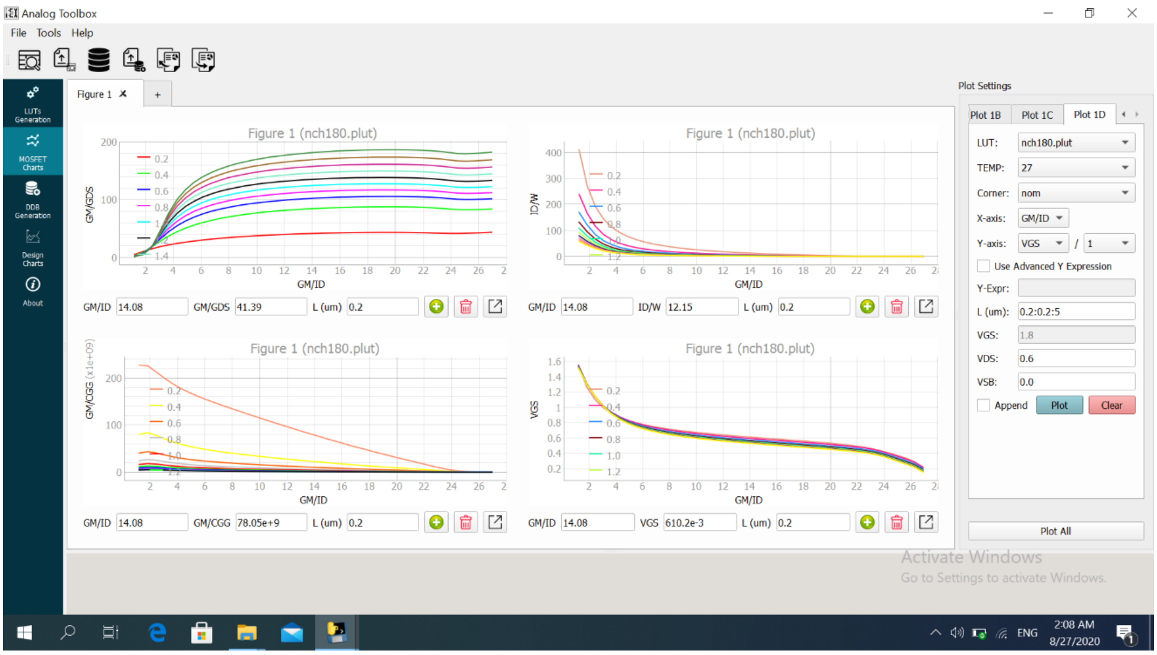
Mini Project: Two-Stage Miller OTA

- ## Part 1: gm/ID design charts

Using $L = 0.2\mu m{:}\,0.2\mu m{:}\,2\mu m$ & $VDS = \frac{VDD}{3} = 0.6$

- $g_m r_o \left(\frac{g_m}{g_{ds}}\right)$ & $\frac{I_D}{W}$ & $\frac{g_m}{C_{gg}}$ & V_{GS} for PMOS



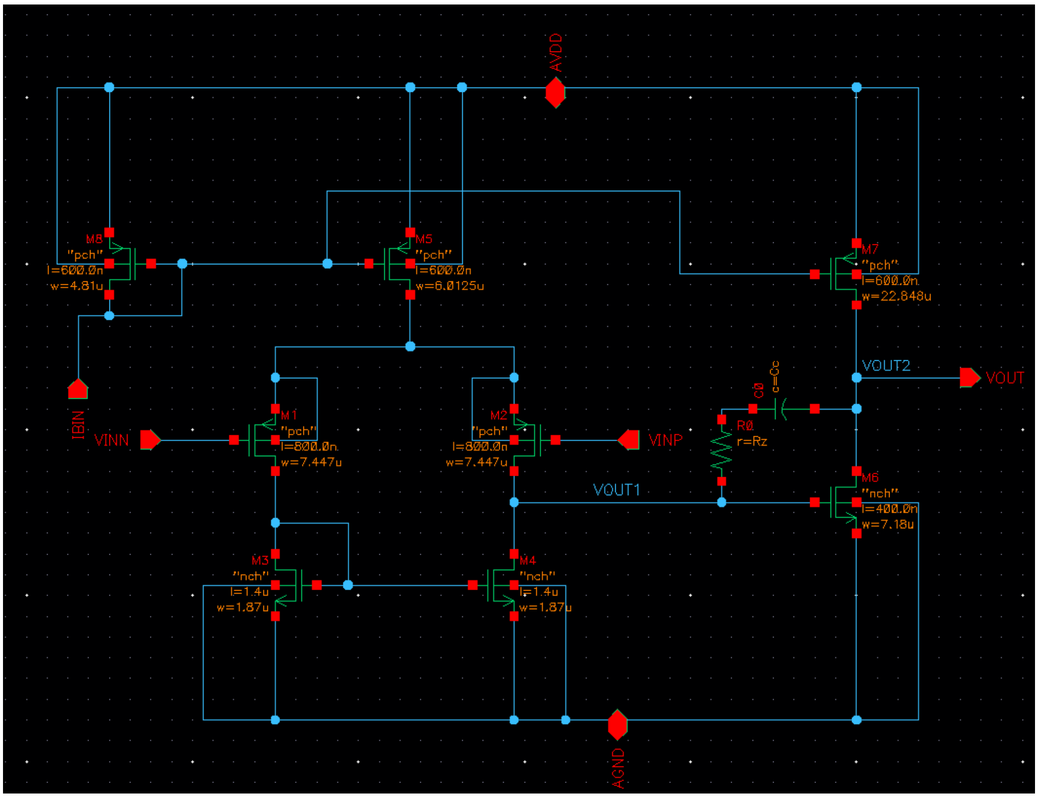
- $g_m r_o \left(\frac{g_m}{g_{ds}}\right)$ & $\frac{I_D}{W}$ & $\frac{g_m}{C_{gg}}$ & V_{GS} for NMOS

- **<u>Part 2: OTA design</u>**

Parameter	Spec
Supply voltage	$1.8\ v$
Static gain error	$\leq\ 0.05\%$
CMRR @ DC	$\geq 74\ db$
Phase margin	$\geq 70°$
OTA current consumption	$\leq 60\ \mu A$
CMIR-high	$\geq 1v$
CMIR-low	$\leq 0.2\ v$
Output swing	$0.2 - 1.6\ v$
Load	$5\ pF$
Buffer closed loop rise time	$\leq 70\ ns$
Slew rate	$5\ V/\mu S$

∵ CMIR limits are close to ground (0.2-1)

∴ the desired OTA is OTA with PMOS input pair



- <u>Design procedures</u>

2) let $C_c = \frac{1}{2} C_l = 2.5\ pF$

3) $\because\ t_{rise} = 2.2\ RC \ \ \rightarrow \therefore RC = \frac{t_{rise}}{2.2} \leq 31.818\ ns$

$\because\ W_u = \dfrac{1}{2\pi\ RC} \geq 5.002MHZ\ , \qquad W_u = \dfrac{g_{m1,2}}{2\pi C_c} \rightarrow\ g_{m1,2} = 2\pi C_c W_u$

$$\therefore\ g_{m1,2} \geq 78.571\ \mu S$$

4) $\because SR = \frac{I_{B1}}{C_c} = 5\ \ V/\mu S \ \ \rightarrow\ \ I_{B1} = SR *\ C_c = 12.5\ \mu A$

$\because$ total current budget $= 60\ \mu A \ \ \ \rightarrow\ \therefore\ I_{B2} = 60 - 12.5 = 47.5\mu A$

- $I_{D1,2,3,4} = \frac{1}{2} I_{B1} = 6.25\ \mu A\ \ \& I_{D5} = I_{B1} = 12.5\mu A\ \ \&\ \ I_{D6,7} = 47.5\ \mu A$

5) $\because g_{m1,2} \geq 78.571\ \mu\ \ \&\ \ I_{D1,2} = 6.25\ \mu \ \ \ \rightarrow\ \therefore \left(\frac{g_m}{I_D}\right)_{1,2} \geq 12.571$

$$\text{Let } \left(\frac{g_m}{I_D}\right)_{1,2} = 13$$

6) $\because A_{CL} = \frac{A_{OL}}{1+\beta A_{OL}}\ ,\ $ for a buffer $\beta = 1 \ \ \rightarrow\ A_{CL} = \frac{A_{OL}}{1+A_{OL}} = \frac{1}{1+\frac{1}{A_{OL}}} \approx 1 - \frac{1}{A_{OL}}$

Static gain error $\varepsilon = \frac{|A_{CL,actual} - A_{CL,ideal}|}{A_{CL,ideal}} * 100 = \frac{\left|1-\frac{1}{A_{OL}}-1\right|}{1} * 100 = \frac{1}{A_{OL}} * 100$

$$\therefore\ A_{OL} = \frac{1}{\varepsilon} * 100 \qquad \rightarrow\ \ A_{OL} \geq 2000(66.02db)$$

7) assume $A_{v1} = 2A_{v2}\ \ \&\ \ A_{OL} = A_{v1}A_{v2}$

$$\therefore\ \ A_{v1} \geq 63.246\ (36.02db)\ \ \ \&\ \ \ A_{v2} \geq 31.623\ (30db)$$

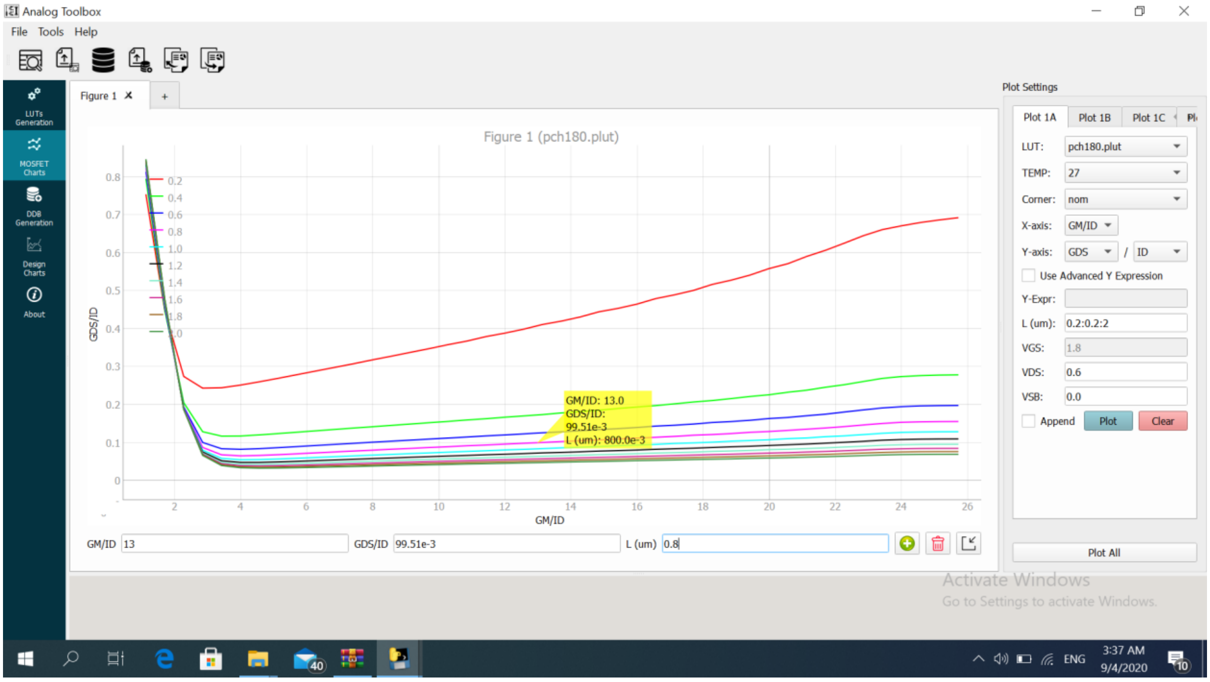
8) $\because A_{v1} = g_{m1,2}(r_{o1,2} \backslash\backslash r_{o3,4}) = g_{m1,2}\left(\frac{1}{g_{ds1,2}} \backslash\backslash \frac{1}{g_{ds3.4}}\right)$

