THE UNIVERSITY OF TEXAS AT DALLAS

Department Of Electrical Engineering

EECT 7326 ADVANCED ANALOG IC DESIGN

**HOMEWORK-1**

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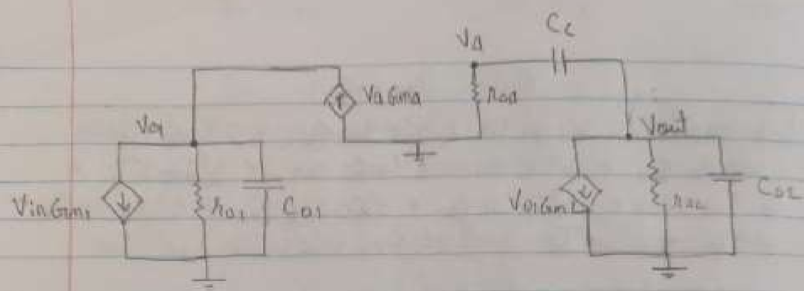
**Q1-a,b,]**




i) KCL at node $V_{o1}$ we get

$$V_a G_{ma} = V_{in} G_{m1} + \frac{V_{o1}}{r_{o1}} + V_{o1} s C_{o1}$$

$$V_a G_{ma} - V_{in} G_{m1} = V_{o1} \left[ g_{o1} + s C_{o1} \right]$$

$$V_{o1} = \left[ \frac{V_a G_{ma} - V_{in} G_{m1}}{g_{o1} + s C_{o1}} \right] \quad \ldots (1)$$

ii) KCL at node $V_a$

$$\frac{V_a}{r_{oa}} = -(V_a - V_{out}) s C_c$$

$$\therefore \frac{V_a}{r_{oa}} + V_a s C_c = V_{out} s C_c$$

$$\therefore V_a = \frac{V_{out} \cdot s C_c}{(g_{oa} + s C_c)} \quad \ldots (2)$$

iii) KCL at node $V_{out}$

$$s C_c (V_a - V_{out}) = V_{o1} G_{mL} + \frac{V_{out}}{r_{o2}} + V_{out} \cdot s C_{o2}$$

$$V_a s C_c - V_{o1} G_{mL} = V_{out} \left[ g_{o2} + s C_{o2} + s C_c \right]$$

$$V_{out} = \frac{V_a s C_c - V_{o1} G_{mL}}{\left[ g_{o2} + s C_{o2} + s C_c \right]} \quad \ldots (3)$$

$$V_{out}\left[g_{o2}+sC_c+sC_{o2}\right] = \frac{s^2C_c^2 \cdot V_{out}}{(g_{oa}+sC_c)} - G_{mL}\left[\frac{V_aG_{ma}-V_{in}G_{m1}}{g_{o1}+sC_{o1}}\right]$$

$$V_{out}\left[g_{o2}+sC_c+sC_{o2}\right] - \frac{s^2C_c^2V_{out}}{(g_{oa}+sC_c)} = -\frac{V_aG_{ma}G_{mL}}{(g_{o1}+sC_{o1})} + \frac{V_{in}G_{m1}G_{mL}}{(g_{o1}+sC_{o1})}$$

$$V_{out}\left[(g_{o2}+sC_c+sC_{o2}) - \frac{s^2C_c^2}{(g_{oa}+sC_c)}\right] + \frac{V_aG_{ma}G_{mL}}{(g_{o1}+sC_{o1})} = +\frac{V_{in}G_{m1}G_{mL}}{(g_{o1}+sC_{o1})}$$

$$V_{out}\left[(g_{o2}+sC_c+sC_{o2}) - \frac{s^2C_c^2}{(g_{oa}+sC_c)}\right] + \frac{G_{ma}\cdot G_{mL}\cdot sC_c\cdot V_{out}}{(g_{o1}+sC_{o1})(g_{oa}+sC_c)} = \frac{+V_{in}G_{m1}G_{mL}}{(g_{o1}+sC_{o1})}$$

$$V_{out}\left\{\left[(g_{o2}+sC_c+sC_{o2}) - \frac{s^2C_c^2}{(g_{oa}+sC_c)}\right] + \frac{G_{ma}G_{mL}\cdot sC_c}{(g_{o1}+sC_{o1})(g_{oa}+sC_c)}\right\} = \frac{+V_{in}G_{m1}G_{mL}}{(g_{o1}+sC_{o1})}$$

$$\frac{V_{out}}{V_{in}} = \frac{G_{m1}G_{mL}}{(g_{o1}+sC_{o1})\left\{\frac{(g_{o2}+sC_c+sC_{o2})(g_{oa}+sC_c)-s^2C_c^2}{(g_{oa}+sC_c)} + \frac{G_{ma}G_{mL}\cdot sC_c}{(g_{oa}+sC_c)(g_{o1}+sC_{o1})}\right\}}$$

$$= \frac{G_{m1}G_{mL}(g_{oa}+sC_c)}{(g_{o1}+sC_{o1})(g_{o2}+sC_c+sC_{o2})(g_{oa}+sC_c)-s^2C_c^2(g_{o1}+sC_{o1})+G_{ma}G_{mL}sC_c}$$

$$= \frac{G_{m1}G_{mL}(g_{oa}+sC_c)}{(g_{o1}g_{oa}+sC_cg_{o1}+sC_{o1}g_{oa}+s^2C_{o1}C_c)(g_{o2}+sC_c+sC_{o2}) - s^2C_c^2(g_{o1}+sC_{o1})+G_{ma}G_{mL}sC_c}$$

$$\frac{V_{out}}{V_{in}} = \frac{G_{m1} G_{mL} (g_{oa} + sC_c)}{\left[ g_{o1} g_{oa} g_{o2} + sC_c g_{o1} g_{o2} + sC_{o1} g_{oa} g_{o2} + s^2 C_{o1} C_c g_{o2} + sC_c g_{o1} g_{oa} + \cancel{s^2 C_c^2 g_{o1}} + s^2 C_{o1} C_c g_{oa} + \cancel{s^3 C_{o1} C_c^2} + g_{o1} g_{oa} sC_{o2} + s^2 C_c C_{o2} g_{o1} + s^2 C_{o1} C_{o2} g_{oa} + s^3 C_{o1} C_{o2} C_c - \cancel{s^2 C_c^2 g_{o1}} - \cancel{s^3 C_c^2 C_{o1}} + G_{ma} G_{mL} s C_c \right]}$$

$$= \frac{G_{m1} G_{mL} (g_{oa} + sC_c)}{\left[ g_{o1} g_{oa} g_{o2} + sC_c g_{o1} g_{o2} + sC_{o1} g_{oa} g_{o2} + sC_c g_{o1} g_{oa} + sC_{o2} g_{o1} g_{oa} + sC_c G_{ma} G_{mL} + s^2 C_{o1} C_c g_{o2} + s^2 C_{o1} C_c g_{oa} + s^2 C_c C_{o2} g_{o1} + s^2 C_{o1} C_{o2} g_{oa} + s^3 C_{o1} C_{o2} C_c \right]}$$

$$= \frac{G_{m1} G_{mL} (g_{oa} + sC_c)}{g_{o1} g_{o2} g_{oa} + s\left[ g_{o1} g_{o2} C_c + C_{o1} g_{oa} g_{o2} + g_{o1} g_{oa} C_c + C_{o2} g_{o1} g_{oa} + C_c G_{ma} G_{mL} \right] + s^2 \left[ C_{o1} C_c g_{o2} + C_{o1} C_c g_{oa} + C_c C_{o2} g_{o1} + C_{o1} C_{o2} g_{oa} \right] + s^3 (C_{o1} C_{o2} C_c)}$$

$$= \frac{g_{oa} \left[ G_{m1} G_{mL} \left( 1 + sC_c/g_{oa} \right) \right]}{g_{o1} g_{o2} g_{oa} \left\{ 1 + s\left[ C_c/g_{oa} + C_{o1}/g_{o1} + C_c/g_{o2} + C_{o2}/g_{o2} + \frac{C_c G_{ma} G_{mL}}{g_{o1} g_{o2} g_{oa}} \right] + s^2 \left[ C_{o1} C_c / g_{oa} g_{o1} + \frac{C_{o1} C_c}{g_{o1} g_{o2}} + C_c C_{o2} / g_{o2} g_{oa} + C_{o1} C_{o2} / g_{o1} g_{o2} \right] + s^3 \left[ \frac{C_{o1} C_{o2} C_c}{g_{o1} g_{o2} g_{oa}} \right] \right.}$$

