ECE 523 HW4 – Folded Cascode Opamp Design

0. Performance Summary

The specifications and achieved performance of the designed folded cascode amplifier are summarized in the following table.

Table. 1 Design summary.

Target Specifications		Achieved Performance (by corners)		
Supply	2.5V	**Slow**	**Typical**	**Fast**
Load	10pF±2pF	12pF	10pF	8pF
DC Gain	>60dB	60.1dB	62.0dB	63.5dB
UGB	>80MHz	83.7MHz	117.4MHz	169.1MHz
Phase Margin	>60 degree	73.8 degree	70.5 degree	65.1 degree
Output Swing	$>1V_{pp}$	$1.27V_{pp}$	$1.59V_{pp}$	$1.85V_{pp}$
Power	<8mW	7.57mW	7.36mW	7.05mW
Input Offset	<3mV	456uV	435uV	418uV

1. Introduction

In this assignment, we are going to design an Opamp satisfying the above specifications. The most important part of this task is to take into consideration different design corners. The normal approach is to identify the worst case scenario, which is the starting point of the design flow. In this problem, the worst case is simply the "slow" corner.

2. Design Equations

The schematic of the adopted folded cascode opamp topology is shown in the figure below. Sooch cascode biasing scheme is utilized to generate optimal biasing for the transistors.

Several equations can be used to simplify the design trade-off:

Single pole transfer function: $A(s)=\frac{V_o(s)}{V_{in}(s)}=\frac{A_0}{1+\frac{s}{p_1}}$

DC Gain: $A_0=g_{m1}r_{out}=g_{m1}\cdot\{[g_{m6}r_{o6}(r_{o4}||r_{o2})]||(g_{m8}r_{o8}r_{o10})\}$

Dominant pole: $p_1=\frac{1}{C_L\{[g_{m6}r_{o6}(r_{o4}||r_{o2})]||(g_{m8}r_{o8}r_{o10})\}}$

UGB: $UGB=\frac{g_{m1}}{C_L}$

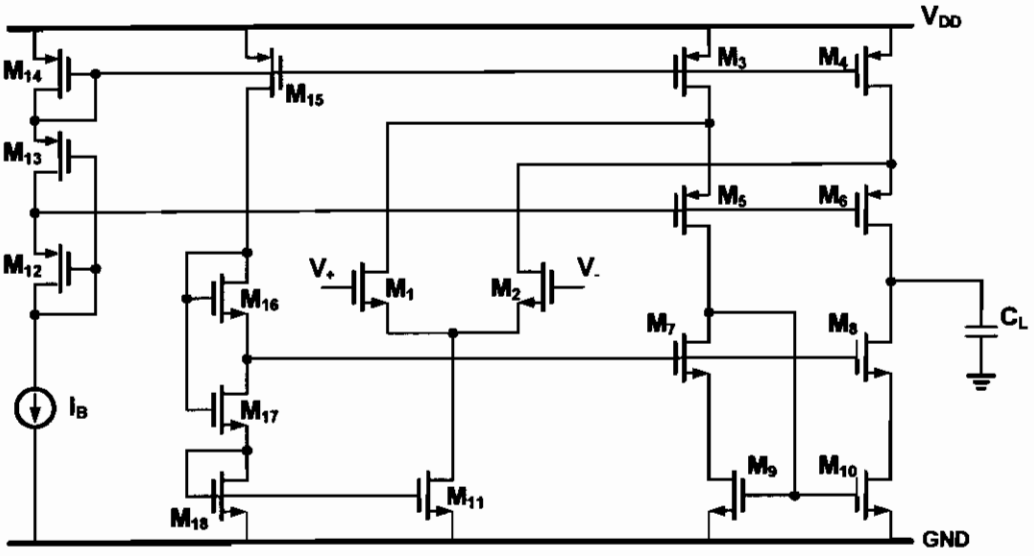

Fig. 1 Schematic of the utilized folded cascode operational amplifier.

3. Simulation Results

The biasing current (provided by an ideal current source) is 90uA. The transistor sizes are listed in the table below.