Assume $r_{o1,2} = r_{o3,4} \ \ \ \rightarrow\ \frac{1}{g_{ds1,2}} = \frac{1}{g_{ds3,4}} \ \ \ \rightarrow\ \therefore\ \ A_{v1} = \frac{g_{m1,2}}{2g_{ds1,2,3,4}}$

$$\therefore\ g_{ds1,2,3,4} \leq 642.333\ nS$$

➢ $\left(\frac{g_{ds}}{I_D}\right)_{1,2} \leq 102.773\, m \;\&\; \left(\frac{g_m}{I_D}\right)_{1,2} = 13$

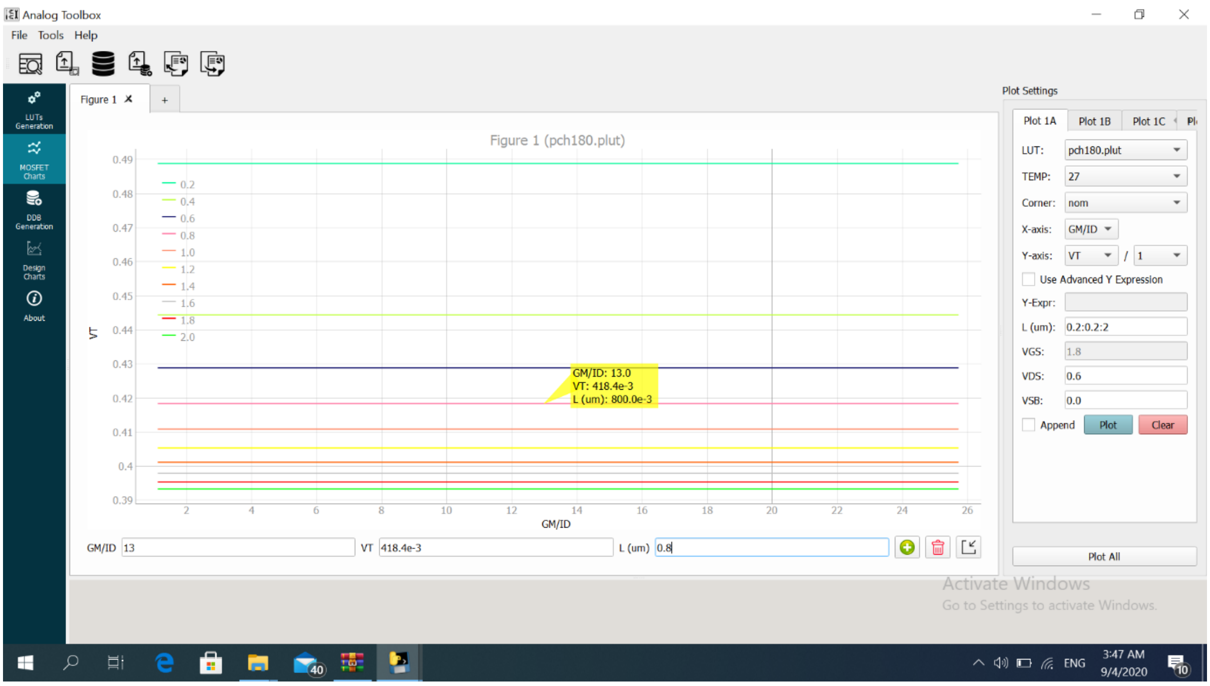
$\therefore$ from design charts:



➢ $L_{1,2} = 0.8\ \mu m$

➢ $\left(\frac{I_D}{W}\right)_{1,2} = 839.3m \quad \therefore \quad W_{1,2} = 7.447\mu m$

➢ $V_{GS1,2} = 564.4\ mv$



➢ $V_{th1,2} = 418.4\ mv$

9) $\because \left(\frac{g_{ds}}{I_D}\right)_{3,4} \leq 102.773\, m\ \&\ assuming \left(\frac{g_m}{I_D}\right)_{3,4} = 15$

$\therefore$ from design chart:

- $L_{3,4} = 1.4\ \mu m$

10) $\because PM \geq 70° \quad \rightarrow \therefore\ let\ PM \approx 76\ \ \&\ W_{p2} = 4W_u = 20.008\ MHZ$

$\because W_{p2} = \frac{g_{m6}}{2\pi\, C_l} \ \rightarrow \therefore\ g_{m6} = 2\pi C_l * W_{p2} = 628.57\ \mu S\ \ \&\ I_{D6} = 47.5\ \mu A$

$$\therefore \left(\frac{g_m}{I_D}\right)_6 = 13.233$$

11) $\because CMIR_{high} = V_{DD} - V_{GS1,2} - V_5^* \geq 1$

$$\therefore\ V_5^* \leq V_{DD} - V_{GS1,2} - 1 \quad \rightarrow \quad V_5^* \leq 235.6m \ \rightarrow \therefore \left(\frac{g_m}{I_D}\right)_5 \geq 8.489$$

$\because swing_{high} = V_{DD} - V_7^* \geq 1.6 \quad \rightarrow \quad V_7^* \leq 0.2 \quad \rightarrow \therefore \left(\frac{g_m}{I_D}\right)_7 \geq 10$

$\because M_{5,7,8}$ are identical (have the same $\frac{g_m}{I_D}$ $\&\ L$)

$$\therefore \text{let} \left(\frac{g_m}{I_D}\right)_{5,7,8} = 10$$

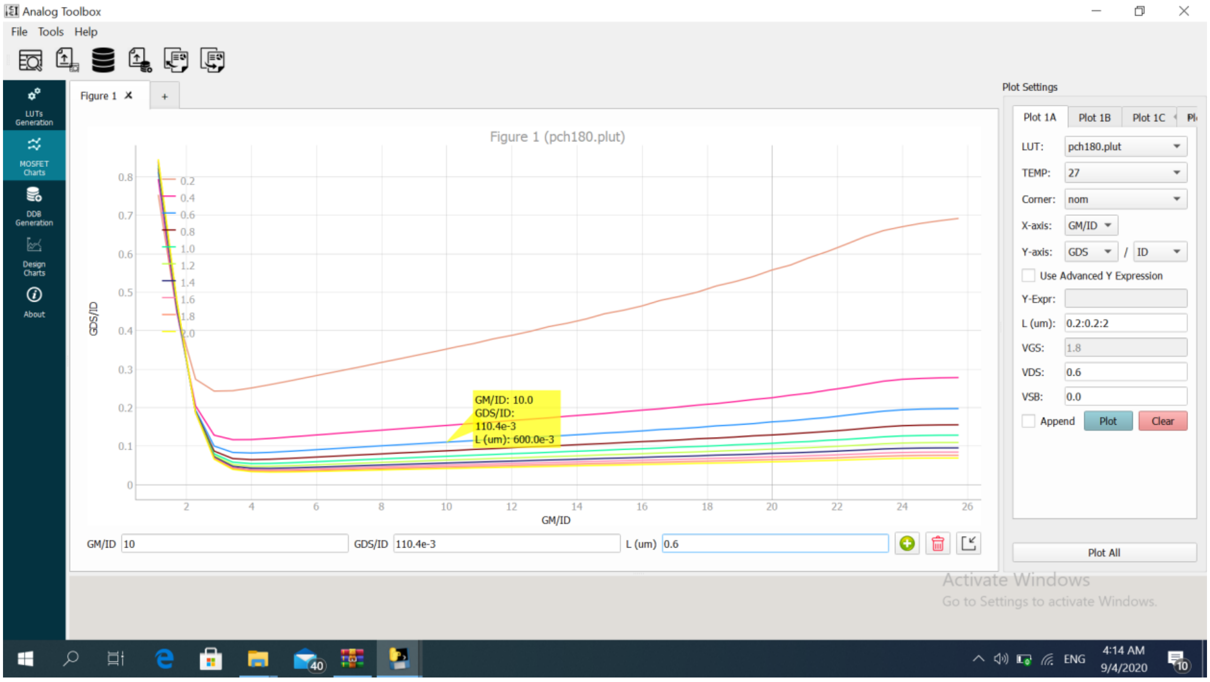
12) $\because CMRR = \frac{A_{v1}}{A_{vCM}} \ \rightarrow \therefore\ A_{vCM} = \frac{A_{v1}}{CMRR} \ \rightarrow\ A_{vCM} \leq 0.0126(-38db)$

$$\because A_{vCM} = \frac{1}{2g_{m3,4}R_{ss}} = \frac{1}{2g_{m3,4}r_{o5}} = \frac{g_{ds5}}{2g_{m3,4}} \rightarrow g_{ds5} = 2g_{m3,4} * A_{vCM}$$

Assume $\left(\frac{g_m}{I_D}\right)_{3,4} = 10$ & $I_{D3,4} = 6.25\mu \rightarrow \therefore g_{m3,4} = 62.5\ \mu S$

$$\therefore g_{ds5} \leq 1.574\ \mu S \quad \& \quad \left(\frac{g_{ds}}{I_D}\right)_5 \leq 125.893\ m$$

From design chart:



- $L_{5,7,8} = 0.6\ \mu m$

13) $\because \left(\frac{g_{ds}}{I_D}\right)_7 = 110.4\ m$ & $I_{D7} = 47.5\ \mu$ $\quad \therefore \ g_{ds7} = 5.244\ \mu S$

14) $\because \ A_{v2} = g_{m6}(r_{o6} \backslash\backslash r_{o7}) = g_{m6}\left(\frac{1}{g_{ds6}} \backslash\backslash \frac{1}{g_{ds7}}\right)$

$\because A_{v2} \geq 31.623\ (30db)$ & $g_{m6} = 628.57\ \mu S \quad \rightarrow \therefore \ g_{ds6} \leq 14.633\ \mu S$