Now $s^3 \left[ C_{o1} C_{o2} C_c / g_{o1} g_{o2} g_{oa} \right] << 1$

$\therefore$

$$\therefore \frac{V_{out}}{V_{in}} = \frac{g_{oa}\left[G_{m1}G_{mL}\left(1+sC_c/g_{oa}\right)\right]}{g_{o1}\,g_{o2}\,\cancel{g_{oa}}\left[1+s\left[C_c/g_{oa}+C_{o1}/g_{o1}+C_c/g_{o2}+C_{o2}/g_{o2}+\frac{C_cG_{ma}G_{mL}}{g_{o1}g_{o2}g_{oa}}\right]+s^2\left[\frac{C_{o1}C_c}{g_{o1}g_{oa}}+\frac{C_{o1}C_c}{g_{o1}g_{o2}}+\frac{C_cC_{o2}}{g_{o2}g_{oa}}+\frac{C_{o1}C_{o2}}{g_{o1}g_{o2}}\right]\right]}$$

$$= \frac{\dfrac{G_{m1}G_{mL}\left(1+sC_c/g_{oa}\right)}{g_{o1}\,g_{o2}}}{1+s\left[\dfrac{C_c}{g_{oa}}+\dfrac{C_{o1}}{g_{o1}}+\dfrac{C_c}{g_{o2}}+\dfrac{C_{o2}}{g_{o2}}+\dfrac{C_cG_{mL}G_{ma}}{g_{o1}g_{o2}g_{oa}}\right]+s^2\left[\dfrac{C_{o1}C_c}{g_{o1}g_{oa}}+\dfrac{C_{o1}C_c}{g_{o1}g_{o2}}+\dfrac{C_cC_{o2}}{g_{o2}g_{oa}}+\dfrac{C_{o1}C_{o2}}{g_{o1}g_{o2}}\right]}$$

Now $g_{oa} = \dfrac{1}{r_{oa}} = \dfrac{1}{1/G_{ma}} = G_{ma}$

$g_{o1} = 1/r_{o1}$

$g_{o2} = 1/r_{o2}$

$$= \frac{G_{m1}G_{mL}r_{o1}r_{o2}\left(1+sC_c/G_{ma}\right)}{1+s\left[G_{ma}C_c+C_{o1}r_{o1}+C_cr_{o2}+C_{o2}r_{o2}+C_cG_{mL}r_{o1}r_{o2}\right]+s^2\left[C_{o1}C_cr_{o1}G_{ma}+C_{o1}C_cr_{o1}r_{o2}+C_cC_{o2}r_{o2}G_{ma}+C_{o1}C_{o2}r_{o1}r_{o2}\right]}$$

$\because$ Gma is of the order of $10^{-6}$ and Caps are of the order of $10^{-12}$ compared to $r_0$ terms, which are of the order of $10^3$ to $10^6$.
$\therefore$ ignoring smaller terms from denominator we get

$$\frac{V_{out}}{V_{in}} = \frac{G_{m1} G_{mL} r_{01} r_{02} (1 + sC_c/G_{ma})}{1 + s\left[C_{01} r_{01} + C_c r_{02} + C_{02} r_{02} + C_c G_{mL} \cdot r_{01} r_{02}\right] + s^2\left[C_{01} C_1 r_{01} r_{02} + C_{01} C_{02} r_{01} r_{02}\right]}$$

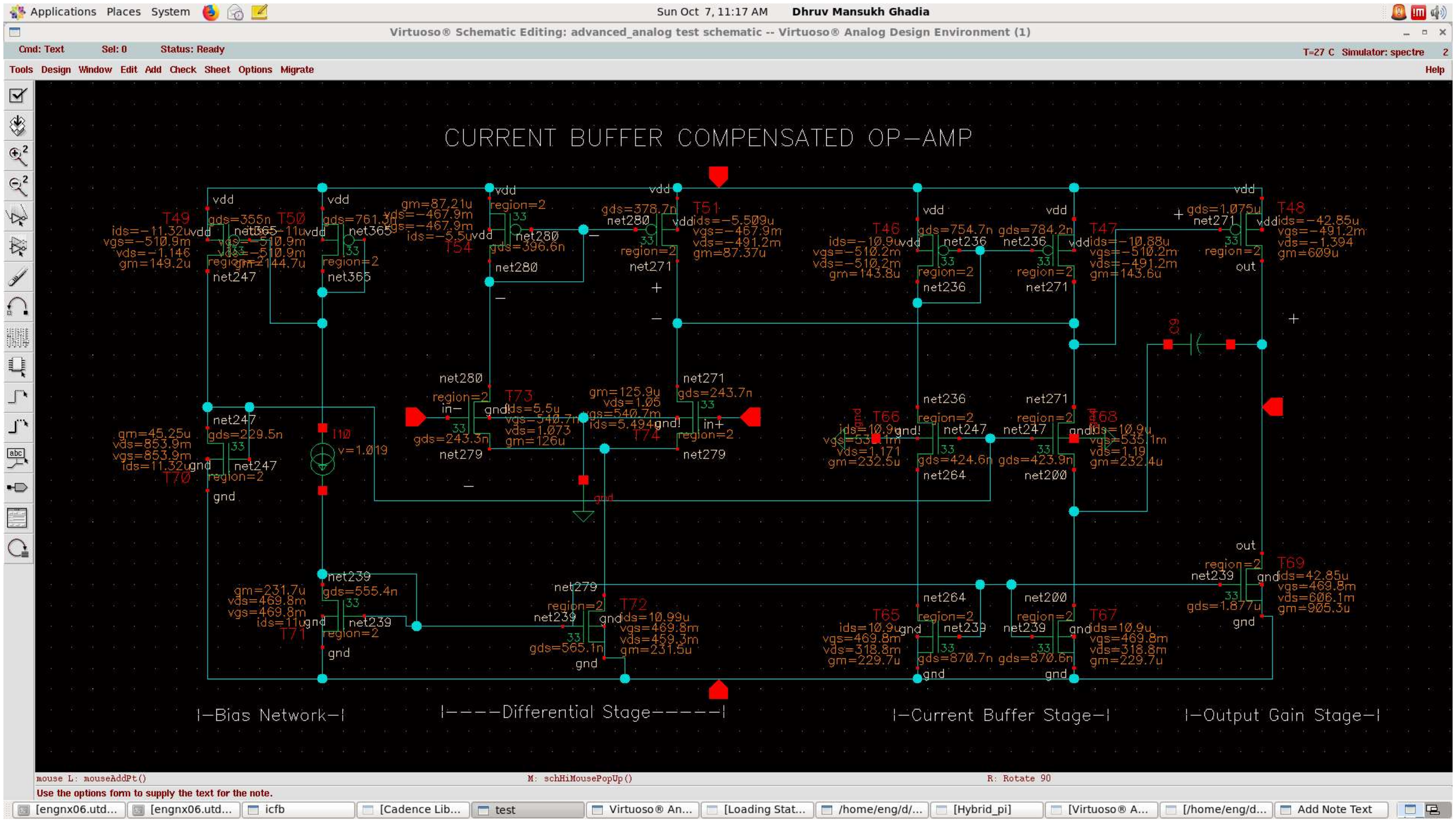
$$\therefore \frac{V_{out}}{V_{in}} \approx \frac{G_{m1} G_{mL} r_{01} r_{02} (1 + sC_c/G_{ma})}{1 + s(C_{01} r_{01} + C_c r_{02} + C_{02} r_{02} + C_c G_{mL} r_{01} r_{02}) + s^2(C_{01} C_1 r_{01} r_{02} + C_{01} C_{02} r_{01} r_{02})}$$