Table. 2 Transistor Sizes

	W/L (um/um)		W/L (um/um)		W/L (um/um)
M1	150/0.6	M7	280/1.5	M13	7/0.4
M2	150/0.6	M8	280/1.5	M14	5/0.3
M3	82/0.3	M9	40/0.4	M15	5/0.3
M4	82/0.3	M10	40/0.4	M16	20/0.4
M5	200/0.6	M11	82/0.4	M17	5/0.4
M6	200/0.6	M12	30/0.4	M18	4/0.4

The frequency responses of the designed Opamp at different corners are shown in the following figures.

1) Fast @ -40 degree

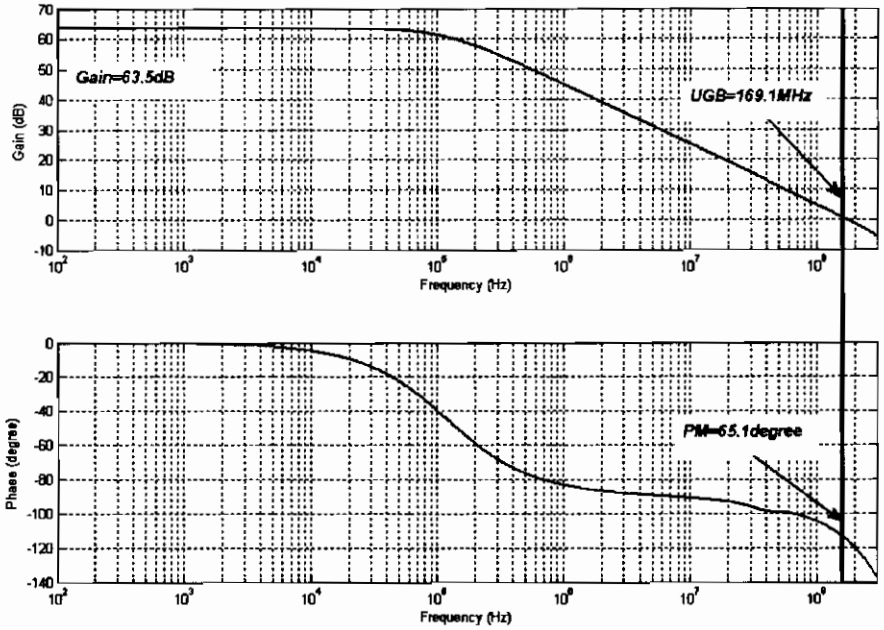

Fig. 2 Frequency response of the designed Opamp in fast corner.

2) Typical @ 27 degree

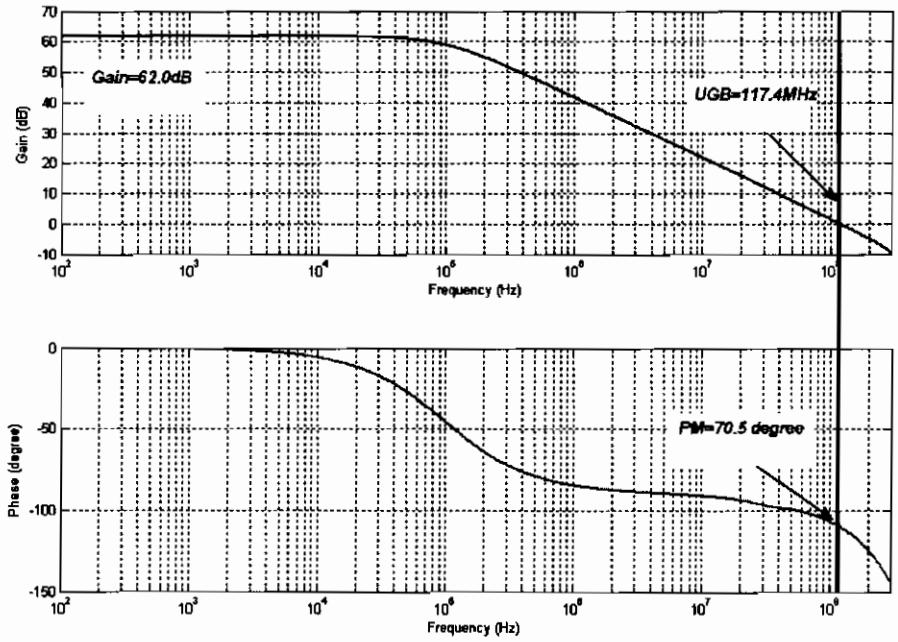

Fig. 3 Frequency response of the designed Opamp in typical corner.

