7.M1	XAMP.X8.M1
MODEL	2_CUBAQN	2_CUBAQP	2_CUBAQN
ID	1.02E-05	-8.85E-05	8.86E-05
VGS	9.13E-01	-1.82E+00	9.13E-01
VDS	9.13E-01	-2.51E+00	2.50E+00
VBS	0.00E+00	0.00E+00	0.00E+00
VTH	8.14E-01	-8.49E-01	8.00E-01
VDSAT	9.77E-02	-7.89E-01	1.07E-01
GM	1.38E-04	1.75E-04	1.09E-03
GDS	2.11E-07	9.10E-07	2.27E-06
GMB	7.10E-05	4.69E-05	5.50E-04
CBD	2.61E-13	9.70E-14	7.31E-13

CBS	3.16E-13	1.34E-13	1.03E-12
CGSOV	1.11E-13	5.52E-14	3.63E-13
CGDOV	1.11E-13	5.52E-14	3.63E-13
CGBOV	1.54E-15	1.55E-15	7.13E-16
CGS	1.37E-12	6.83E-13	2.08E-12
CGD	0.00E+00	0.00E+00	0.00E+00
CGB	0.00E+00	0.00E+00	0.00E+00

9.20

**** SMALL SIGNAL BIAS SOLUTION TEMPERATURE = 25.000 DEG C

**** CURRENT STEP PARAM RBIAS = 800.0000E+03

****

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(100)	0.0000	(VDD)	2.5000	(VSS)	-2.5000	(1000)	-486.7E-06
(VIN+)	0.0000	(VIN-)	-730.1E-06	(VOUT)	-.0032	(XAMP.2)	1.3657
(XAMP.4)	-1.3382	(XAMP.6)	-1.6301	(XAMP.10)	.9441		

**** MOSFETS

NAME	XAMP.X1.M1	XAMP.X2.M1	XAMP.X3.M1	XAMP.X4.M1	XAMP.X5.M1
MODEL	2_CUBAQN	2_CUBAQN	2_CUBAQP	2_CUBAQP	2_CUBAQN
ID	2.59E-06	2.61E-06	-2.59E-06	-2.61E-06	5.20E-06
VGS	1.34E+00	1.34E+00	-1.13E+00	-1.13E+00	8.70E-01
VDS	2.70E+00	2.28E+00	-1.13E+00	-1.56E+00	1.16E+00
VBS	-1.16E+00	-1.16E+00	0.00E+00	0.00E+00	0.00E+00
VTH	1.28E+00	1.28E+00	-8.51E-01	-8.51E-01	8.14E-01
VDSAT	7.42E-02	7.45E-02	-2.51E-01	-2.51E-01	6.96E-02
GM	5.23E-05	5.25E-05	1.58E-05	1.59E-05	9.81E-05
GDS	5.07E-08	5.47E-08	4.15E-08	3.51E-08	1.23E-07
GMB	1.72E-05	1.73E-05	4.84E-06	4.87E-06	5.10E-05
CBD	1.05E-13	1.07E-13	3.29E-14	3.15E-14	2.53E-13
CBS	1.27E-13	1.27E-13	4.08E-14	4.08E-14	3.16E-13
CGSOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGDOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGBOV	1.54E-15	1.54E-15	1.55E-15	1.55E-15	1.54E-15
CGS	6.81E-13	6.81E-13	1.98E-13	1.98E-13	1.37E-12
CGD	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