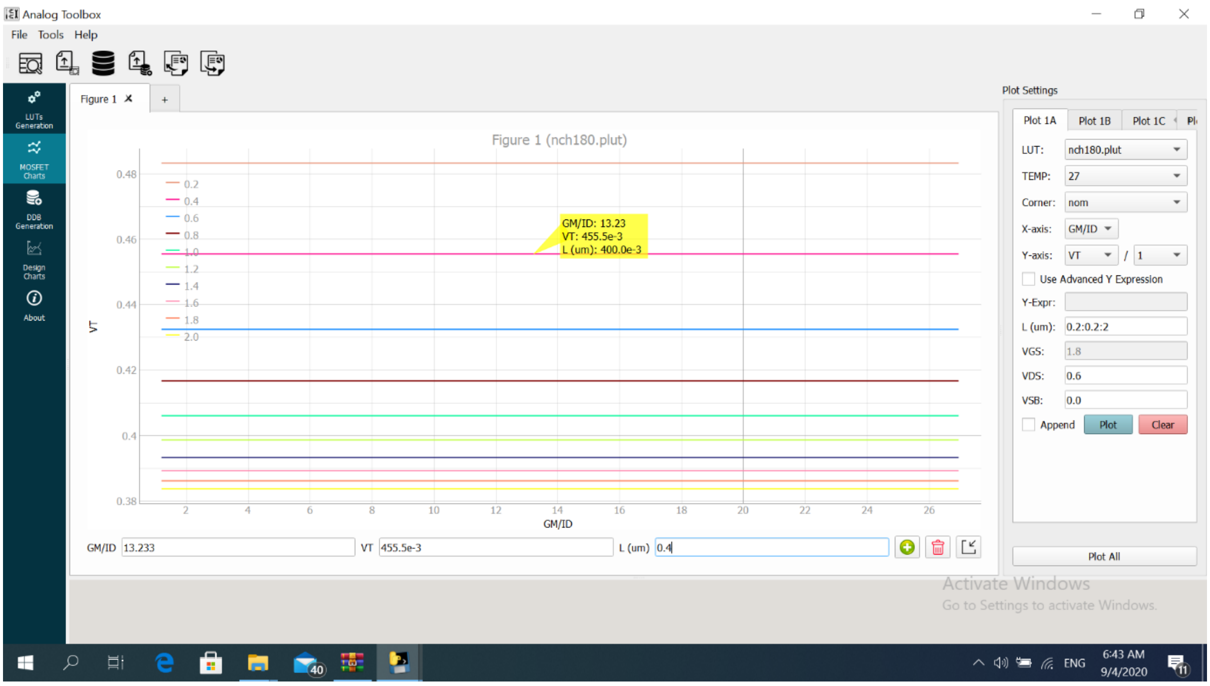
$$\therefore \left(\frac{g_{ds}}{I_D}\right)_6 \leq 308.063\ m \quad \& \quad \left(\frac{g_m}{I_D}\right)_6 = 13.233$$

$\therefore$ from design charts:

➢ $L_6 = 0.4\ \mu m$

➢ $\left(\frac{I_D}{W}\right)_6 = 6.615\ \ \&\ I_{D6} = 47.5\ \mu \quad \rightarrow \therefore\ W_6 = 7.18\ \mu m$

➢ $V_{GS6} = 604.1\ mv$



➢ $V_{th7} = 455.5\ mv$

15) $\because V_{GS3,4} = V_{GS6} = 604.1\ mv \quad \& \ L_{3,4} = 1.4\ \mu m$

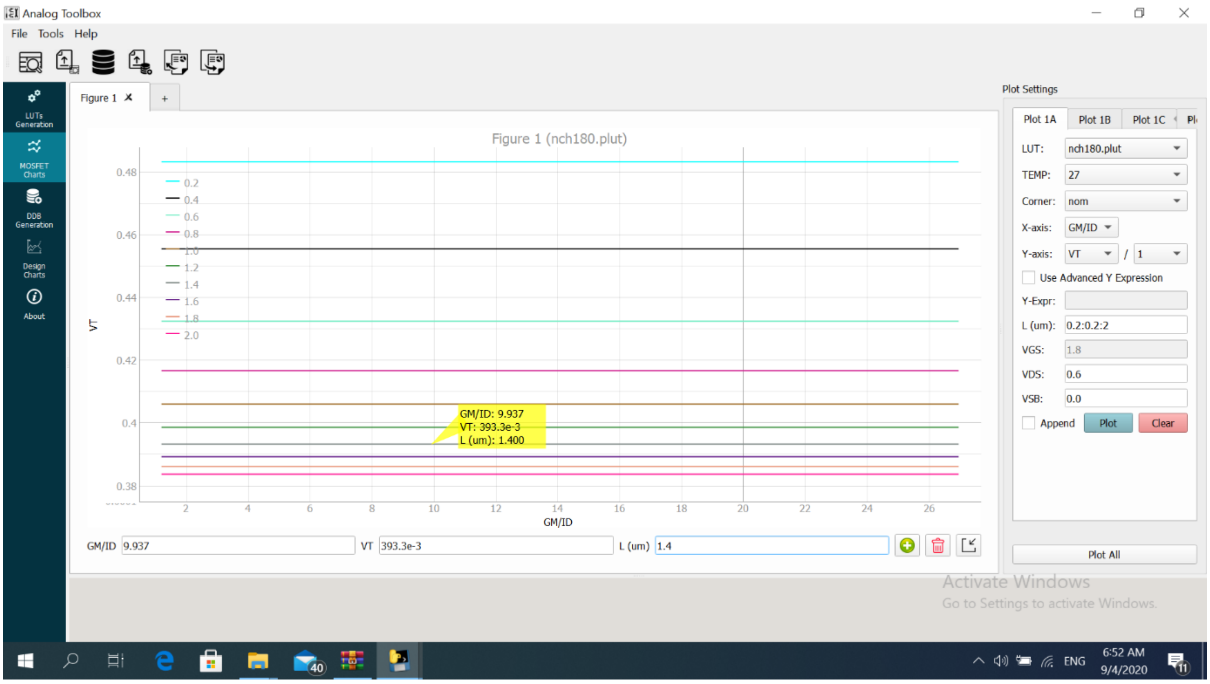
$\therefore$ from design chart:

- $\left(\frac{g_m}{I_D}\right)_{3,4} = 9.937$

$\because \left(\frac{g_m}{I_D}\right)_{3,4} = 9.937 \approx 10 (\left(\frac{g_m}{I_D}\right)_{3,4}$ assumed before) $\therefore$ no need for re iteration

➢ $\left(\frac{I_D}{W}\right)_{3,4} = 3.342 \quad \rightarrow \therefore \; W_{3,4} = 1.87\ \mu m$

➢ $V_{GS3,4} = 604.1\ mv$



➢ $V_{th3,4} = 393.3\ mv$

$\because \left(\frac{g_m}{I_D}\right)_{5,7,8} = 10 \;\; \& \;\; L_{5,7,8} = 0.6\ \mu m$

$\therefore$ from design charts:

- $\left(\frac{I_D}{W}\right)_{5,7,8} = 2.079$
  - ✓ $\because I_{D5} = 12.5\ \mu \;\; \rightarrow \; \therefore \;\; W_5 = 6.0125\ \mu m$
  - ✓ $\because I_{D7} = 47.5\ \mu \;\; \rightarrow \; \therefore \;\; W_7 = 22.848\ \mu m$
  - ✓ $\because I_{D8} = 10\ \mu \;\; \rightarrow \; \therefore \;\; W_8 = 4.81\ \mu m$

➢ $V_{GS5,7,8} = 625.2\ mv$

➢ $V_{th5,7,8} = 428.8\ mv$

16) $\because CMIR_{low} = -|V_{GS1,2}| + V^*_{1,2} + V_{GS3,4} \le 0.2 \quad \rightarrow \therefore\ V_{GS3,4} \le 633.754\ mv$

$\because swing_{low} = V^*_6 \le 0.2 \quad \rightarrow \quad \left(\frac{g_m}{I_D}\right)_6 \ge 10$

$\because V_{GS3,4} = 604.1\ mv < 633.754\ mv \quad \& \left(\frac{g_m}{I_D}\right)_6 = 13.233 > 10$

And $CMIR_{high}$ & $swing_{high}$ were obtained in the design

$\therefore \frac{g_m}{I_D}$ choices does not violate CMIR & swing specs

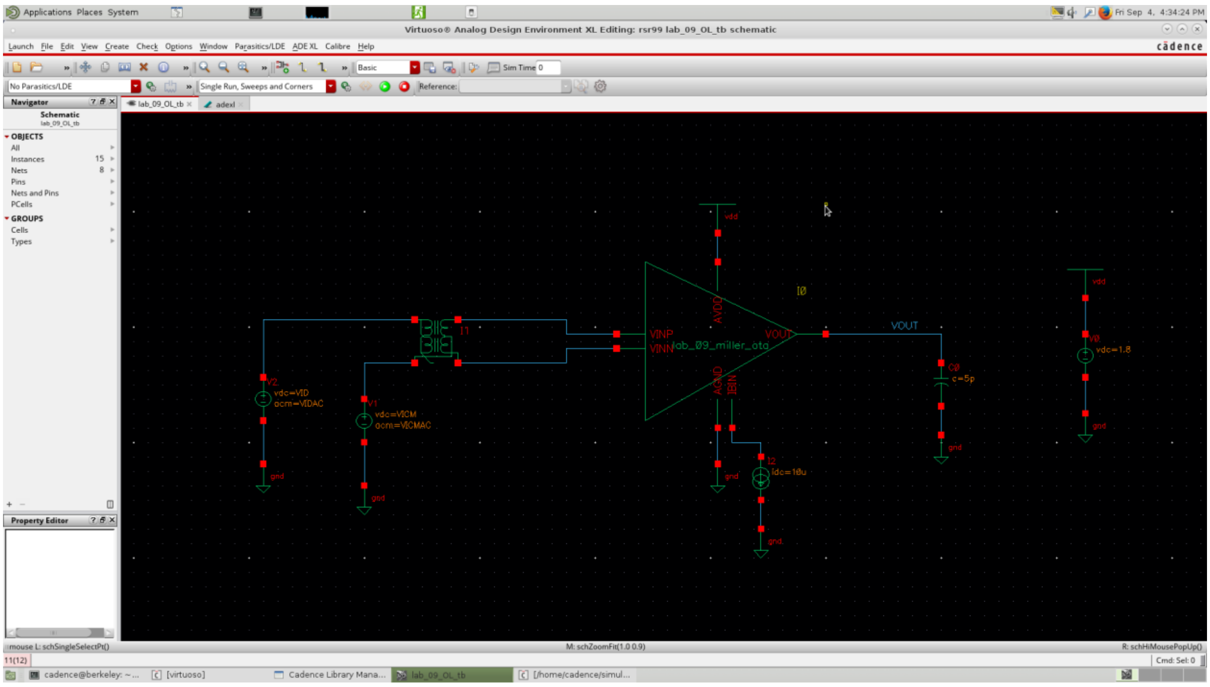
17) $\because W_z = \frac{1}{C_c\left(\frac{1}{g_{m6}} - R_z\right)} \quad \rightarrow \therefore$ to place the zero at infinity

$$\frac{1}{g_{m6}} - R_z = 0 \quad \rightarrow \quad R_z = \frac{1}{g_{m6}} = 1591\ \Omega = 1.591\ k\Omega$$