3) Slow @ 100 degree

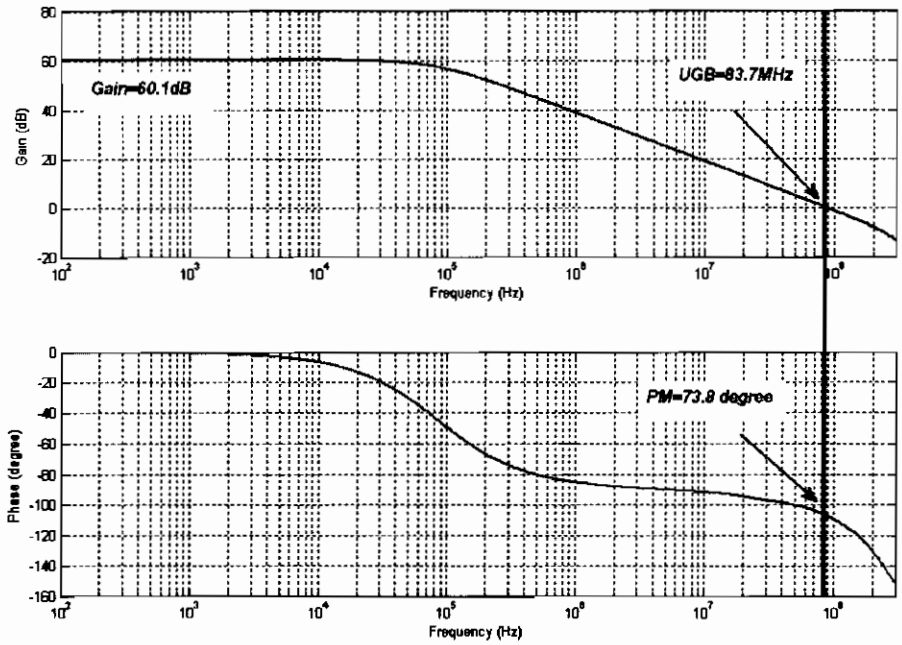

Fig. 4 Frequency response of the designed Opamp in slow corner.

```
**** Folded Cascode Opamp ******
.include 'tsmc25.txt'
.option post=1 dcon=1

* Sources

vdd vdd 0 2.5
I1 IC 0 90u


vdc1 v1 0 1.25
vdc2 v2 0 1.25
vac vac 0 ac 1
E1 In1 v1 vac 0 0.5
E2 In2 v2 vac 0 -0.5

* Transistor width
.para W18=4u
.para W17=5u
.para W16=20u

.para W15=5u
.para W14=5u

.para W13=7u
.para W12=30u

.para W11=82u

.para W10=40u
.para W9=40u
.para W8=280u
.para W7=280u

.para W6=200u
.para W5=200u
.para W4=82u
.para W3=82u

.para W2=150u
.para W1=150u

MP12 IC   IC SM12  SM12 CMOSP W=W12 L=0.4u AD='W12*0.66u' AS='W12*0.66u' PD='2*W12+1.32u'
PS='2*W12+1.32u'
MP13 SM12 IC SM13  SM13 CMOSP W=W13 L=0.4u AD='W13*0.66u' AS='W13*0.66u' PD='2*W13+1.32u'
PS='2*W13+1.32u'
MP14 SM13 SM13 Vdd  Vdd CMOSP W=W14 L=0.3u AD='W14*0.66u' AS='W14*0.66u' PD='2*W14+1.32u'
PS='2*W14+1.32u'
MP15 DM15 SM13 Vdd  Vdd CMOSP W=W15 L=0.3u AD='W15*0.66u' AS='W15*0.66u' PD='2*W15+1.32u'
PS='2*W15+1.32u'
MP16 DM15 DM15 SM16 0   CMOSN W=W16 L=0.4u AD='W16*0.66u' AS='W16*0.66u' PD='2*W16+1.32u'
PS='2*W16+1.32u'
MP17 SM16 DM15 SM17 0   CMOSN W=W17 L=0.4u AD='W17*0.66u' AS='W17*0.66u' PD='2*W17+1.32u'
PS='2*W17+1.32u'
MP18 SM17 SM17 0    0   CMOSN W=W18 L=0.4u AD='W18*0.66u' AS='W18*0.66u' PD='2*W18+1.32u'
PS='2*W18+1.32u'

MN11 A    SM17 0    0   CMOSN W=W11 L=0.4u AD='W11*0.66u' AS='W11*0.66u' PD='2*W11+1.32u'
PS='2*W11+1.32u'

MN1  B    IN1  A    0   CMOSN W=W1  L=0.6u AD='W1*0.66u'  AS='W1*0.66u'  PD='2*W1+1.32u'
PS='2*W1+1.32u'
MN2  C    IN2  A    0   CMOSN W=W2  L=0.6u AD='W2*0.66u'  AS='W2*0.66u'  PD='2*W2+1.32u'
PS='2*W2+1.32u'
MN3  B    SM13 Vdd  Vdd CMOSP W=W3  L=0.3u AD='W3*0.66u'  AS='W3*0.66u'  PD='2*W3+1.32u'
PS='2*W3+1.32u'
MN4  C    SM13 Vdd  Vdd CMOSP W=W4  L=0.3u AD='W4*0.66u'  AS='W4*0.66u'  PD='2*W4+1.32u'
PS='2*W4+1.32u'
MN5  D    SM12 B    B   CMOSP W=W5  L=0.6u AD='W5*0.66u'  AS='W5*0.66u'  PD='2*W5+1.32u'
PS='2*W5+1.32u'
MN6  OUT  SM12 C    C   CMOSP W=W6  L=0.6u AD='W6*0.66u'  AS='W6*0.66u'  PD='2*W6+1.32u'
PS='2*W6+1.32u'
MN7  D    SM16 F    0   CMOSN W=W7  L=1.5u AD='W7*0.66u'  AS='W7*0.66u'  PD='2*W7+1.32u'
PS='2*W7+1.32u'
MN8  OUT  SM16 G    0   CMOSN W=W8  L=1.5u AD='W8*0.66u'  AS='W8*0.66u'  PD='2*W8+1.32u'
PS='2*W8+1.32u'
```

```
MN9  F    D    0    0   CMOSN W=W9  L=0.4u AD='W9*0.66u'  AS='W9*0.66u'  PD='2*W9+1.32u'
PS='2*W9+1.32u'
MN10 G    D    0    0   CMOSN W=W10 L=0.4u AD='W10*0.66u' AS='W10*0.66u' PD='2*W10+1.32u'
PS='2*W10+1.32u'

Cl OUT 0 12p


.op
.temp 100
.probe Gain=par('V(vo)/V(vac)')
.probe Phase=par('vp(OUT)')
.ac dec 100 100 300MEG
.tf V(OUT) vac
*.pz V(OUT) vac

.MEAS AC ug when vdb(OUT) = 0
.MEAS AC pm find vp(OUT) when vdb(OUT) = 0
.MEAS AC av max vdb(OUT)

.end
```

```