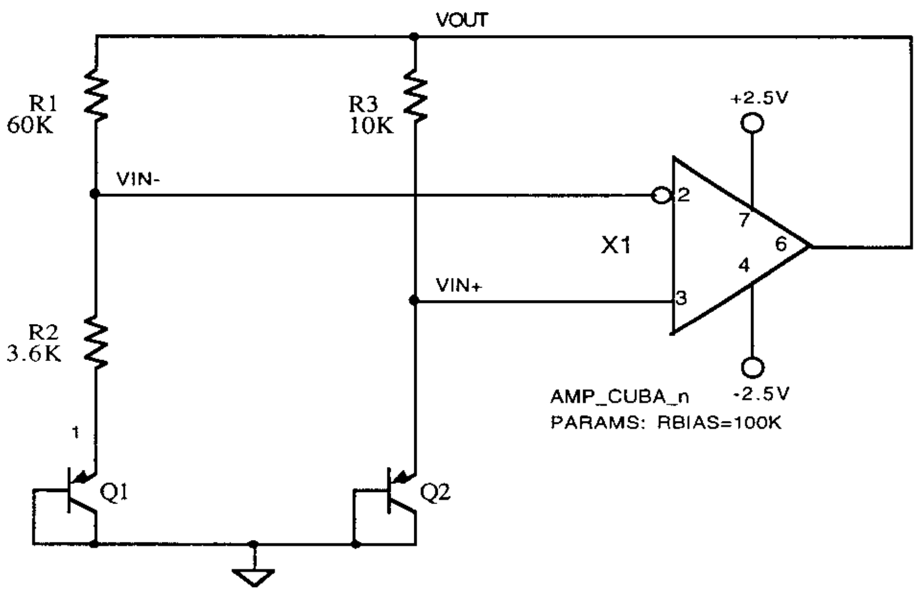
NAME	XAMP.X6.M1	XAMP.X7.M1	XAMP.X8.M1
MODEL	2_CUBAQN	2_CUBAQP	2_CUBAQN
ID	5.16E-06	-4.79E-05	4.79E-05
VGS	8.70E-01	-1.56E+00	8.70E-01
VDS	8.70E-01	-2.50E+00	2.50E+00
VBS	0.00E+00	0.00E+00	0.00E+00
VTH	8.14E-01	-8.49E-01	8.00E-01
VDSAT	6.94E-02	-5.80E-01	7.86E-02
GM	9.77E-05	1.28E-04	8.03E-04
GDS	1.38E-07	4.79E-07	1.52E-06
GMB	5.08E-05	3.59E-05	4.08E-04
CBD	2.63E-13	9.70E-14	7.31E-13
CBS	3.16E-13	1.34E-13	1.03E-12
CGSOV	1.11E-13	5.52E-14	3.63E-13
CGDOV	1.11E-13	5.52E-14	3.63E-13
CGBOV	1.54E-15	1.55E-15	7.13E-16
CGS	1.37E-12	6.83E-13	2.08E-12

CGD	0.00E+00	0.00E+00	0.00E+00
CGB	0.00E+00	0.00E+00	0.00E+00

•Based on the previous amplifier we can built a precise ***bandgap voltage reference***.

•The principle is trying to generate a voltage reference with zero tempo, adding in a proper way two voltage sources with opposite ***tempco***.

•The structure is the one in the following scheme.



•Let's analyze the simple circuit assuming that **X1** has infinite gain (op.amp.):

$$\frac{V_{OUT} - V_{IN-}}{R_1} = \frac{V_{IN-} - V_{B1}}{R_2}$$

(9.3)

Being

$$V_{IN-} = V_{IN+} = V_{B2}$$

(9.4)

we get

$$V_{OUT} = \frac{R_1}{R_2}\left(V_{B2} - V_{B1}\right) + V_{B2}$$

(9.5)

Remembering, (2.3), that

$$I_{D1} \approx I_S \, e^{V_{B1} / V_T}$$

and

$$I_{D2} \approx I_S \, e^{V_{B2} / V_T}$$

taking into account the ratio

$$I_{D2} = nI_{D1}$$

we can compute the difference ***(V_{B2}-V_{B1})*** between the two junction voltages and the (9.5) becomes

$$V_{OUT} = \frac{R_1}{R_2} V_T \ln(n) + V_{B2}$$

(9.6)

It is worth to remind that

$$V_T = \frac{kT}{q}$$

(9.7)

and ***n*** is the ratio between the currents through $\boldsymbol{R_3}$ and $\boldsymbol{R_1}$. In fact ***n*** is also the ratio of the two resistances.

•The requirement is to have zero *tempco* for $\boldsymbol{V_{OUT}}$, that means to have the derivative zero.

$$\frac{\partial V_{OUT}}{\partial T} = \frac{R_1}{R_2} \frac{\partial V_T}{\partial T} \ln(n) - 2.2 * 10^{-3} = 0$$

(9.8)

$$\frac{R_1}{R_2} \frac{k}{q} \ln(n) = 2.2 * 10^{-3}$$

(9.9)

$$\frac{R_1}{R_2} \ln(n) = 2.2 * 10^{-3} \frac{1.6 * 10^{-19}}{1.38 * 10^{-23}} = 25.6$$

(9.10)

•In this conditions we have

$$V_{OUT} = 25.6 * 26mV + 600mV = 1.24V \quad (9.11)$$

that corresponds to the *bandgap voltage* $\boldsymbol{V_{GO}}$.