$\therefore$ we get $p_1 \approx -\dfrac{1}{G_{mL} r_{01} r_{02} C_c}$

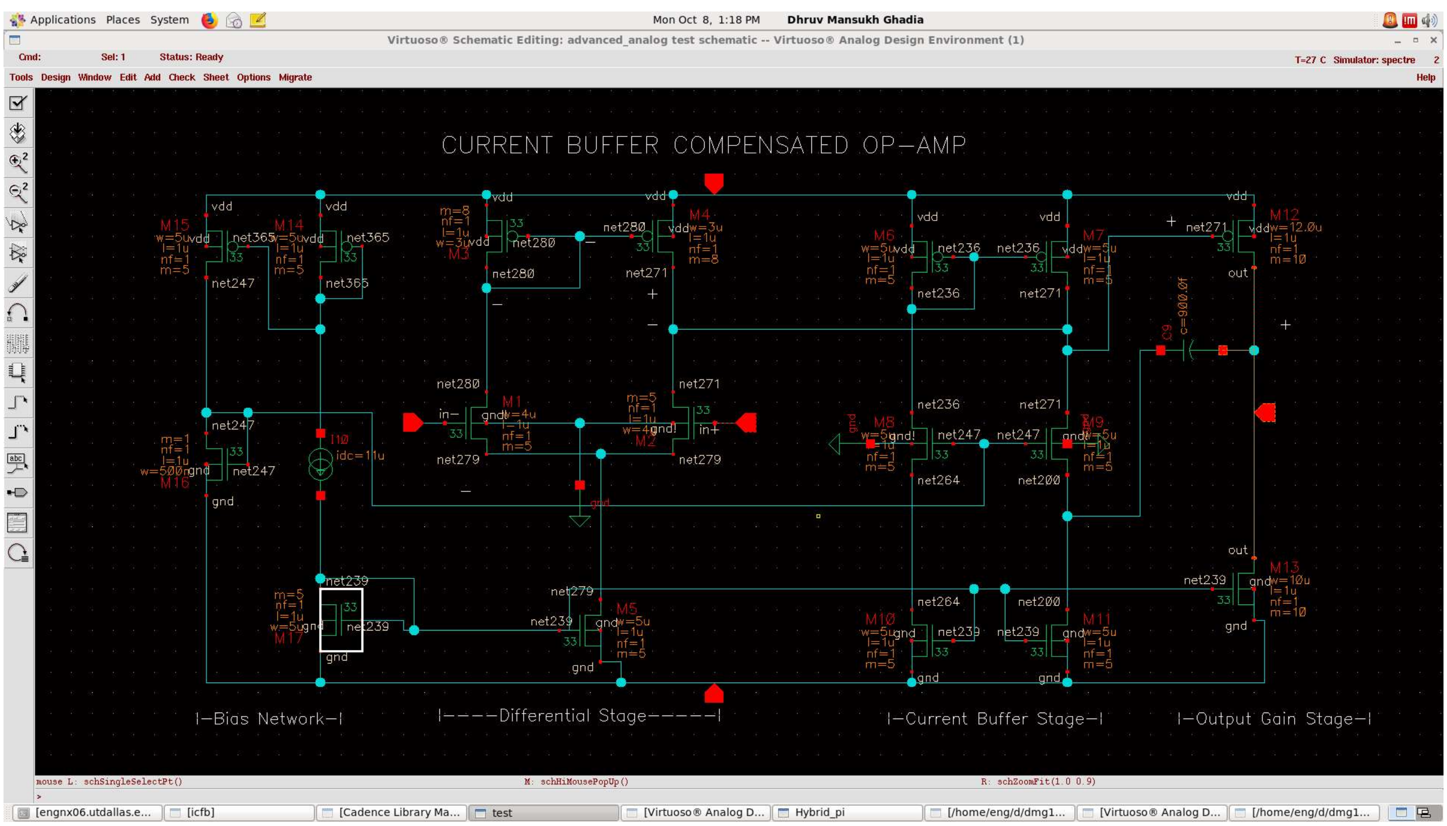
$$Z_1 \approx -\frac{G_{ma}}{C_c}$$

## Q1-b] Current Buffer Compensated Op-amp Design and Simulation

### Circuit Schematic with DC Operating point:




### Circuit Schematic with Transistor Sizes:



## TRANSISTOR SIZE SUMMARY:

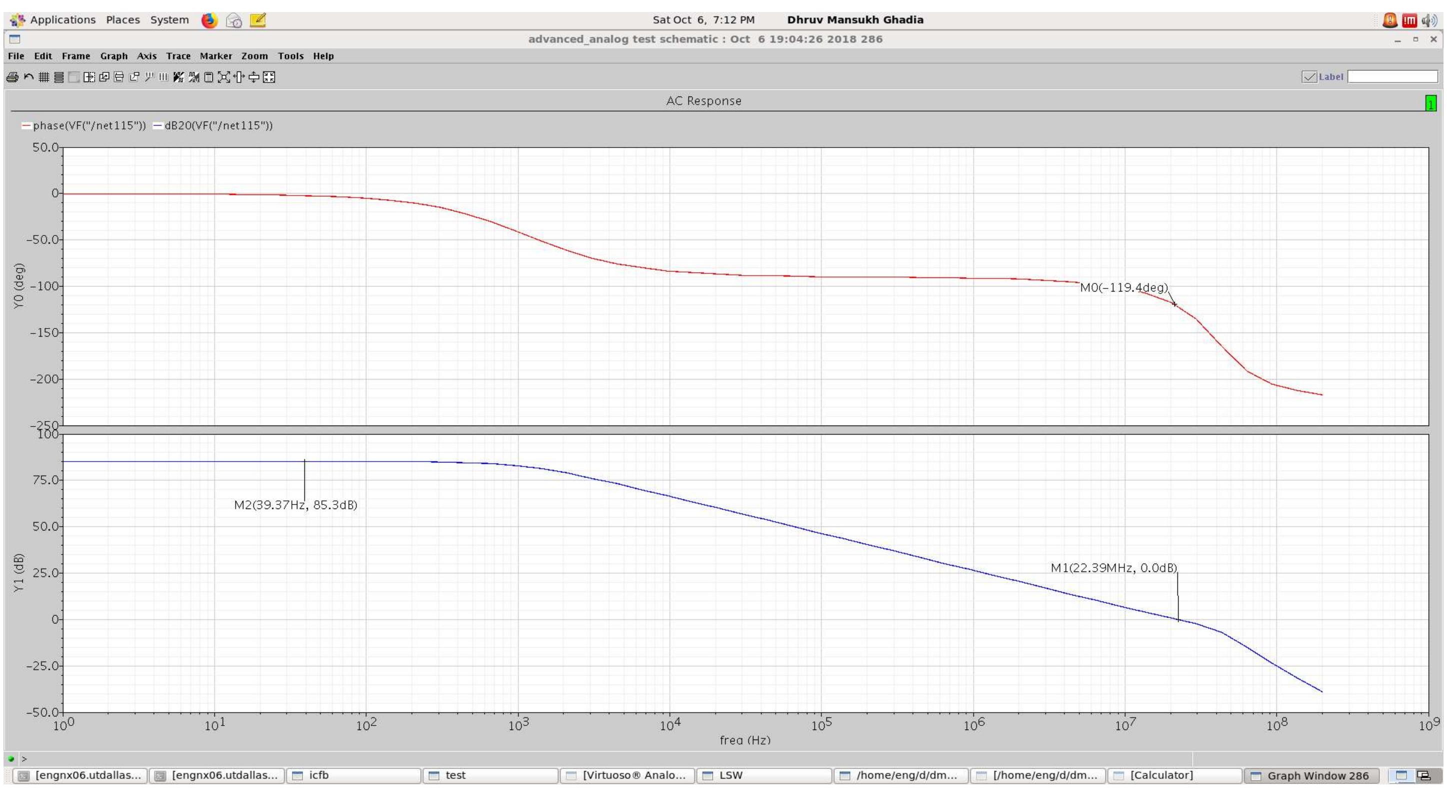
| Transistor | Width/Length | Multiplicity | Network |
|---|---|---|---|
| M1 | 4u/1u | 5 | Differential Input Stage |
| M2 | 4u/1u | 5 | |
| M3 | 3u/1u | 8 | |
| M4 | 3u/1u | 8 | |
| M5 | 5u/1u | 5 | |
| M6 | 5u/1u | 5 | Current Buffer Stage |
| M7 | 5u/1u | 5 | |
| M8 | 5u/1u | 5 | |
| M9 | 5u/1u | 5 | |
| M10 | 5u/1u | 5 | |
| M11 | 5u/1u | 5 | |
| M12 | 12u/1u | 10 | Output Stage |
| M13 | 10u/1u | 10 | |
| M14 | 5u/1u | 5 | Bias Network |
| M15 | 5u/1u | 5 | |
| M16 | 0.5u/1u | 1 | |
| M17 | 5u/1u | 5 | |