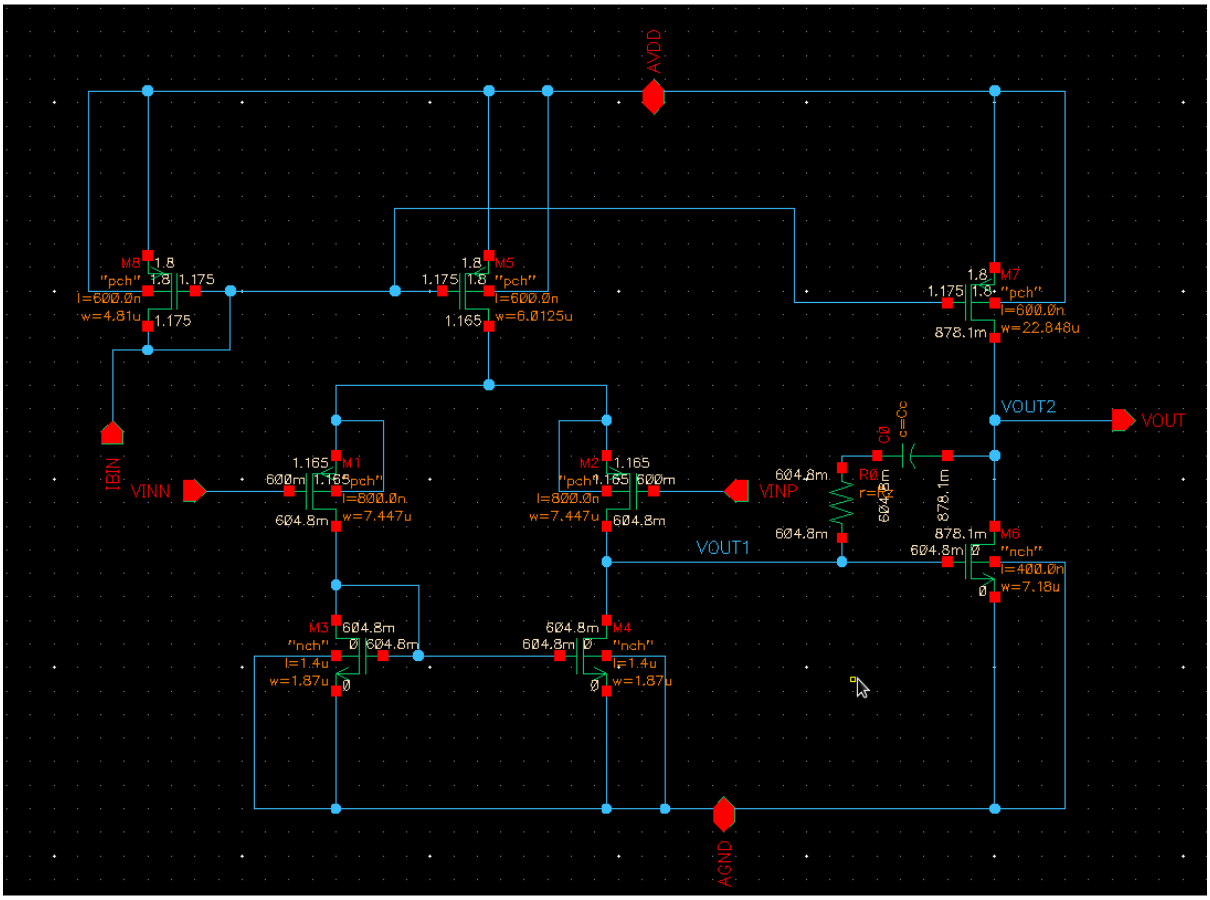
- A table showing design parameters as calculated from design charts

	$W(\mu)$	$L(\mu)$	$g_m(\mu)$	$I_D(\mu)$	$\frac{g_m}{I_D}$	$V^*(m)$	$V_{GS}(m)$	$V_{th}(m)$	$V_{ov}(m)$
$M_{1,2}$	7.447	0.8	81.25	6.25	13	153.846	564.4	418.4	146
M_6	7.18	0.4	628.57	47.5	13.233	151.137	604.1	455.5	148.6
$M_{3,4}$	1.87	1.4	62.106	6.25	9.937	201.268	604.1	393.3	210.8
M_5	6.0125	0.6	125	12.5	10	200	625.2	428.8	196.4
M_7	22.848	0.6	475	47.5	10	200	625.2	428.8	196.4
M_8	4.81	0.6	100	10	10	200	625.2	428.8	196.4

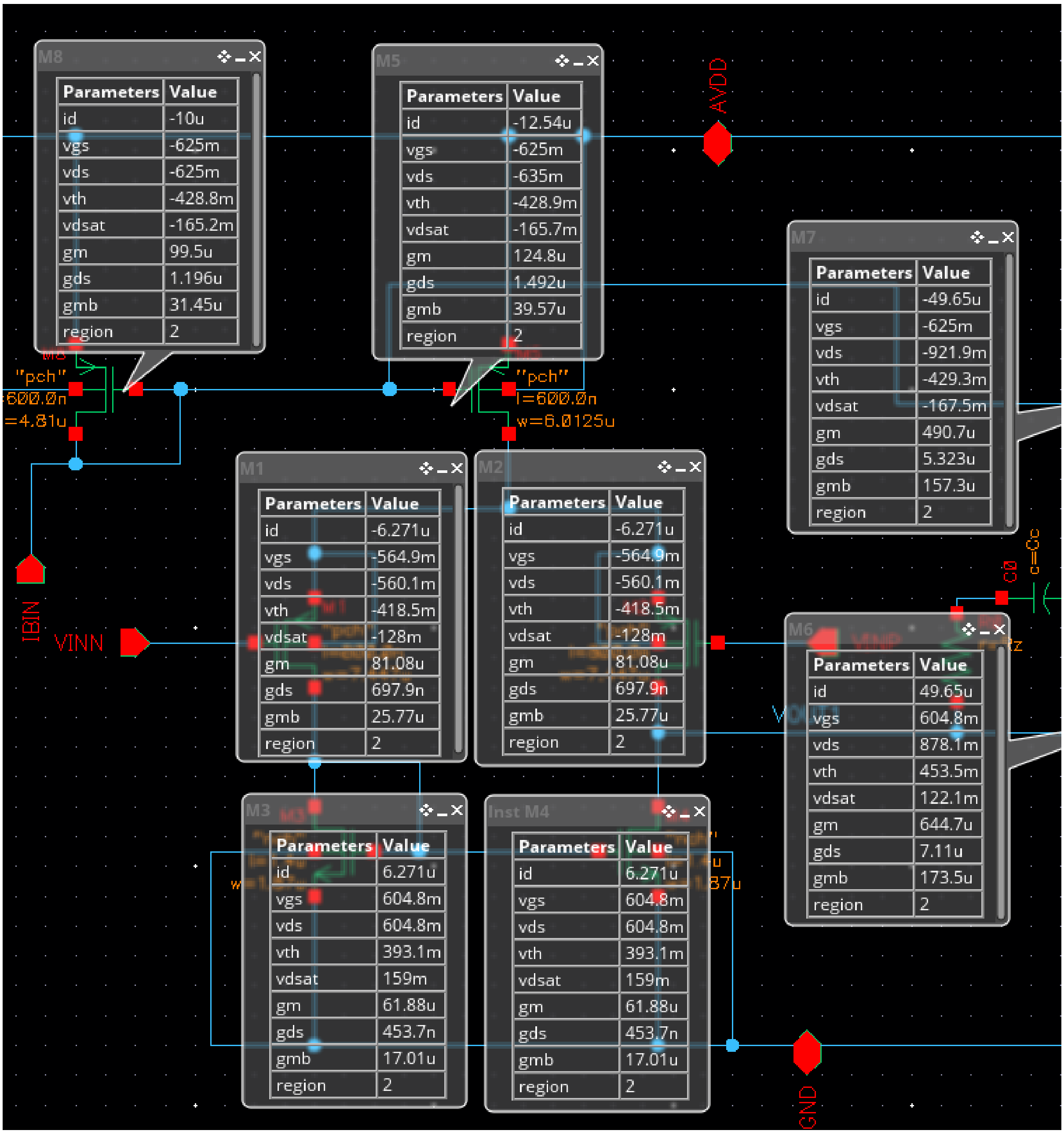
- **<u>Part 3: Open-Loop OTA Simulation</u>**



1)

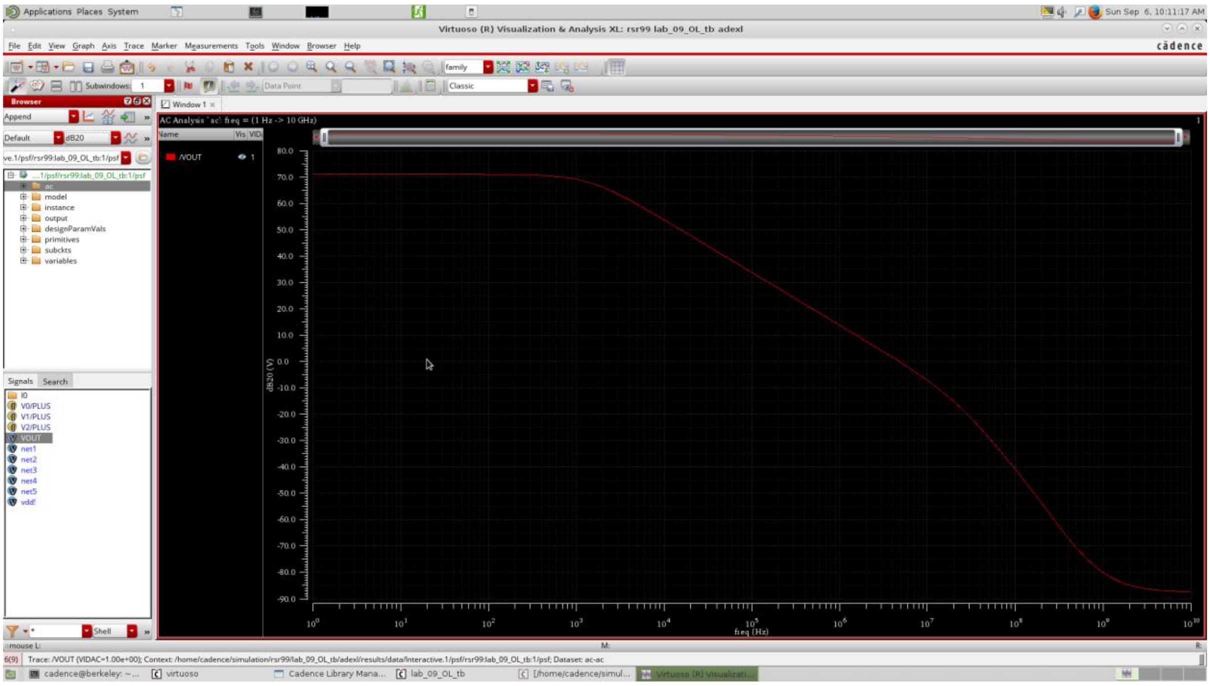


- The OTA with DC node voltages
- $V_{out1} = 604.8\ mv$ as $V_{out1} = V_{GS3,4,6}$
- $V_{out2} = 878.1\ mv$ as $V_{out2} = V_{DS6} = V_{DD} - V_{DS7} \approx \frac{V_{DD}}{2}$



- DC OP
- The current & g_m in the input pair are exactly equal

2) <u>Diff small signal ccs</u>



- Diff gain (db) vs frequency

ymax(mag(v("/VOUT" ?result "ac")))	3.637E3
ymax(dB20(mag(v("/VOUT" ?result "ac"))))	71.22
bandwidth(mag(v("/VOUT" ?result "ac")) 3 "low")	1.371E3
gainBwProd(mag(v("/VOUT" ?result "ac")))	5.000E6
unityGainFreq(mag(v("/VOUT" ?result "ac")))	4.874E6