•We just remind here the definition of bandgap voltage, $\boldsymbol{V_{GO}}$.

•The junction voltage $\boldsymbol{V_{BE}}$, can be expressed by

$$V_{BE} \cong V_{GO} - \frac{kT}{q} \ln \frac{const}{I_C} \quad (9.11)$$

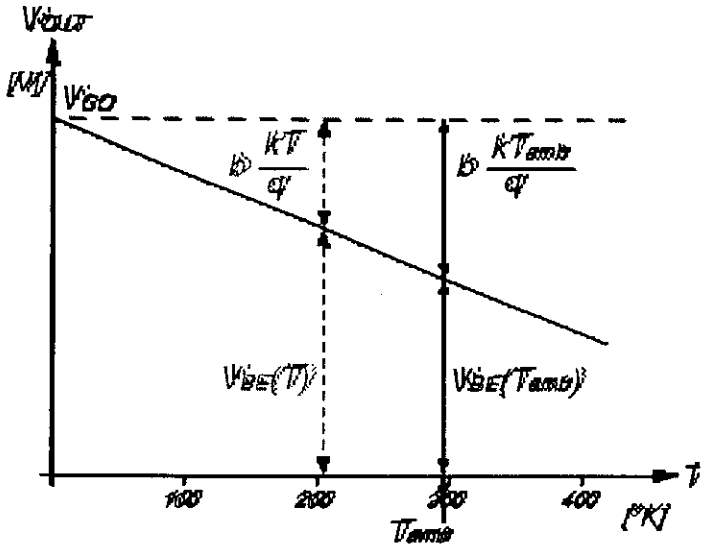
that can be easily compared with (9.6), from which we understand that

$$V_{OUT} = V_{GO} \quad (9.12)$$

•In our case we would have

$$V_{OUT} = \frac{60}{3.65} * 26mV \ln(6) + 600mV = \approx 1.3V$$

The correct value will be obtained with simulation. $\boldsymbol{V_{GO}}$ is the extrapolated value of $\boldsymbol{V_{BE}}$ at $\boldsymbol{T[°K]=0}$.



•It should be noted that pnp transistor are obtained in CMOS technology with the so called ***lateral bipolar***. The base is the n-well (p substrate) while source and drain are emitter and collector (or viceversa). To control the value ***n*** one can also play with the transistor dimensions, changing the current density through the emitter base junction.