## GAIN AND PHASE:

**Unity Gain Frequency Achieved = 22.33MHz**

**Phase Margin Achieved = 60.6°**

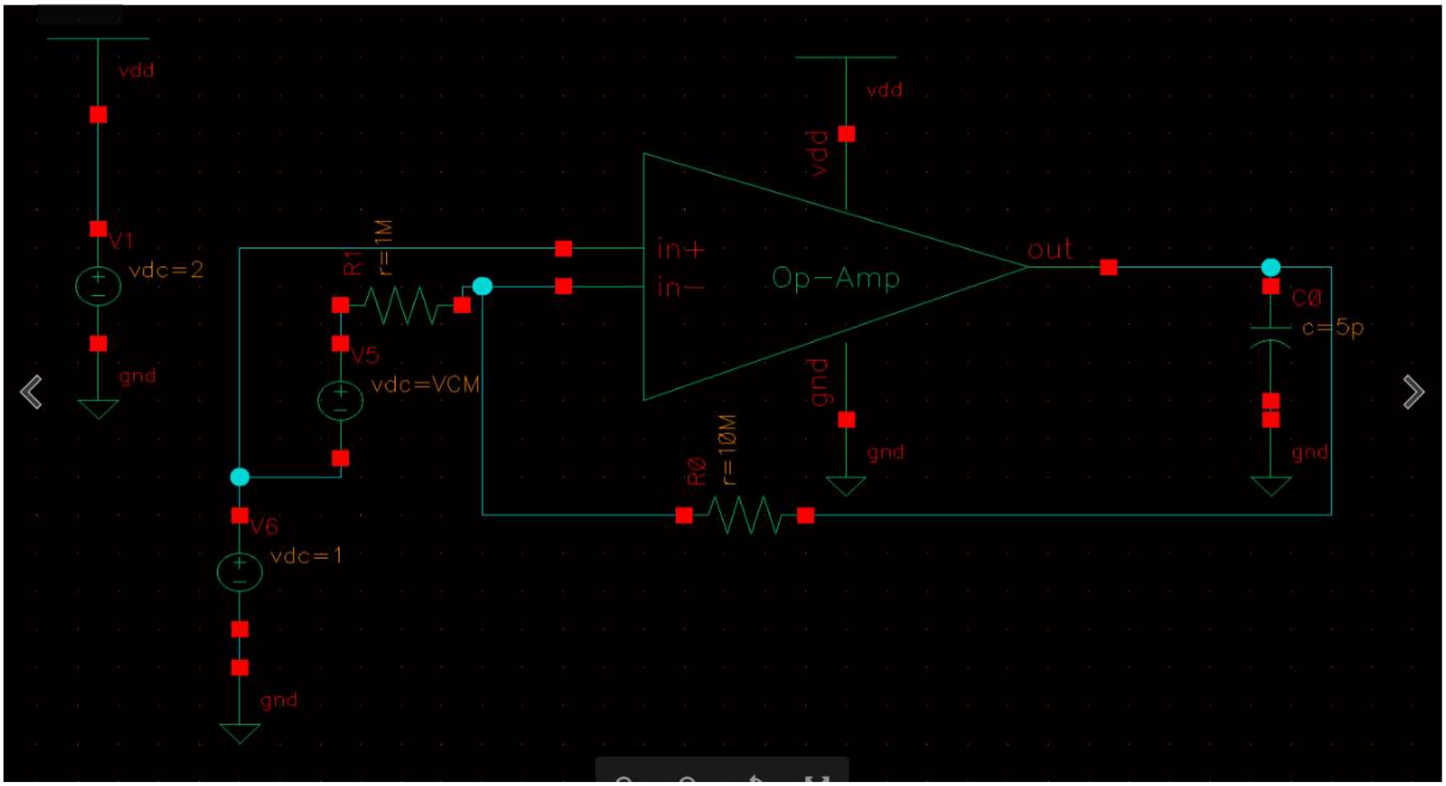
**DC Gain = 85.3 dB**

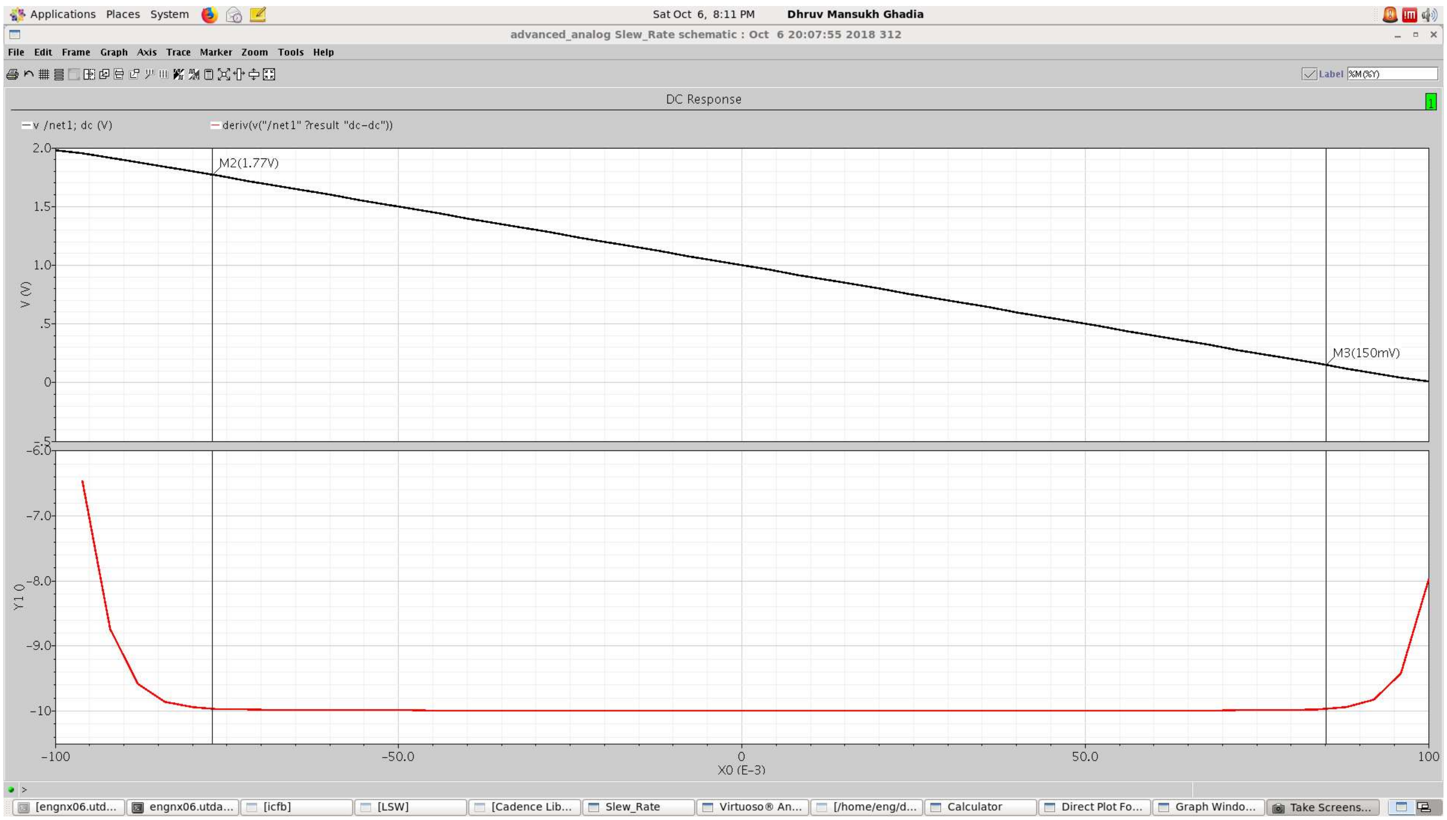


**OUTPUT VOLTAGE SWING RANGE:**

**Vo(min) = 0.146V Vo(max)=1.8V**

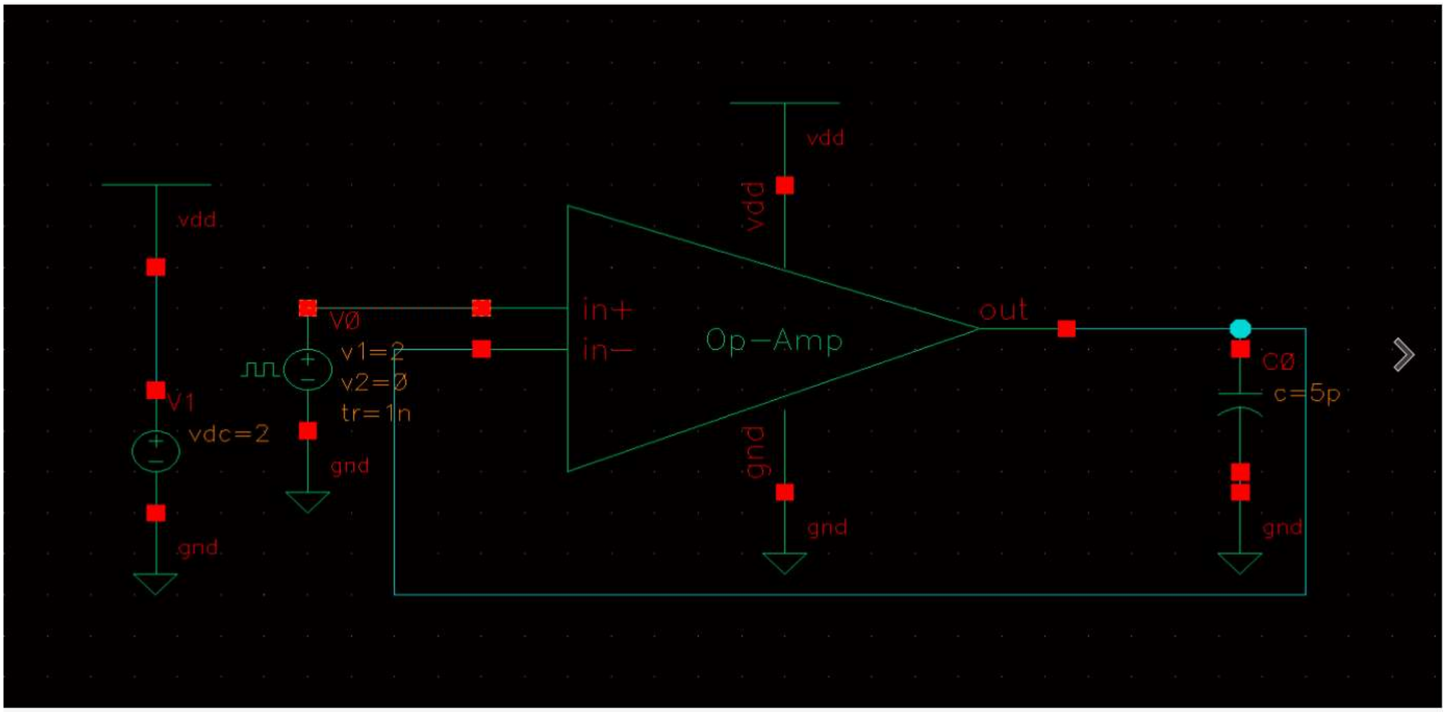
**Test Bench:**



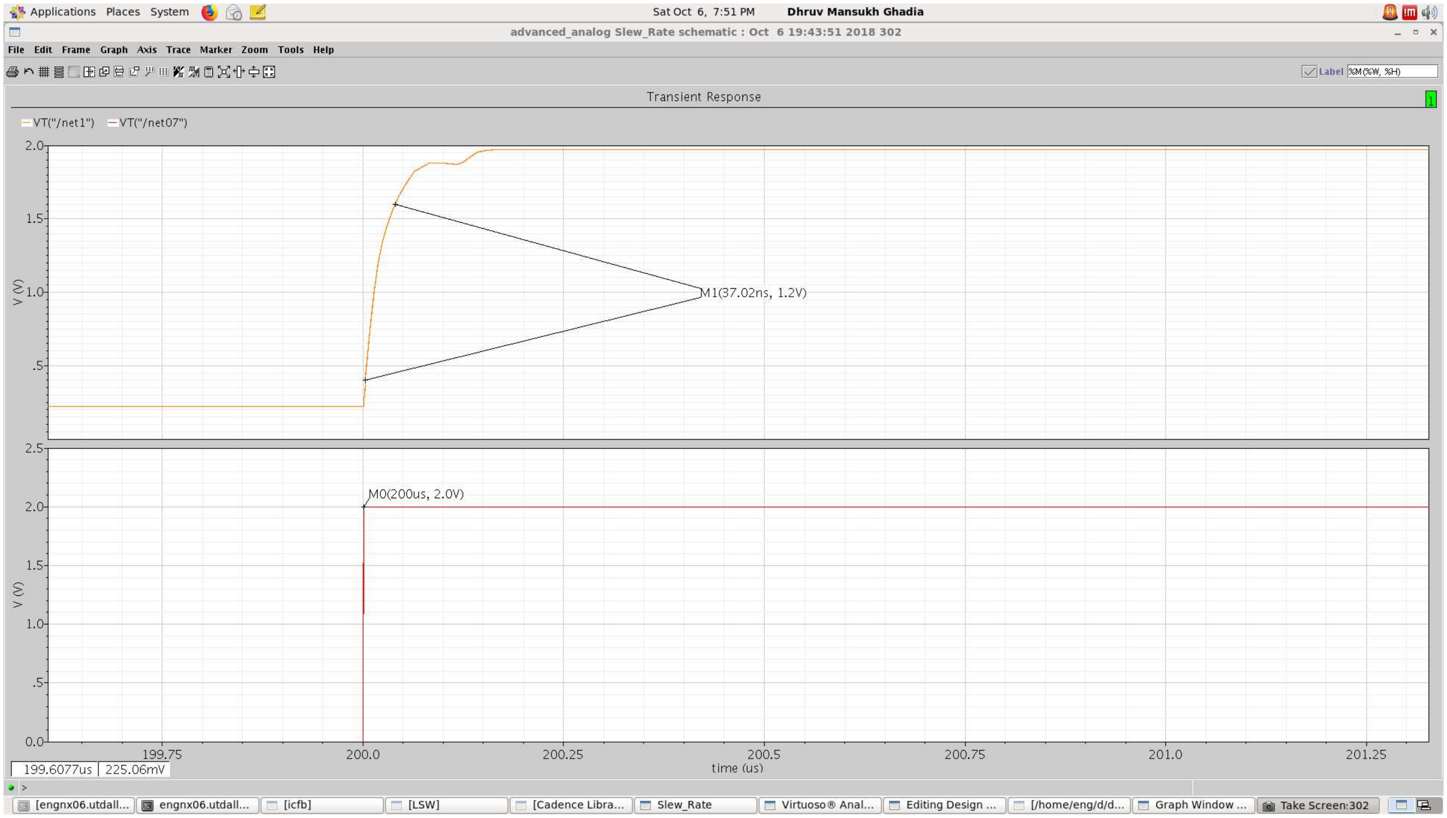



**SLEW RATE:**

**Test Bench:**

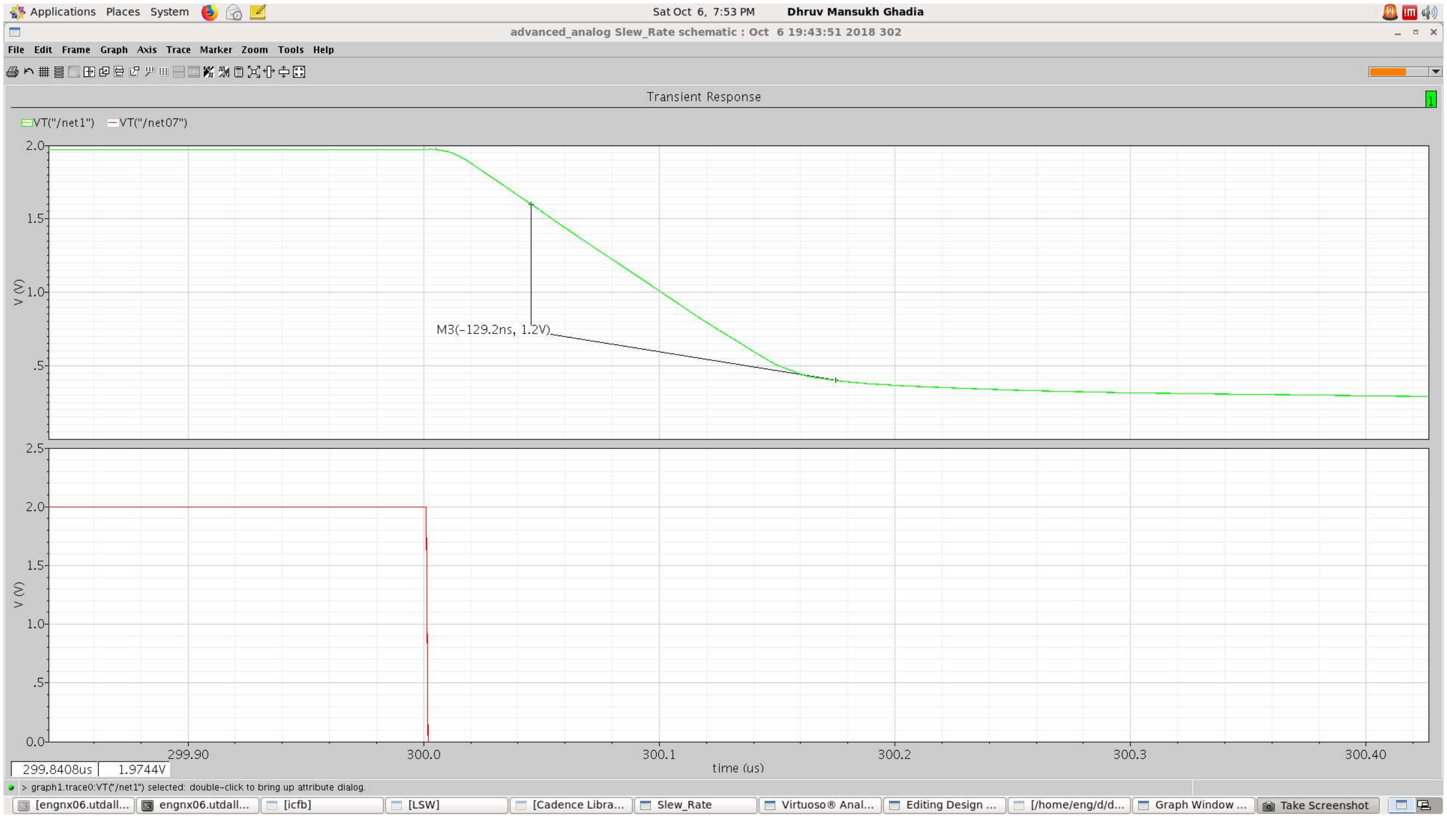