1****** HSPICE -- C-2009.03-SP1 32-BIT (May 25 2009) winnt ******
 ******
 **** folded cascode opamp ******

  ******  operating point information tnom=  25.000 temp= 100.000 *****
 ***** operating point status is all       simulation time is     0.
    node    =voltage      node    =voltage      node    =voltage

 +0:a       = 503.6622m 0:b       =   2.0189  0:c       =   2.0189
 +0:d       = 758.3396m 0:dm15    =   1.7857  0:f       = 306.0261m
 +0:g       = 306.0261m 0:ic      = 445.8406m 0:in1     =   1.2500
 +0:in2     =   1.2500  0:out     = 758.3396m 0:sm12    =   1.1907
 +0:sm13    =   1.5173  0:sm16    = 997.0245m 0:sm17    = 805.7755m
 +0:v1      =   1.2500  0:v2      =   1.2500  0:vac     =   0.
 +0:vdd     =   2.5000


 ****  voltage sources

 subckt
 element  0:vdd      0:vdc1     0:vdc2     0:vac
  volts      2.5000     1.2500     1.2500     0.
  current   -3.0275m    0.         0.         0.
  power      7.5688m    0.         0.         0.

     total voltage source power dissipation=    7.5688m       watts


 ***** current sources

 subckt
 element  0:i1
  volts    445.8406m
  current   90.0000u
  power    -40.1256u


     total current source power dissipation= -40.1256u       watts

 **** voltage-controlled voltage sources


 subckt
 element  0:e1       0:e2
  volts      0.         0.
  current    0.         0.




 **** mosfets


 subckt
 element  0:mp12     0:mp13     0:mp14     0:mp15     0:mp16     0:mp17
 model    0:cmosp    0:cmosp    0:cmosp    0:cmosp    0:cmosn    0:cmosn
 region      Saturati     Linear   Saturati   Saturati   Saturati     Linear
  id       -90.0000u  -90.0000u  -90.0000u  -87.0294u   87.0294u   87.0294u
  ibs        0.         0.         0.         0.         0.         0.
  ibd        0.         0.         0.         0.         0.         0.
  vgs     -744.9029m   -1.0715  -982.6925m -982.6925m  788.6946m  979.9436m
  vds     -744.9029m -326.5641m -982.6925m -714.2809m  788.6946m  191.2490m
  vbs        0.         0.         0.         0.      -997.0245m -805.7755m
  vth     -545.1027m -544.2107m -512.0164m -513.2340m  626.8471m  601.6251m
  vdsat   -211.1436m -461.0600m -417.7534m -416.7907m  160.7066m  339.9749m
  vod     -199.8002m -527.2563m -470.6761m -469.4585m  161.8475m  378.3185m
  beta       4.1037m  868.5438u  896.7656u  896.4217u    8.1657m    1.9836m
  gam eff  384.1817m  382.9626m  381.4380m  381.4380m  271.8008m  279.4113m
  gm       710.6991u  226.6375u  321.9933u  312.2634u    1.0061m  336.0138u
  gds        8.1582u  129.7502u   10.6751u   11.6126u   19.6687u  284.8749u
  gmb      174.0014u   58.9211u   72.7617u   70.0469u  155.2112u   55.3274u
  cdtot     68.0003f   18.7529f   11.1742f   11.7090f   44.0312f   14.6342f
  cgtot     90.2981f   21.5968f   12.6924f   12.6965f   61.2918f   16.8911f
```

