



VL 804

Analog Power Integrated Circuits

ASSIGNMENT 1

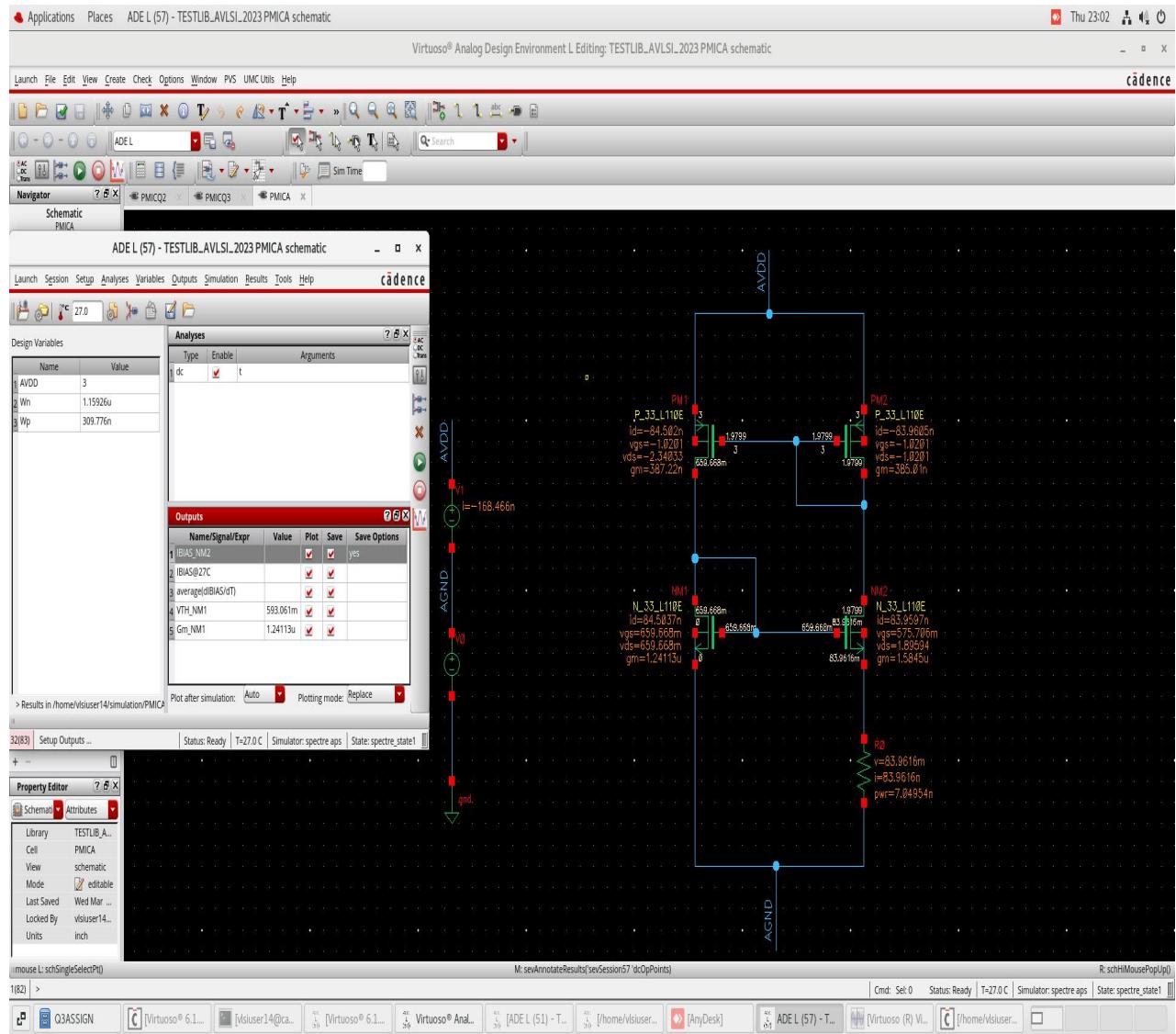
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Acknowledgement: Prof. Manikandan R.R.