- DC gain , BW , GBW & UGF from simulation
- Analytically:
  - DC gain $= A_v = A_{v1}A_{v2} = g_{m1,2}(r_{o2}\backslash\backslash r_{o4}) * g_{m6}(r_{o6}\backslash\backslash r_{o7})$

$$= g_{m1,2}\left(\frac{1}{g_{ds2}}\backslash\backslash\frac{1}{g_{ds4}}\right) * g_{m6}\left(\frac{1}{g_{ds6}}\backslash\backslash\frac{1}{g_{ds7}}\right) = 3.65k = 71.25db$$

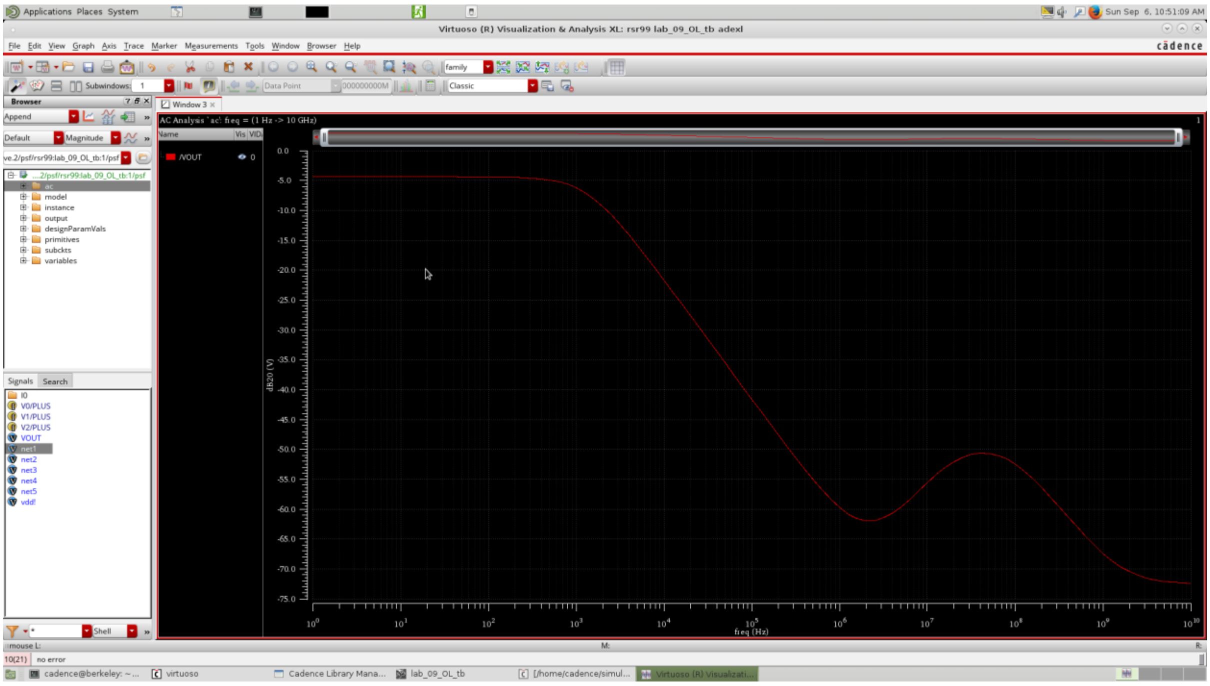
  - $BW = \frac{1}{(r_{o2}\backslash\backslash r_{o4})*\left(C_c(g_{m6}(r_{o6}\backslash\backslash r_{o7}))\right)} = \frac{1}{g_{m6}\left(\frac{1}{g_{ds6}}\backslash\backslash\frac{1}{g_{ds7}}\right)\left(\frac{1}{g_{ds2}}\backslash\backslash\frac{1}{g_{ds4}}\right)C_c}$

$$= 8.883\ kr/s = 1.414\ kHZ$$

  - $GBW = A_v * BW = \frac{g_{m1,2}}{C_c} = 32.432\ Mr/s = 5.162MHZ$

	Simulation results	Hand analysis results
$DC\ gain$	$3.637k = 71.22db$	$3.65k = 71.25db$
BW	$1.371kHZ$	$1.414kHZ$
GBW	$5MHZ$	$5.162MHZ$

3) CM small signal ccs



- CM gain (db) vs frequency

ymax(mag(v("/VOUT" ?result "ac")))	609.7E-3
ymax(dB20(mag(v("/VOUT" ?result "ac"))))	-4.298

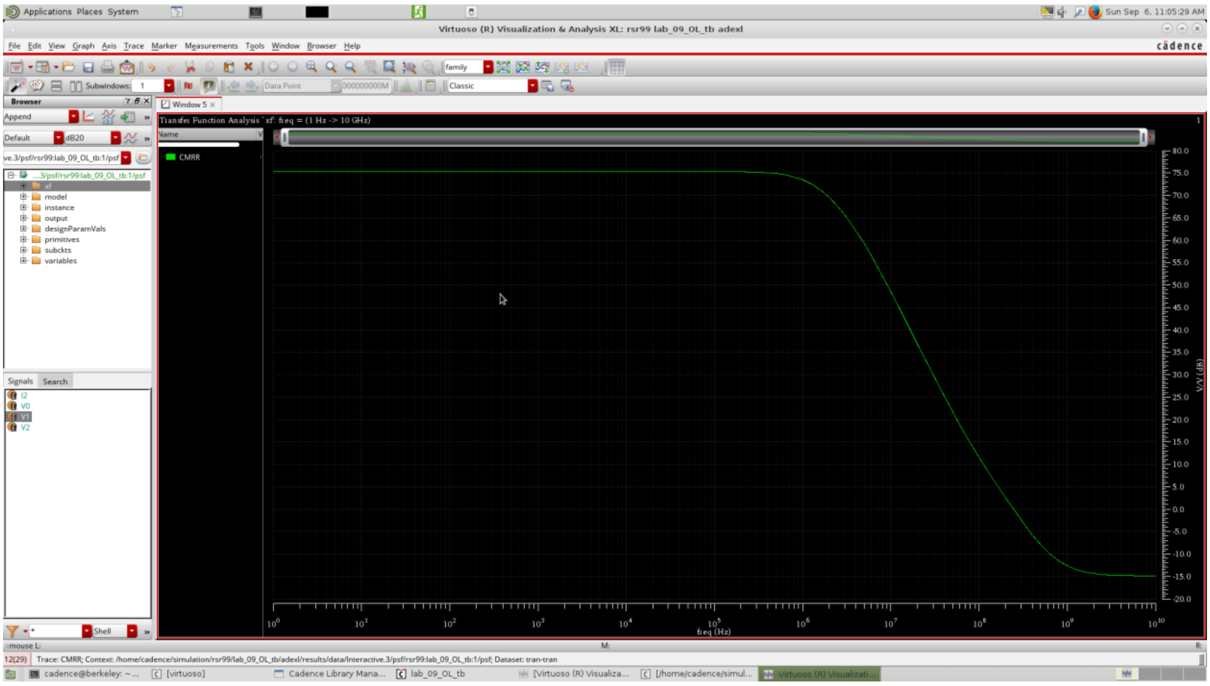
- CM gain from simulation
- Analytically:

  ➢ CM gain $= A_{vCM} = A_{v1CM} * A_{v2} = \frac{1}{2g_{m3,4}r_{o5}} * g_{m6}(r_{o6} \backslash\backslash r_{o7})$

$$= \frac{g_{ds5}}{2g_{m3,4}} * g_{m6}\left(\frac{1}{g_{ds6}} \backslash\backslash \frac{1}{g_{ds7}}\right) = 625.13m = -4.08db$$

	Simulation results	Hand analysis results
CM gain	$609.7m = -4.298db$	$625.13m = -4.08db$

4) CMRR



- CMRR (db) vs frequency

Expression	ymax(value((mag(getData("/V2" ?result "xf")) / mag(getData("/V1" ?result "xf"))) "VID...
Value	5.966E3
Expression	ymax(dB20(value((mag(getData("/V2" ?result "xf")) / mag(getData("/V1" ?result "xf")))...
Value	75.51

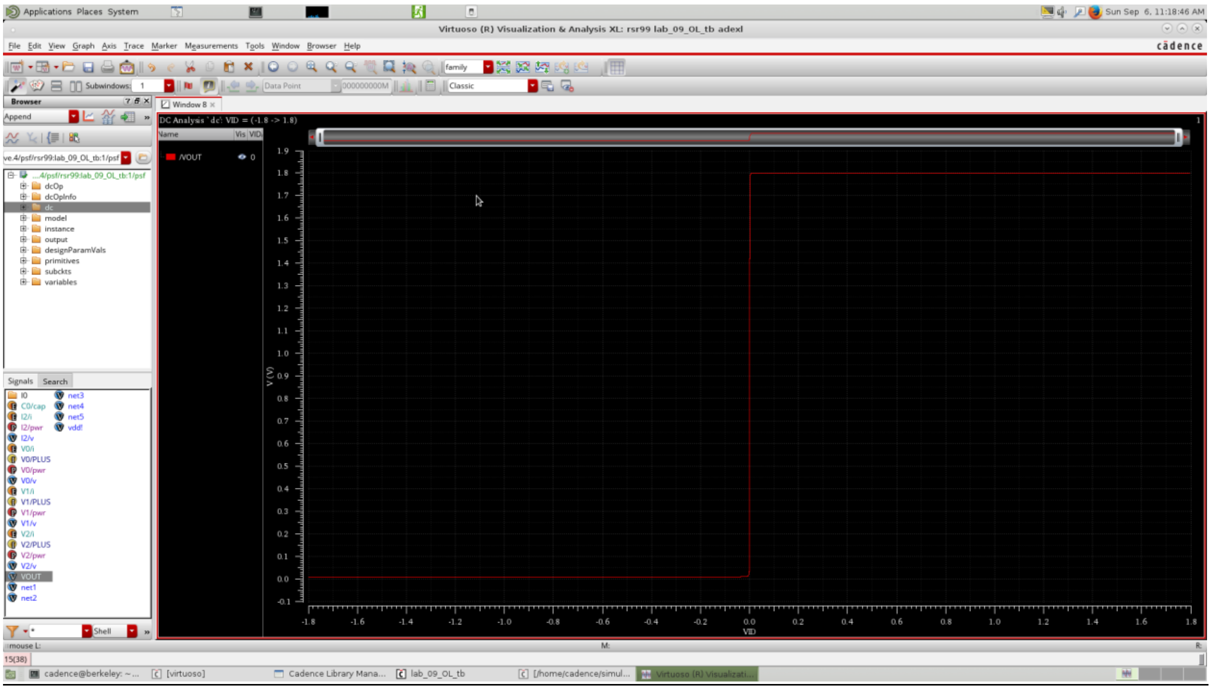
- CMRR from simulation
- Analytically:

➢ $$CMRR = \frac{A_v}{A_{vCM}} = \frac{g_{m1,2}(r_{o2}\backslash\backslash r_{o4}) * g_{m6}(r_{o6}\backslash\backslash r_{o7})}{\frac{1}{2g_{m3,4}r_{o5}} * g_{m6}(r_{o6}\backslash\backslash r_{o7})} = g_{m1,2}\left(\frac{1}{g_{ds2}}\backslash\backslash\frac{1}{g_{ds4}}\right) * \frac{2g_{m3,4}}{g_{ds5}}$$