cstot	112.9781f	26.6664f	17.7517f	17.7539f	67.3141f	17.5934f
cbtot	123.6415f	30.9373f	20.1884f	20.7165f	68.4703f	19.4385f
cgs	68.4990f	16.0504f	9.2746f	9.2788f	46.5884f	11.5578f
cgd	19.5068f	5.2755f	3.1999f	3.2044f	14.1259f	5.4091f

subckt element	0:mp18	0:mn11	0:mn1	0:mn2	0:mn3	0:mn4
model	0:cmosn	0:cmosn	0:cmosn	0:cmosn	0:cmosp	0:cmosp
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	87.0294u	1.6964m	848.2216u	848.2216u	-1.4252m	-1.4252m
ibs	0.	0.	0.	0.	0.	0.
ibd	0.	0.	0.	0.	0.	0.
vgs	805.7755m	805.7755m	746.3378m	746.3378m	-982.6925m	-982.6925m
vds	805.7755m	503.6622m	1.5152	1.5152	-481.1497m	-481.1497m
vbs	0.	0.	-503.6622m	-503.6622m	0.	0.
vth	449.1689m	451.3616m	518.9155m	518.9155m	-517.2436m	-517.2436m
vdsat	304.3654m	303.0338m	210.9672m	210.9672m	-434.6209m	-434.6209m
vod	356.6066m	354.4139m	227.4223m	227.4223m	-465.4488m	-465.4488m
beta	1.6665m	34.1687m	40.3243m	40.3243m	14.7298m	14.7298m
gam eff	300.6511m	296.8143m	282.3463m	282.3463m	384.3620m	384.3620m
gm	491.1155u	9.5759m	7.9437m	7.9437m	5.0115m	5.0115m
gds	13.2334u	399.7945u	102.8802u	102.8802u	381.0161u	381.0161u
gmb	101.8305u	2.0048m	1.4042m	1.4042m	1.1784m	1.1784m
cdtot	10.3483f	214.3166f	319.8632f	319.8632f	196.0624f	196.0624f
cgtot	12.7022f	261.0142f	604.5147f	604.5147f	209.7730f	209.7730f
cstot	16.6613f	330.0581f	625.0276f	625.0276f	284.8911f	284.8911f
cbtot	18.4261f	367.5964f	561.4854f	561.4854f	335.2902f	335.2902f
cgs	9.7573f	200.4576f	492.9841f	492.9841f	152.9184f	152.9184f
cgd	2.8124f	58.1243f	104.4663f	104.4663f	53.6348f	53.6348f