**Positive Slew Rate = 32.4V/us**

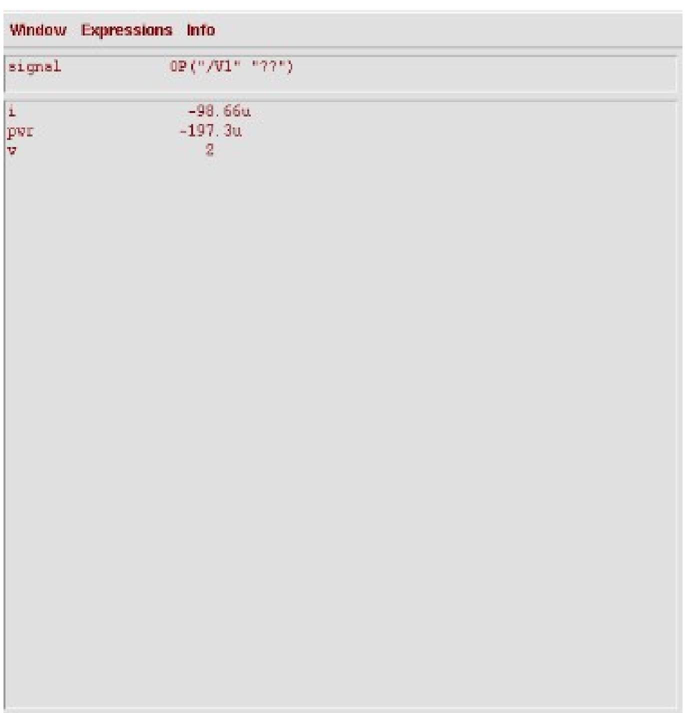


**Negative Slew Rate = 9.28V/us**

**Total Slew rate= (9.28+32.4)/2= 20.84 V/us**




## TOTAL POWER CONSUMPTION (Including Bias network):




**Total Current without including Bias Network = 11uA +11uA +11uA +42uA = 75uA**

**Power Consumption = 2V x 75uA=150uW**

**HYBRID-PI MODEL SIMULATION:**

For Hybrid - pi

For 60° PM $\quad C_c = 0.22\, C_L$

$C_L = 5pF$

$\therefore C_c = 0.22 \times 5pF$

$C_c = 1.1\, pF$

Now $Gm_1 = UGB \times C_c$

$= 2\pi \times 20 \times 10^6 \times 1.1p$

$Gm_1 = 138.23\, \mu$

$Gm_L \approx 10\, Gm_1$

$\approx 10 \times 138.23\, \mu$

$Gm_L \approx 1.38\, m$

Assume $\lambda = 0.25$

Slew Rate $= \dfrac{I_5}{C_c} \Rightarrow I_5 = 2.2\, \mu A$

$r_{ds} = \dfrac{1}{\lambda I_d} = \dfrac{1}{2 \times 0.25 \times 2.2} = 1.6\, M\Omega$