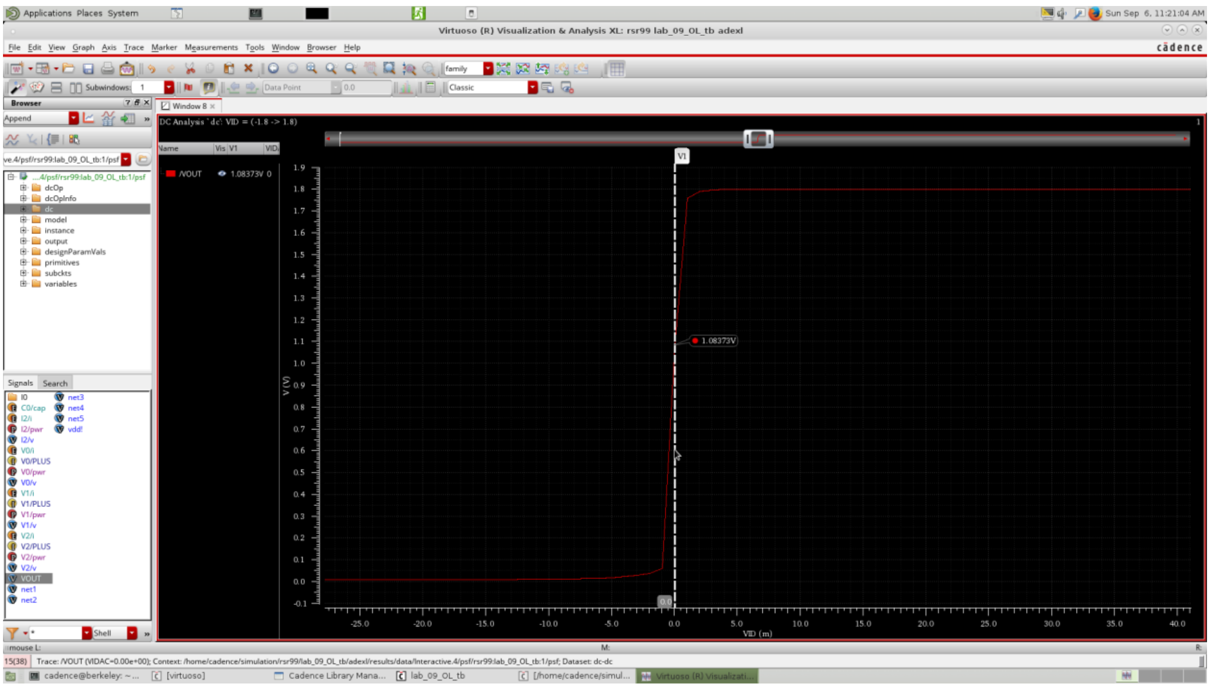
$$= 5.84k = 75.33db$$

	Simulation results	Hand analysis results
CMRR	$5.966k = 75.51db$	$5.84k = 75.33db$

5) <u>Diff large signal ccs</u>

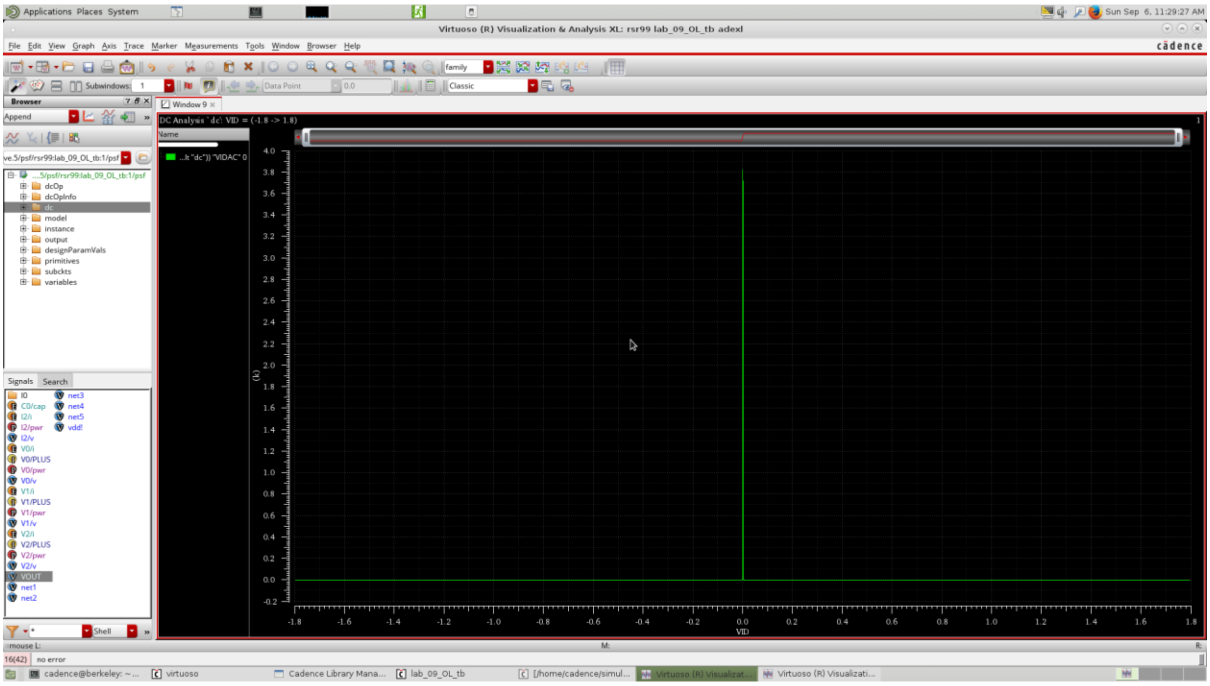


- $V_{out}\ vs\ V_{id}\ @\ V_{iCM} = \frac{V_{DD}}{2} = 0.9$



- $V_{out} = 1.08373v\ @\ V_{id} = 0\ \&\ V_{iCM} = 0.9$

	From $V_{out}\ vs\ V_{id}\ @\ V_{iCM} = 0.9$	From $DC\ OP\ @\ V_{iCM} = 0.6$
$V_{out}\ @\ V_{id} = 0$	$1.08373v$	$878.1mv$



- V_{out} *deriv vs* V_{id}

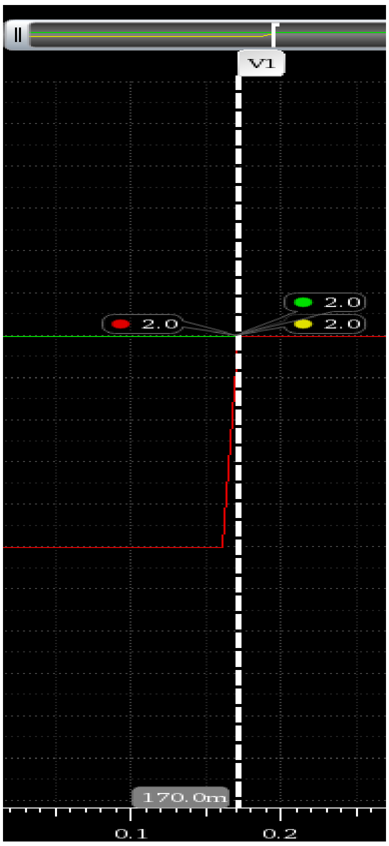
Expression	ymax(value(deriv(v("/VOUT" ?result "dc")) "VIDAC" 0.0))
Value	3.826E3

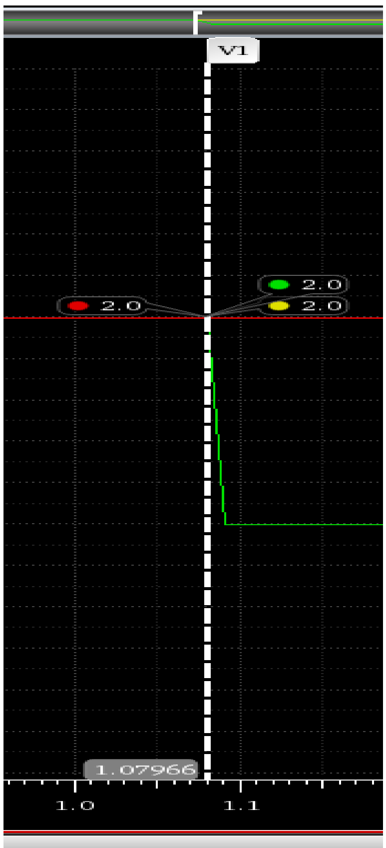
- V_{out} *deriv* peak from simulation

V_{out} derive peak	A_{vd}
$3.826k = 71.65db$	$3.637k = 71.22db$

6) <u>CM large signal ccs (region vs VICM)</u>

- Region OP vs V_{iCM}





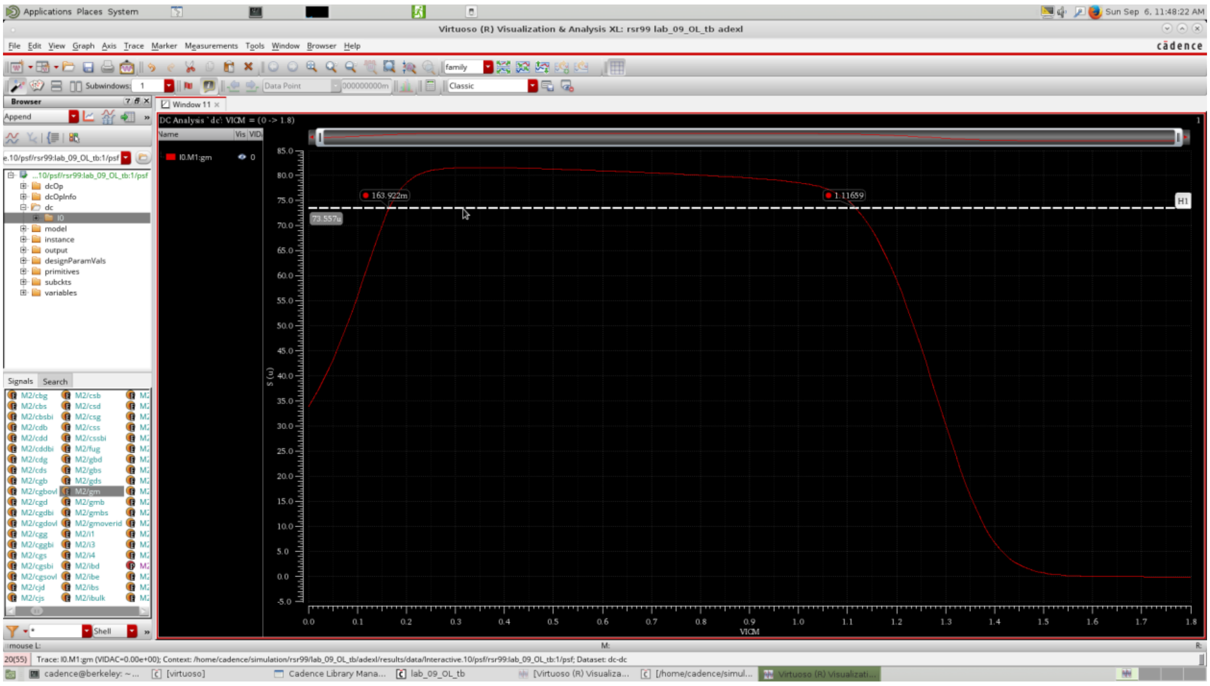
- $CMIR = (0.17 - 1.07966)$ from simulation