Q1

Schematic And DC Operating Point with ADE L



● Calculation of Width of NMOS(W_n) and PMOS(W_p) and RBIAS

SOP [Q1]

Beta Current Reference & Same for Bandgap Voltage Reference Circuit
W_n & W_p values :-

Given: AVDD = 3V ; Vov = 0.2V ; L = 8μm ; IBIAS = 100nA @ 27°C

NMOS: K_{fit} = 0.7733
 $\mu_n = 0.0363 \text{ M}^2/\text{V}\cdot\text{s}$
 $C_{ox} = 4.6 \times 10^{-3} \text{ F/m}^2$

PMOS: K_{fit} = 0.7733
 $\mu_p = 0.0097 \text{ M}^2/\text{V}\cdot\text{s}$
 $C_{ox} = 4.6 \times 10^{-3} \text{ F/m}^2$

NMOS

- In saturation;

$$\rightarrow I_{Bias_n} = K_{fit} \mu_n C_{ox} \left(\frac{W}{L}\right)_n V_{ov}^2$$

$$\therefore \frac{10^{-7} \times 2}{0.7733 \times 0.0363 \times 4.6 \times 10^{-3} \times (0.2)^2} = \left(\frac{W}{L}\right)_n$$

$$\therefore \left(\frac{W}{L}\right)_n = 387.21978 \mu\text{m}$$

$$W_n = 387.21978 \times 8 \times 10^6 \times 10^{-6}$$

$$W_n = 309.776 \text{ nm}$$

PMOS

- In saturation;

$$\rightarrow I_{Bias_p} = K_{fit} \mu_p C_{ox} \left(\frac{W}{L}\right)_p V_{ov}^2$$

$$\frac{10^{-7} \times 2 \times 8 \times 10^{-6}}{0.7733 \times 0.0097 \times 4.6 \times 10^{-3} \times (0.2)^2} = \left(\frac{W}{L}\right)_p$$

$$\left(\frac{W}{L}\right)_p = 144.908 \times 10^{-3}$$

$$W_p = 1.259 \mu\text{m}$$

$\beta_n = \mu_n C_{ox} \left(\frac{W}{L}\right)_n K_{fit}$

$$= 0.7733 \times 0.0363 \times 4.6 \times 10^{-3} \times 387.21978 \times 10^{-3}$$

$$\beta_n = 5 \times 10^6$$

$$\rightarrow I_{BIAS} = I_{ref} = \frac{1}{R_{BIAS}} \left(\frac{2}{\beta_n} \right) \left(1 - \frac{1}{\sqrt{k}} \right)$$

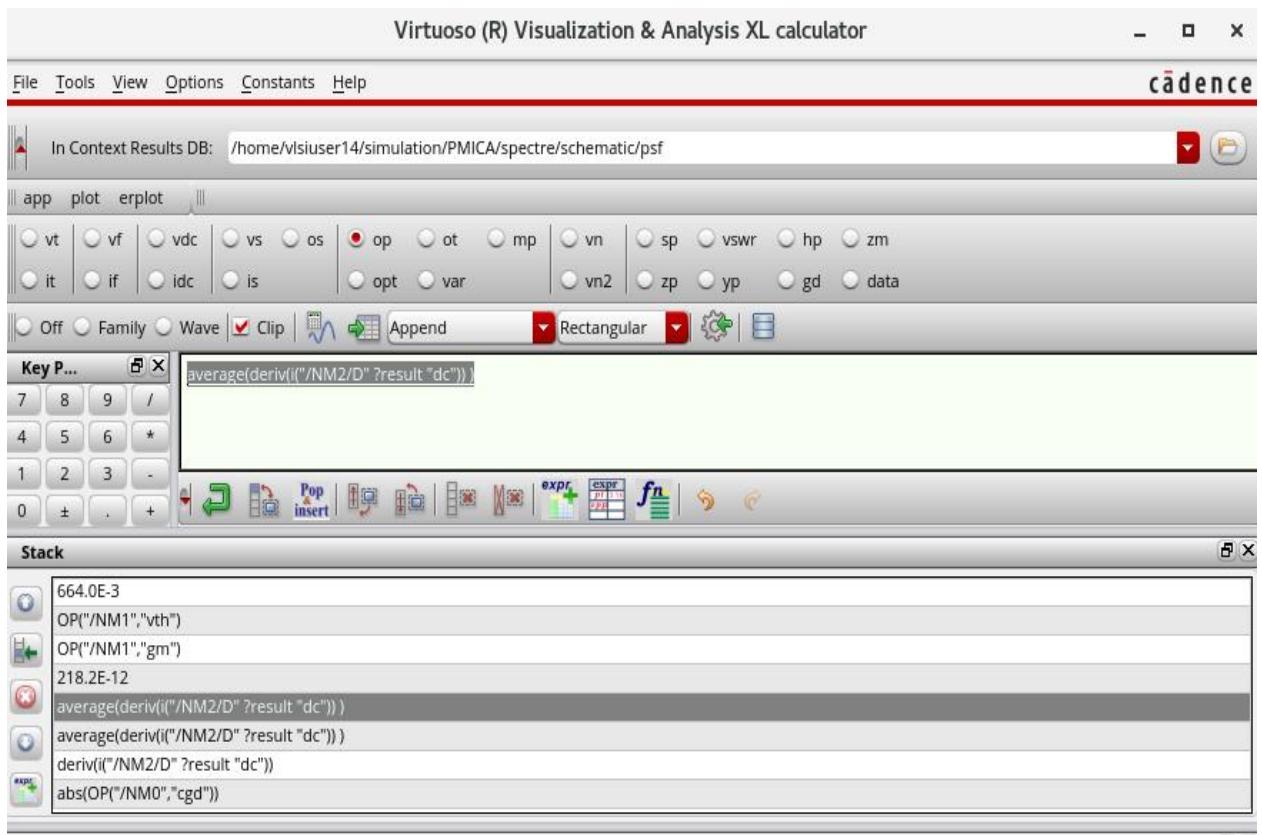
Here $\beta_n = 5 \times 10^6$; $k = 4$ (multiplier)