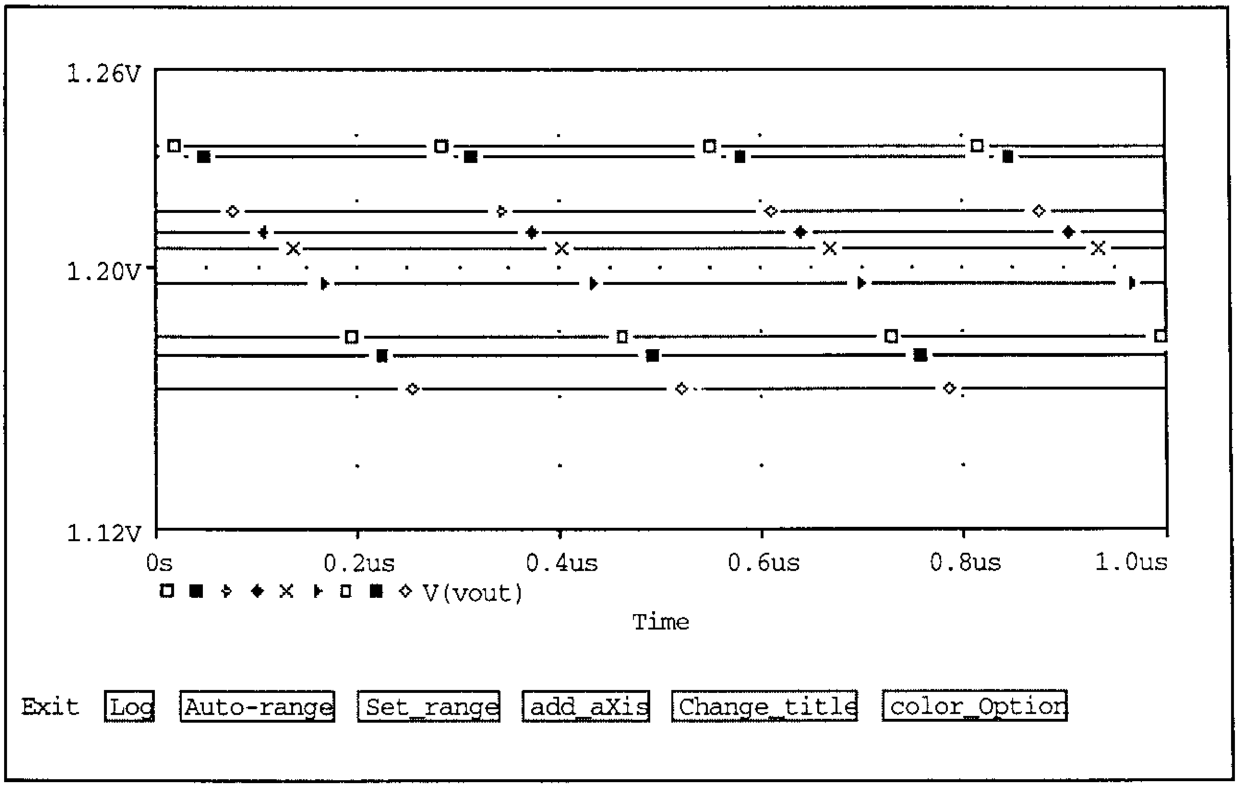
•The SPICE circuit description follows.

```
SPICE File_1
.PROBE
.OP
.TRAN 10N 2u
.TEMP 0, 25, 50
.LIB CUBA.LIB
.LIB MY-BJT.LIB
Q1 0 0 1 QBFT92
Q2 0 0 VIN+ QBFT92
R1 VOUT VIN- 60K
R2 VIN- 1 3.5K
R3 VOUT VIN+ 10K
X1 VIN+ VIN- VDD VSS VOUT AMP_CUBA_n PARAMS: RBIAS=100K
** POWER SPPLY
V1 VDD 0 2.5
V2 0 VSS 2.5
.END        ************************
SPICE File_2
.PROBE
.OP
.TRAN 10N 2u
.TEMP 0, 25, 50
.LIB CUBA.LIB
.LIB MY-BJT.LIB
Q1 0 0 1 QBFT92
Q2 0 0 VIN+ QBFT92
R1 VOUT VIN- 60K
R2 VIN- 1 3.6536K
R3 VOUT VIN+ 10K
X1 VIN+ VIN- VDD VSS VOUT AMP_CUBA_n PARAMS: RBIAS=100K
** POWER SPPLY
V1 VDD 0 2.5
V2 0 VSS 2.5
.END        ************************
SPICE File_3
.PROBE
.OP
.TRAN 10N 3u
.TEMP 0, 25, 50
.LIB CUBA.LIB
.LIB MY-BJT.LIB
Q1 0 0 1 QBFT92
Q2 0 0 VIN+ QBFT92
R1 VOUT VIN- 60K
R2 VIN- 1 3.85K
R3 VOUT VIN+ 10K
X1 VIN+ VIN- VDD VSS VOUT AMP_CUBA_n PARAMS: RBIAS=100K
** POWER SPPLY
```

9.27

```
V1 VDD 0 2.5
V2 0 VSS 2.5
.END          ************************
```

•The three listings differ only for **R2** value. The circuit has been simulated for three different temperatures and the one with the **R2**=3.6536K has the lowest tempo.



The tempco's are -400μV/ ºC, -300μV/ ºC, -330μV/ ºC.
The nominal value at 25 ºC is 1.2062V.
The biasing for the best value, at 25 ºC, is given below.