- Analytically:
  - $CMIR_{low} = -|V_{GS1,2}| + V_{Dsat1,2} + V_{GS3,4} = 0.1679$
  - $CMIR_{high} = V_{DD} - V_{Dsat5} - |V_{GS1,2}| = 1.0694$

	Simulation results	Hand analysis results
$CMIR$	$0.17 - 1.07966$	$0.1679 - 1.0694$

7) <u>CM large signal ccs (GBW vs VICM)</u>

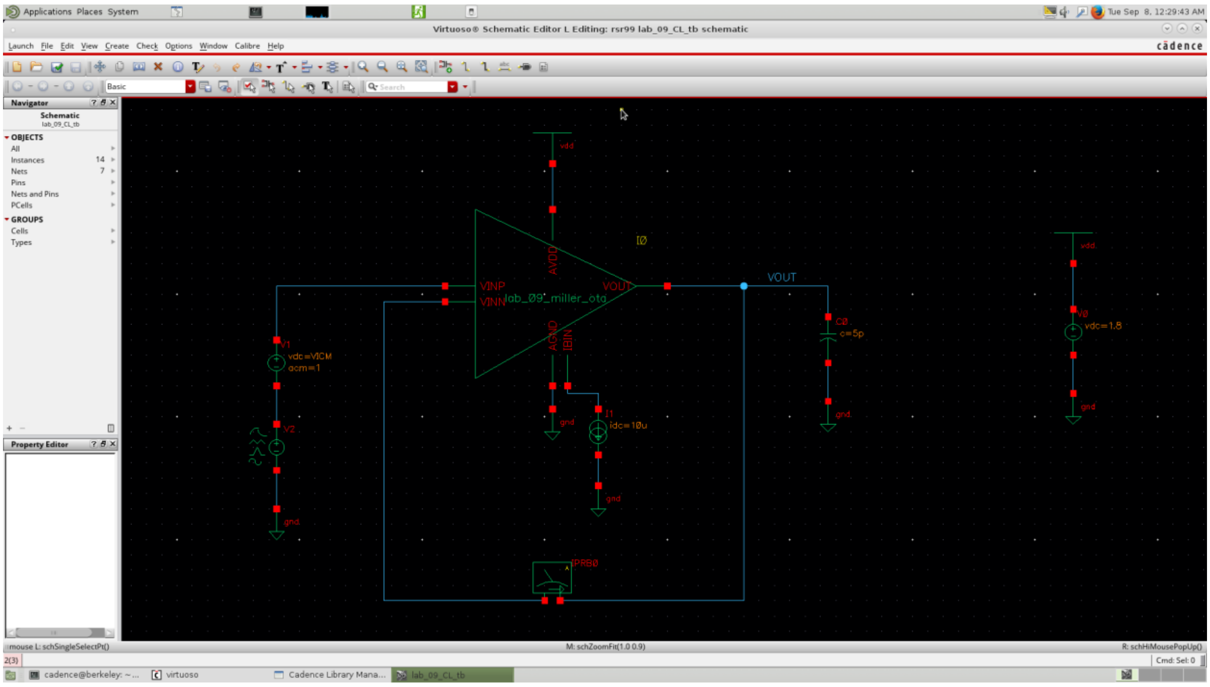
$\because GBW = \frac{g_{m1,2}}{2\pi C_c} \quad \rightarrow \therefore GBW$ variation is itself g_m variation



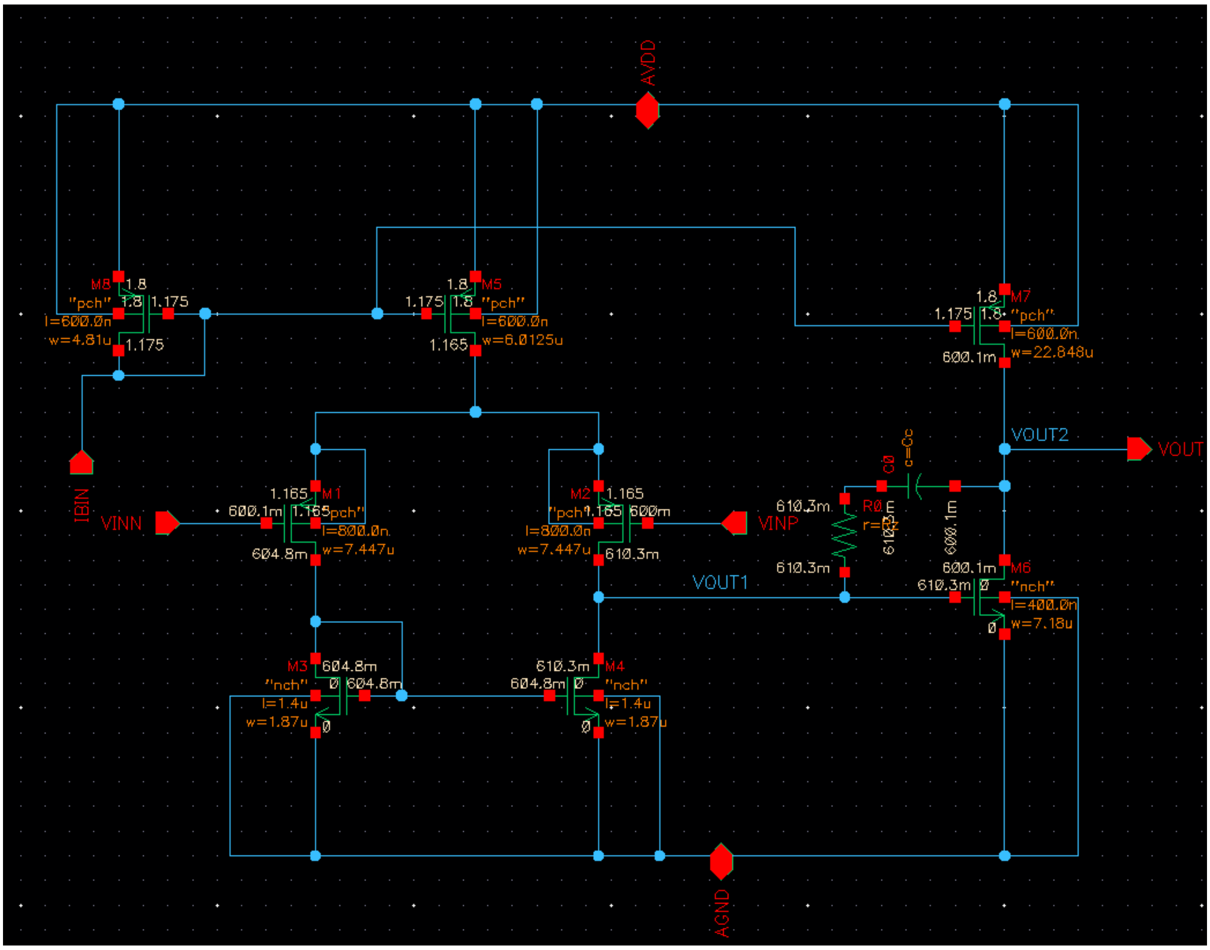
- $g_m(GBW) vs\ V_{iCM}$
- $CMIR = 163.922m - 1.11659$ from simulation

- From both region and GBW simulation: $CMIR = 163.922m - 1.07966$

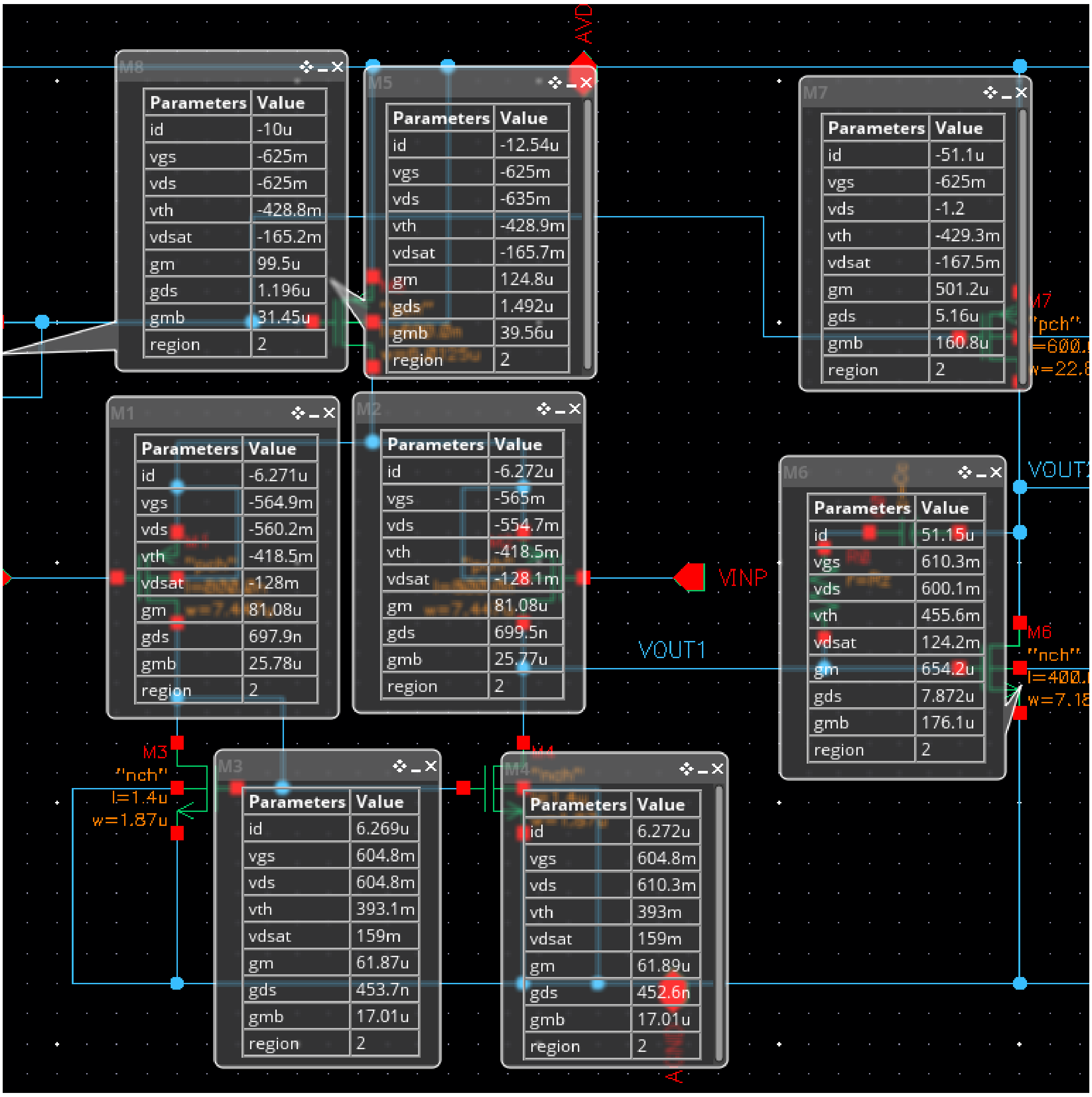
- **<u>Part 4: Closed-Loop OTA Simulation</u>**