$$R_{BIAS} = \frac{1}{10^7} \times \frac{2}{5 \times 10^6} \left(1 - \frac{1}{\sqrt{4}} \right)$$

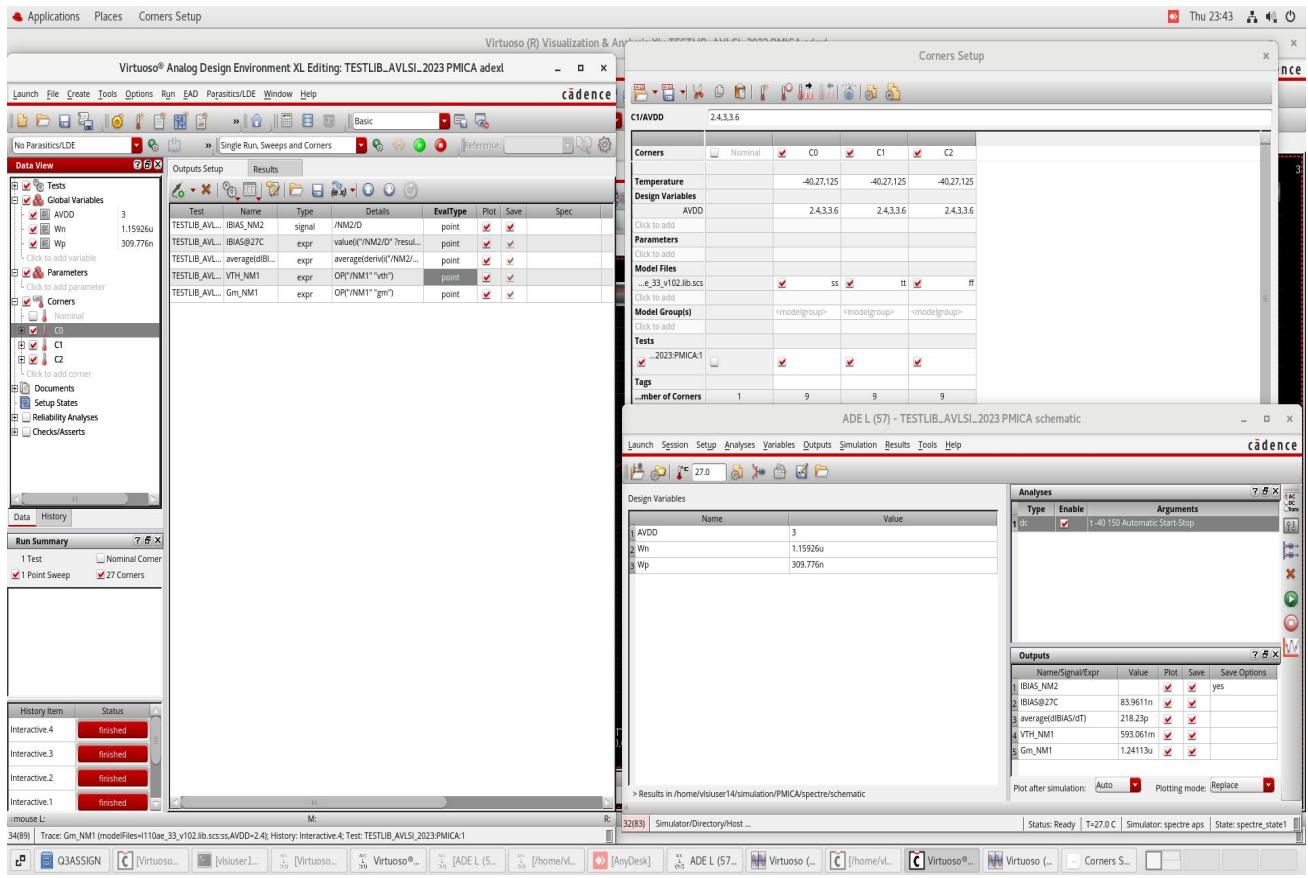
$$= 10^6$$