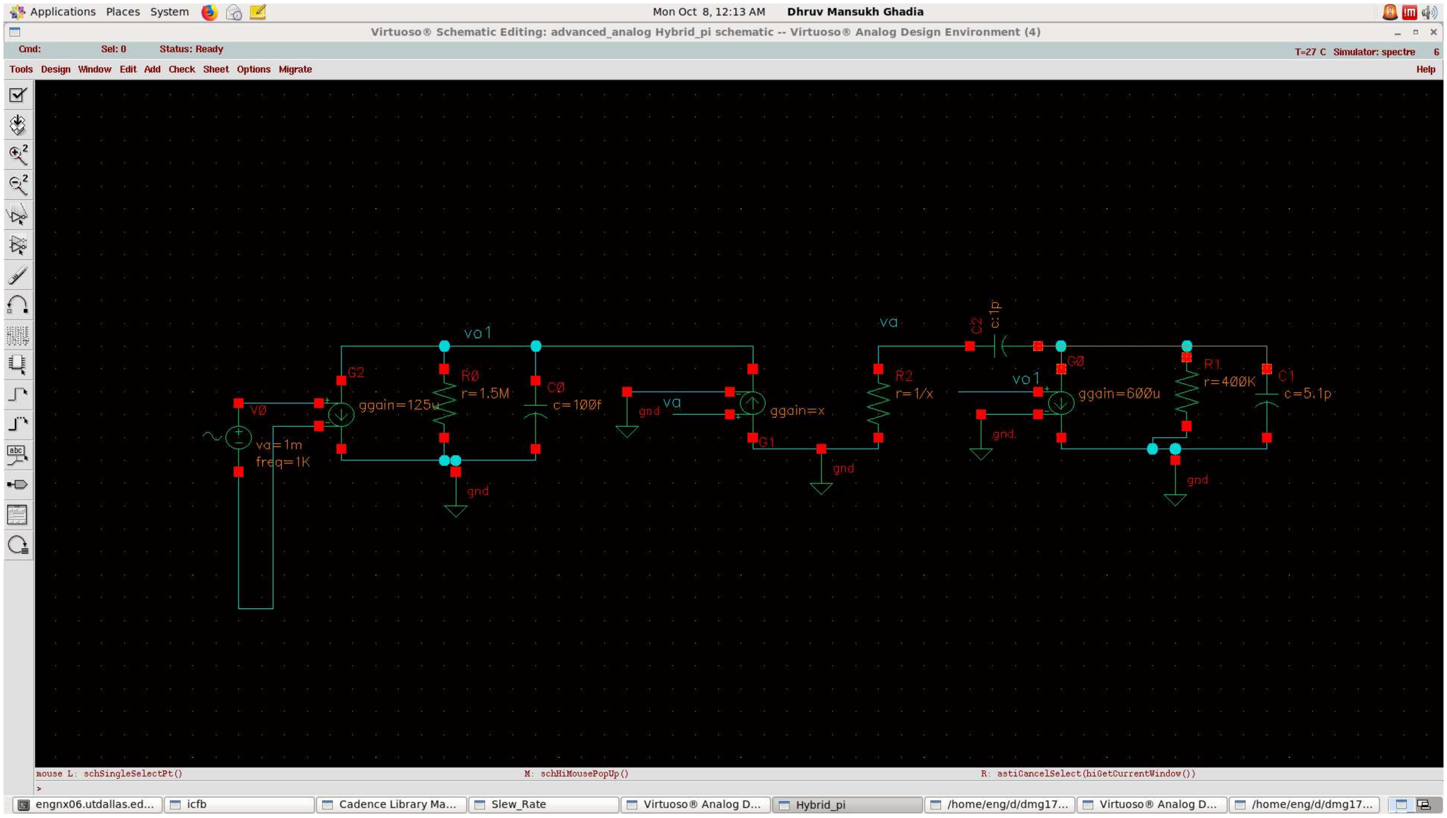
$C_2 \approx C_L = 5pF$

Taking $C_1 = 100\, f$

For $Gm_a << \dfrac{Gm_2\, C_c^2}{C_{o1}(C_{o2}+C_c)} = \dfrac{1.38m \times 1.1}{(0.1)(1.1+5)} << 2.3m$

$\therefore$ Taking $Gm_a = 200\, \mu$

$r_{oA} = \dfrac{1}{Gm_a} = 5K\Omega$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Mon Oct 8, 12:13 AM Dhruv Mansukh Ghadia
Virtuoso® Schematic Editing: advanced_analog Hybrid_pi schematic -- Virtuoso® Analog Design Environment (4)
Cmd: Sel: 0 Status: Ready
T=27 C Simulator: spectre
Tools Design Window Edit Add Check Sheet Options Migrate
Help
vo1
va
V0
va=1m
freq=1K
G2
ggain=125u
R0
r=1.5M
C0
c=100f
gnd
va
ggain=x
G1
R2
r=1/x
C2
c:1p
vo1
G0
ggain=600u
R1
r=400K
C1
c=5.1p
mouse L: schSingleSelectPt()
M: schHiMousePopUp()
R: astiCancelSelect(hiGetCurrentWindow())
engnx06.utdallas.ed...
icfb
Cadence Library Ma...
Slew_Rate
Virtuoso® Analog D...
Hybrid_pi
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Virtuoso® Analog D...
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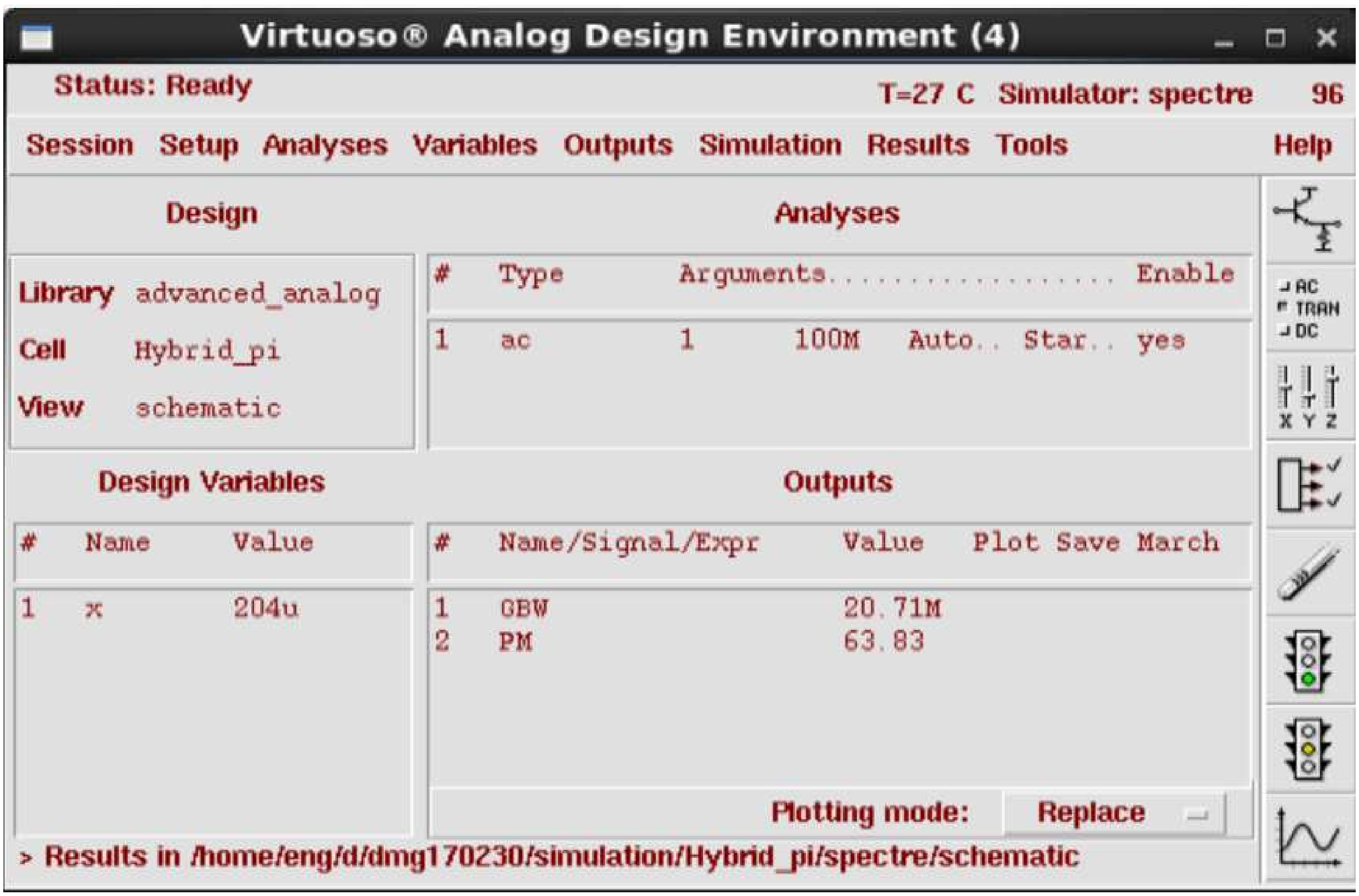
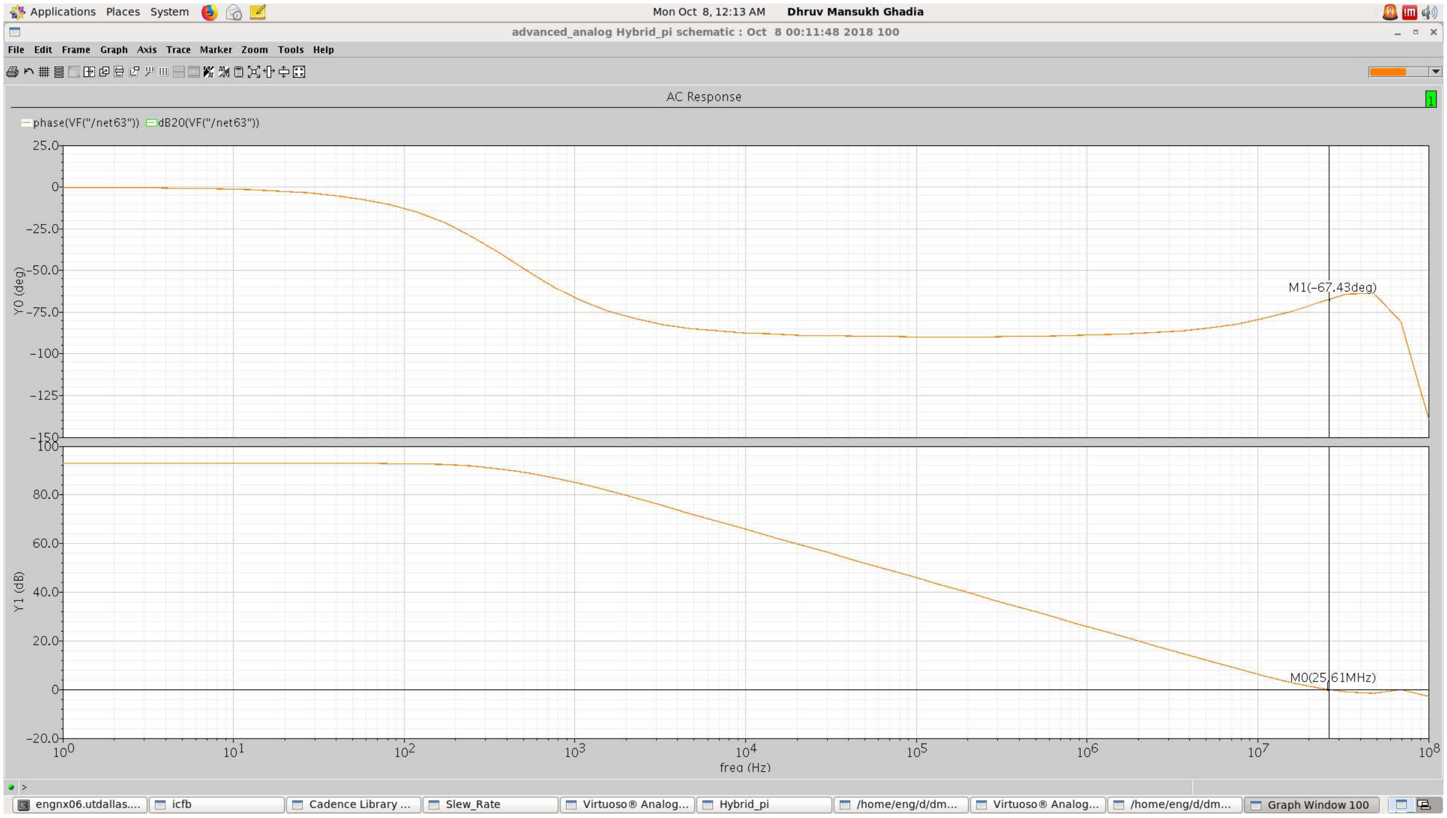