subckt element	0:mn5	0:mn6	0:mn7	0:mn8	0:mn9	0:mn10
model	0:cmosp	0:cmosp	0:cmosn	0:cmosn	0:cmosn	0:cmosn
region	Saturati	Saturati	Saturati	Saturati	Saturati	Saturati
id	-577.0207u	-577.0207u	577.0207u	577.0207u	577.0207u	577.0207u
ibs	0.	0.	0.	0.	0.	0.
ibd	0.	0.	0.	0.	0.	0.
vgs	-828.1068m	-828.1068m	690.9984m	690.9984m	758.3396m	758.3396m
vds	-1.2605	-1.2605	452.3134m	452.3134m	306.0261m	306.0261m
vbs	0.	0.	-306.0261m	-306.0261m	0.	0.
vth	-571.2936m	-571.2936m	469.8572m	469.8572m	453.4228m	453.4228m
vdsat	-254.4359m	-254.4359m	209.8030m	209.8030m	262.6813m	262.6813m
vod	-256.8132m	-256.8132m	221.1412m	221.1412m	304.9167m	304.9167m
beta	16.9240m	16.9240m	29.3771m	29.3771m	16.8136m	16.8136m
gam eff	384.5146m	384.5146m	287.5275m	287.5275m	297.0207m	297.0207m
gm	3.7853m	3.7853m	5.5487m	5.5487m	3.7995m	3.7995m
gds	28.6606u	28.6606u	77.0445u	77.0445u	337.9489u	337.9489u
gmb	990.1925u	990.1925u	1.0445m	1.0445m	799.9307u	799.9307u
cdtot	416.4762f	416.4762f	696.5917f	696.5917f	110.8502f	110.8502f
cgtot	792.7206f	792.7206f	2.2569p	2.2569p	128.0476f	128.0476f
cstot	874.7623f	874.7623f	1.9101p	1.9101p	161.1584f	161.1584f
cbtot	832.8704f	832.8704f	1.4085p	1.4085p	184.7946f	184.7946f
cgs	644.1435f	644.1435f	2.0152p	2.0152p	97.4264f	97.4264f
cgd	130.4619f	130.4619f	190.4717f	190.4717f	29.4158f	29.4158f

**** small-signal transfer characteristics

v(out)/vac = 1.0146k
input resistance at vac = 1.000e+20
output resistance at v(out) = 144.0599k

******
**** folded cascode opamp ******

```
  ******  ac analysis tnom=  25.000 temp= 100.000 *****
   ug=  8.3730E+07
   pm= -1.0619E+02
   av=  6.0125E+01    at=  1.0000E+02
                from=  1.0000E+02    to=  3.0200E+08

          ***** job concluded
1****** HSPICE -- C-2009.03-SP1 32-BIT (May 25 2009) winnt ******
 ******
 **** folded cascode opamp ******

  ******  job statistics summary tnom=  25.000 temp= 100.000 *****

  ******  HSPICE Threads Information  ******
  Command Line Threads Count                  :     1
  Available CPU Count                         :     2
  Actual Model Evaluation(Load) Threads Count :     1
  Actual Solver Threads Count                 :     1


  ******  Circuit Statistics  ******
  # nodes       =      20 # elements   =      26
  # resistors   =       0 # capacitors =       1 # inductors   =       0
  # mutual_inds =       0 # vccs       =       0 # vcvs        =       2
  # cccs        =       0 # ccvs       =       0 # volt_srcs   =       4
  # curr_srcs   =       1 # diodes     =       0 # bjts        =       0
  # jfets       =       0 # mosfets    =      18 # U elements  =       0
  # T elements  =       0 # W elements =       0 # B elements  =       0
  # S elements  =       0 # P elements =       0 # va device   =       0


  ******  Runtime Statistics (seconds)  ******

  analysis           time    # points   tot. iter  conv.iter
  op point           0.00           1          33
  ac analysis        0.03         649         649
  readin             0.05
  errchk             0.01
  setup              0.02
  output             0.00


           total memory used          459  kbytes
           total cpu time            0.14 seconds
           total elapsed time        0.17 seconds
           job started at     12:43:58 02/07/2011
           job ended   at     12:43:58 02/07/2011

 Init: hspice initialization file: C:\synopsys\Hspice_C-2009.03-SP1\hspice.ini
  lic: Release hspice token(s)
```