$R_{BIAS} = 1M\Omega$

- Average Derivative of IBIAS Calculation in Virtuoso Calculator



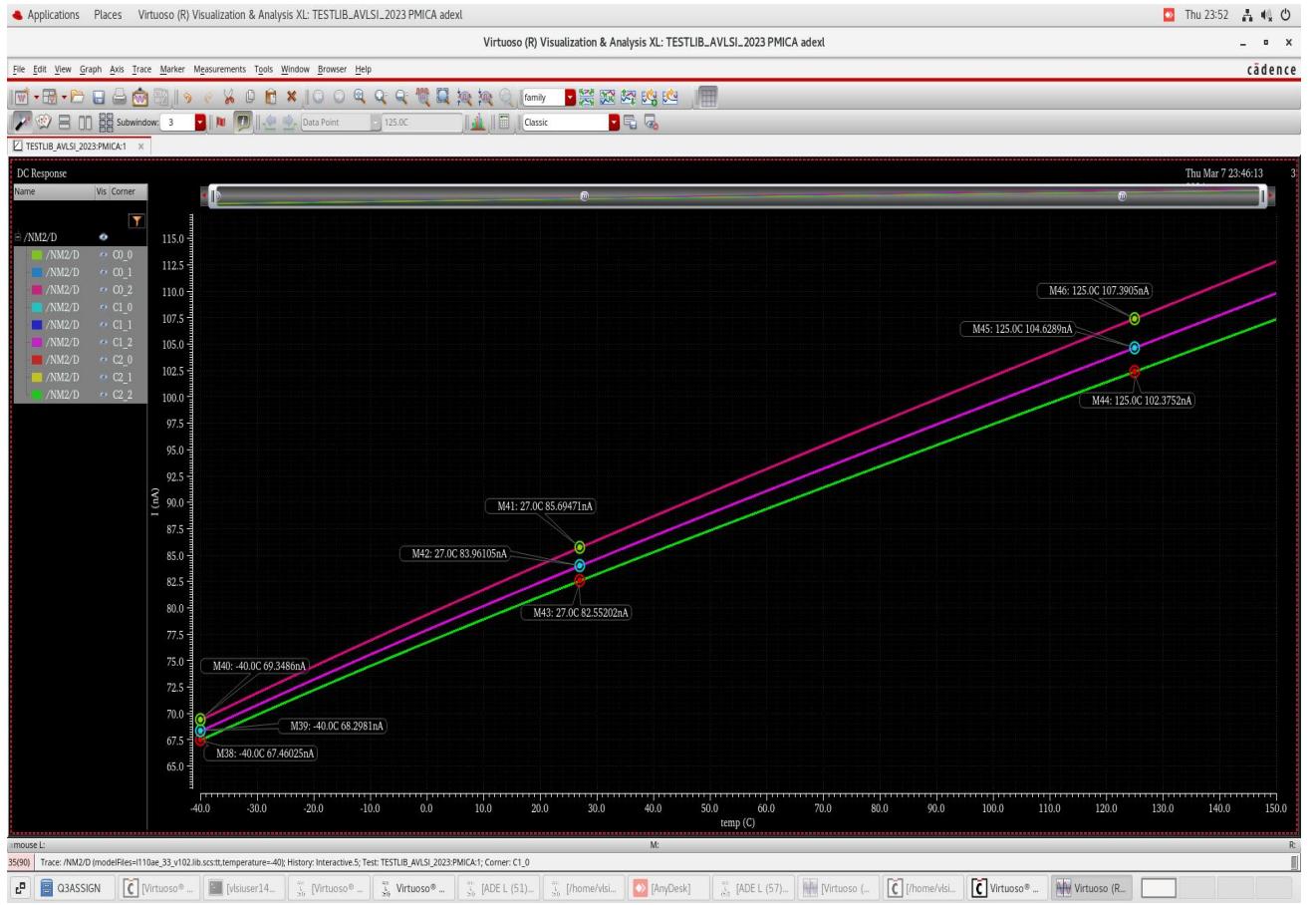
● ADE XL and Corner Setup and ADE L