Virtuoso® Analog Design Environment (4)
Status: Ready
T=27 C Simulator: spectre 96
Session Setup Analyses Variables Outputs Simulation Results Tools Help
Design
Analyses
Library advanced_analog
Cell Hybrid_pi
View schematic
# Type Arguments................. Enable
1 ac 1 100M Auto.. Star.. yes
AC
TRAN
DC
X Y Z
Design Variables
Outputs
# Name Value
1 x 204u
# Name/Signal/Expr Value Plot Save March
1 GBW 20.71M
2 PM 63.83
Plotting mode: Replace
> Results in /home/eng/d/dmg170230/simulation/Hybrid_pi/spectre/schematic

**Gain and Phase Margin(from Hybrid Pi):**

**GBW = 25.61MHz**

**PM = 63.83**




**DESIGN SPECIFICATIONS SUMMARY:**

| **Parameter** | **Target Specifications** | **Achieved Specifications** |
|---|---|---|
| Differential voltage gain | > 80dB | 85.3 dB |
| Output voltage swing range | Vomin: 0.15V<br>Vomax: 0.85V | Vomin: 0.15 V<br>Vomax: 1.7 V |
| Phase Margin: f(GB) | >55° | 60.6° |
| Unity Gain-bandwidth: GB | > 20MHz | 22.3 MHz |
| Slew rate: | >2 V/us | 20.84 V/us |
| Power dissipation | <200 uW | 190 uW |

**Q2-a,b]**

Q2] a) $C_1 = 8$

$C_2 = 3.75$

$C_u =$ unit cap of size $4um \times 4um$

ie $x_u = 4\,\mu m$

Now Let $C_1 = 8C_u$

and $C_2 = 2\,C_u + 1.75\,C_{nu}$

$1+f = 1.75$ $\quad\because\; C_2 = I_2 C_u + (1+f)C_{nu}$

Size of non-unit Capacitance

$C_{nu} = (1+f)\,C_u$

$C_{nu} = 1.75\,C_u$

$N = 1+f = 1.75$

$\therefore\; y_{nu} = x_u\left(N - \sqrt{N^2 - N}\right)$

$= 4\mu\left(1.75 - \sqrt{1.75^2 - 1.75}\right)$

$y_{nu} = 2.417\,um$

$\therefore\; x_{nu} = \dfrac{N x_u^2}{y_{nu}} = \dfrac{1.75 \times 16}{2.417} = 11.58\,um$

we want $\dfrac{P_{nu}}{A_{nu}} = \dfrac{P_u}{A_u}$

$\therefore\; P_{nu} = (2.417 + 11.58) \times 2 = 27.994\,um$

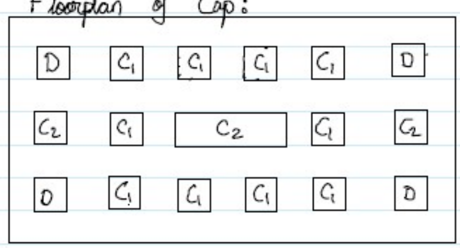
$A_{nu} = 2.417 \times 11.58 = 27.9886\,um^2$

$P_u = 16\,um$

$A_u = 16\,um^2$

$\therefore\; \dfrac{P_{nu}}{A_{nu}} \approx \dfrac{P_u}{A_u} \approx 1$

Floorplan of Cap:




where :

$\square = C_u$

$\boxed{\quad\quad} = C_{nu}$

$\boxed{D}$ = Dummy Caps of unit size

Ideally $\dfrac{P_{nu}}{A_{nu}} = \dfrac{P_{nu}}{A_{nu}} = 1$

Rounding off to nearest $0.1\,um$

$x_{nu} = 11.5\mu$ & $y_{nu} = 2.4\mu$

$P'_{nu} = 2 \times (11.5 + 2.4) = 27.8$ $\quad A'_{nu} = 11.5 \times 2.4 = 27.6$

Actual Ratio : $\dfrac{P'_{nu}}{A'_{nu}} = \dfrac{27.8}{27.6} = 1.00724$

$\%\ error = \dfrac{1.00724 - 1}{1} \times 100$

$\boxed{\%\ error = 0.72\ \%}$

[redacted]