1)

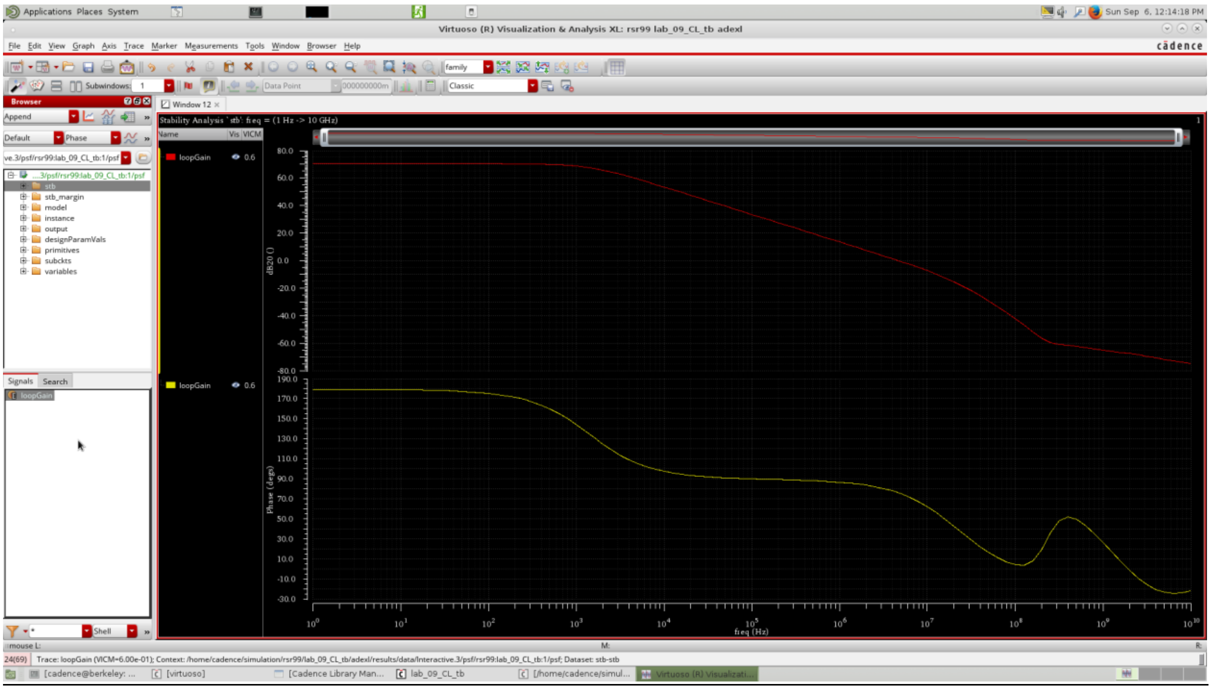


- The OTA with DC node voltages



- DC OP
- The DC voltages at the input terminals of the op amp are not exactly the same
- V_{out1} $(610.3m)$ is not exactly equal to its value in OL simulation (604.8m)
- The currents in the input pair are not exactly equal
- as V_{out} deviates from its CM level in order to follow the input which cause imbalance in the circuit which act as a mismatch

1) <u>Loop gain</u>



- LG (db & phase) vs frequency

ymax(mag(getData("loopGain" ?result "stb")))	3.519E3
ymax(dB20(mag(getData("loopGain" ?result "stb"))))	70.93
bandwidth(mag(getData("loopGain" ?result "stb")) 3 "low")	1.416E3
gainBwProd(mag(getData("loopGain" ?result "stb")))	4.997E6
unityGainFreq(mag(getData("loopGain" ?result "stb")))	4.872E6

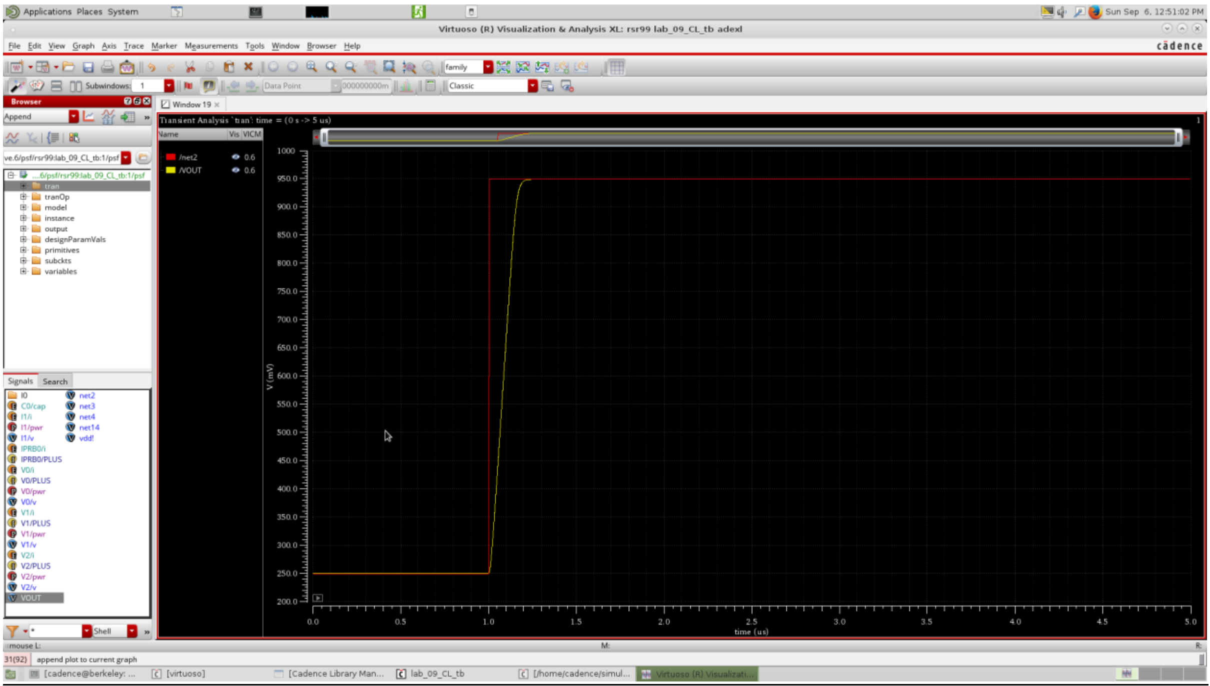
- DC LG , BW , GBW & UGF from simulation

	OL Simulation results	CL Simulation results
$DC\ gain$	$3.637k = 71.22db$	$3.519k = 70.93db$
BW	$1.371kHZ$	$1.416kHZ$
GBW	$5MHZ$	$4.997MHZ$

- Analytically:
  - DC LG $= \beta A_{OL} \approx A_{OL} = A_v = g_{m1,2}\left(\frac{1}{g_{ds2}} \backslash\backslash \frac{1}{g_{ds4}}\right) * g_{m6}\left(\frac{1}{g_{ds6}} \backslash\backslash \frac{1}{g_{ds7}}\right)$ $= 3.533k = 70.96db$
  - $BW = \frac{1}{g_{m6}\left(\frac{1}{g_{ds6}} \backslash\backslash \frac{1}{g_{ds7}}\right)\left(\frac{1}{g_{ds2}} \backslash\backslash \frac{1}{g_{ds4}}\right)C_c} = 9.18k\,r/s = 1.461kHZ$
  - $GBW = DC\ LG * BW = \frac{g_{m1,2}}{2\pi C_c} = 5.162MHZ$

	Simulation results	Hand analysis results
$DC\ LG$	$3.519k = 70.93db$	$3.533k = 70.96db$
BW	$1.416kHZ$	$1.461kHZ$
GBW	$4.997MHZ$	$5.162MHZ$

2) Slew rate



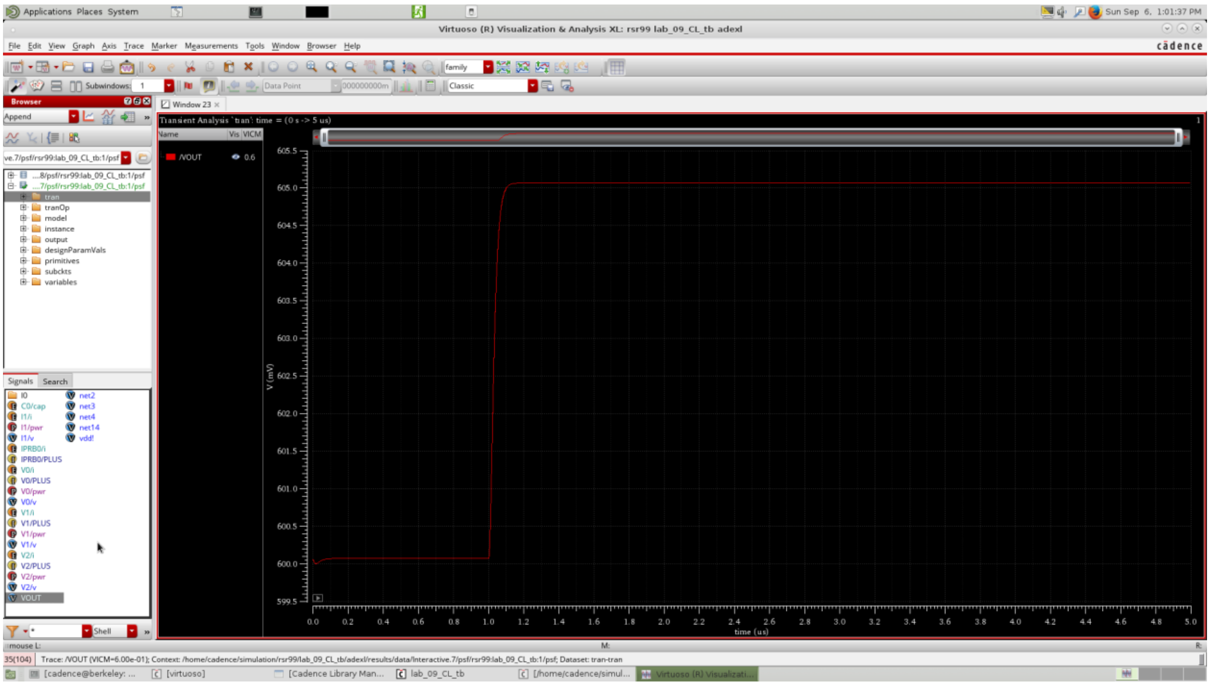
- V_{in}&V_{out} overlaid vs time

slewRat...time")
4.519E6

- Slew rate from simulation
- Analytically:
  - Slew rate $= SR = \frac{I_{B1}}{C_c} = 5.016M\, v/s = 5.016\, v/\mu s$

	Simulation results	Hand analysis results
Slew rate	$4.519\, v/\mu s$	$5.016\, v/\mu s$

3) <u>Settling time</u>



- V_{out} vs time

VOUT" ?result "tran") ..

riseTim...time")
50.98E-9

- V_{out} rise time from simulation
- Analytically:
  - ➢ $t_{rise} = 2.2 * \frac{1}{g_{m1,2}} * C_c = 67.834ns$

	Simulation results	Hand analysis results
Rise time	$50.98ns$	$67.934ns$

- There is no ringing as the system is critically damped.