**** 01/30/96 12:04:29 ********* PSpice 6.0 (Jan 1994) ******** ID# 53788
****

SPICE File_2

**** OPERATING POINT INFORMATION TEMPERATURE = 25.000 DEG C

**** BIPOLAR JUNCTION TRANSISTORS

NAME	Q1	Q2
MODEL	QBFT92	QBFT92
IB	-3.05E-07	-1.82E-06
IC	-1.09E-05	-6.49E-05
VBE	-4.94E-01	-5.39E-01
VBC	0.00E+00	0.00E+00
VCE	-4.94E-01	-5.39E-01
BETADC	3.57E+01	3.57E+01
GM	4.23E-04	2.52E-03
RPI	8.42E+04	1.41E+04
RX	0.00E+00	0.00E+00
RO	2.21E+06	3.70E+05
CBE	1.33E-12	1.43E-12
CBC	1.04E-12	1.04E-12
CBX	0.00E+00	0.00E+00
CJS	0.00E+00	0.00E+00
BETAAC	3.57E+01	3.57E+01
FT	2.84E+07	1.62E+08

**** MOSFETS

NAME	X1.X1.M1	X1.X2.M1	X1.X3.M1	X1.X4.M1	X1.X5.M1
MODEL	2_CUBAQN	2_CUBAQN	2_CUBAQP	2_CUBAQP	2_CUBAQN
ID	1.97E-05	2.00E-05	-1.97E-05	-2.00E-05	3.96E-05
VGS	1.60E+00	1.60E+00	-1.70E+00	-1.70E+00	1.06E+00
VDS	1.86E+00	4.18E-01	-1.70E+00	-3.15E+00	1.44E+00
VBS	-1.44E+00	-1.44E+00	0.00E+00	0.00E+00	0.00E+00
VTH	1.37E+00	1.37E+00	-8.51E-01	-8.50E-01	8.14E-01
VDSAT	2.06E-01	2.08E-01	-6.93E-01	-6.94E-01	1.93E-01
GM	1.45E-04	1.46E-04	4.40E-05	4.47E-05	2.73E-04
GDS	2.24E-07	4.32E-07	2.59E-07	1.76E-07	4.48E-07
GMB	4.42E-05	4.42E-05	1.21E-05	1.23E-05	1.37E-04
CBD	1.08E-13	1.19E-13	3.11E-14	2.86E-14	2.46E-13
CBS	1.23E-13	1.23E-13	4.08E-14	4.08E-14	3.16E-13
CGSOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGDOV	5.53E-14	5.53E-14	1.60E-14	1.60E-14	1.11E-13
CGBOV	1.54E-15	1.54E-15	1.55E-15	1.55E-15	1.54E-15
CGS	6.81E-13	6.81E-13	1.98E-13	1.98E-13	1.37E-12

CGD	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

NAME	X1.X6.M1	X1.X7.M1	X1.X8.M1
MODEL	2_CUBAQN	2_CUBAQP	2_CUBAQN
ID	3.94E-05	-3.98E-04	3.20E-04
VGS	1.06E+00	-3.15E+00	1.06E+00
VDS	1.06E+00	-1.29E+00	3.71E+00
VBS	0.00E+00	0.00E+00	0.00E+00
VTH	8.14E-01	-8.50E-01	7.99E-01
VDSAT	1.92E-01	-1.82E+00	2.02E-01
GM	2.72E-04	2.23E-04	2.10E-03
GDS	5.22E-07	1.48E-04	4.57E-06
GMB	1.36E-04	5.15E-05	1.03E-03
CBD	2.57E-13	1.06E-13	6.85E-13
CBS	3.16E-13	1.34E-13	1.03E-12
CGSOV	1.11E-13	5.52E-14	3.63E-13
CGDOV	1.11E-13	5.52E-14	3.63E-13
CGBOV	1.54E-15	1.55E-15	7.13E-16
CGS	1.37E-12	5.39E-13	2.08E-12
CGD	0.00E+00	4.34E-13	0.00E+00
CGB	0.00E+00	0.00E+00	0.00E+00

**** 01/30/96 12:04:29 ********* PSpice 6.0 (Jan 1994) ******** ID# 53788
****

SPICE File_2

**** INITIAL TRANSIENT SOLUTION TEMPERATURE = 25.000 DEG C

****

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(1)	.4935	(VDD)	2.5000	(VSS)	-2.5000	(VIN+)	.5394
(VIN-)	.5344	**(VOUT)**	**1.2062**	(X1.2)	.7953	(X1.4)	-1.0639
(X1.6)	-1.4446	(X1.10)	-.6456				

VOLTAGE SOURCE CURRENTS

NAME	CURRENT
V1	-4.769E-04
V2	-3.990E-04

TOTAL POWER DISSIPATION 2.19E-03 WATTS