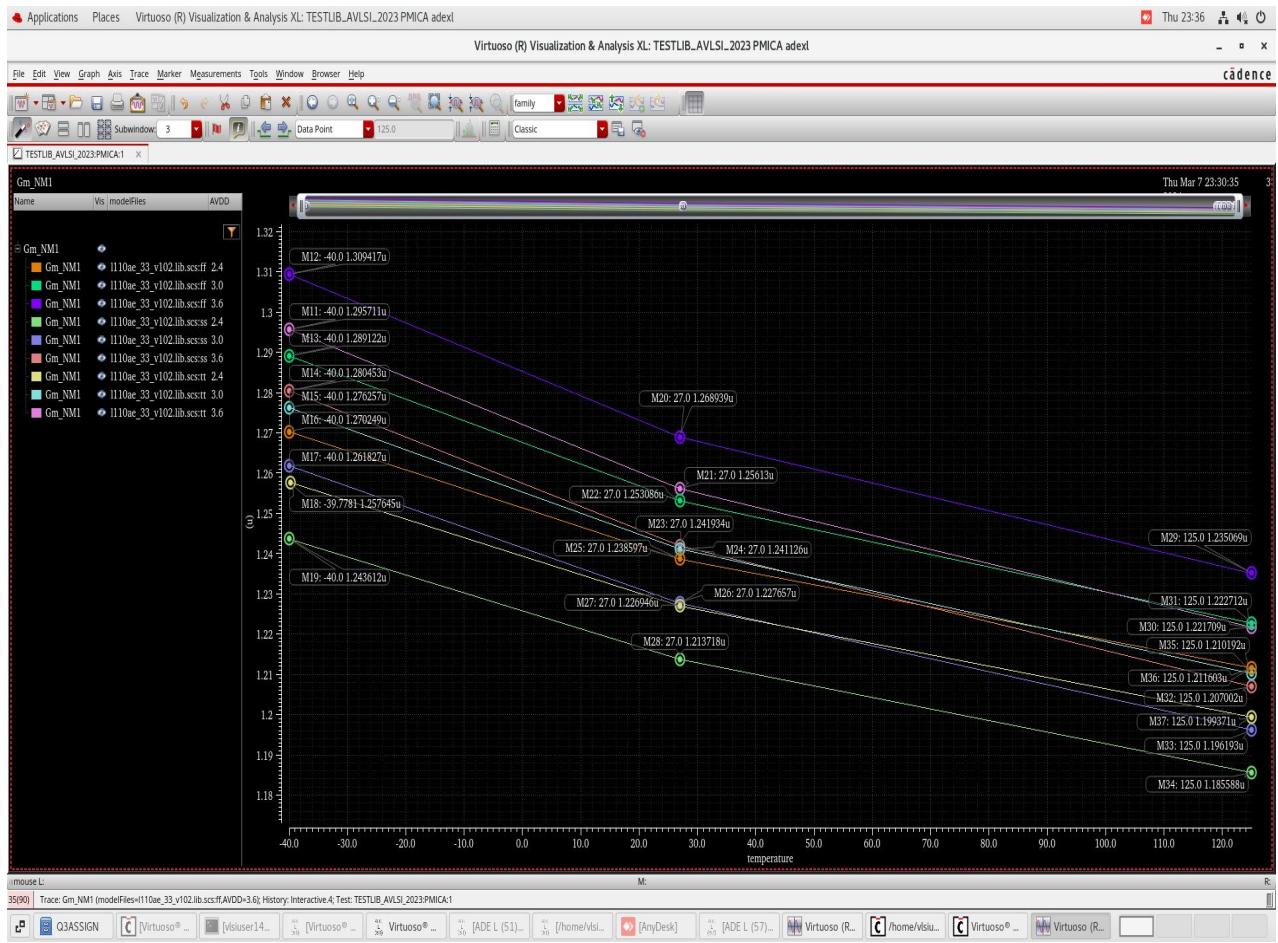
● IBIAS @ 27C and TT Corners



- **I_{BIAS} at 3V and 3 Different Corner(ss, tt, ff) Temperature Sweep**



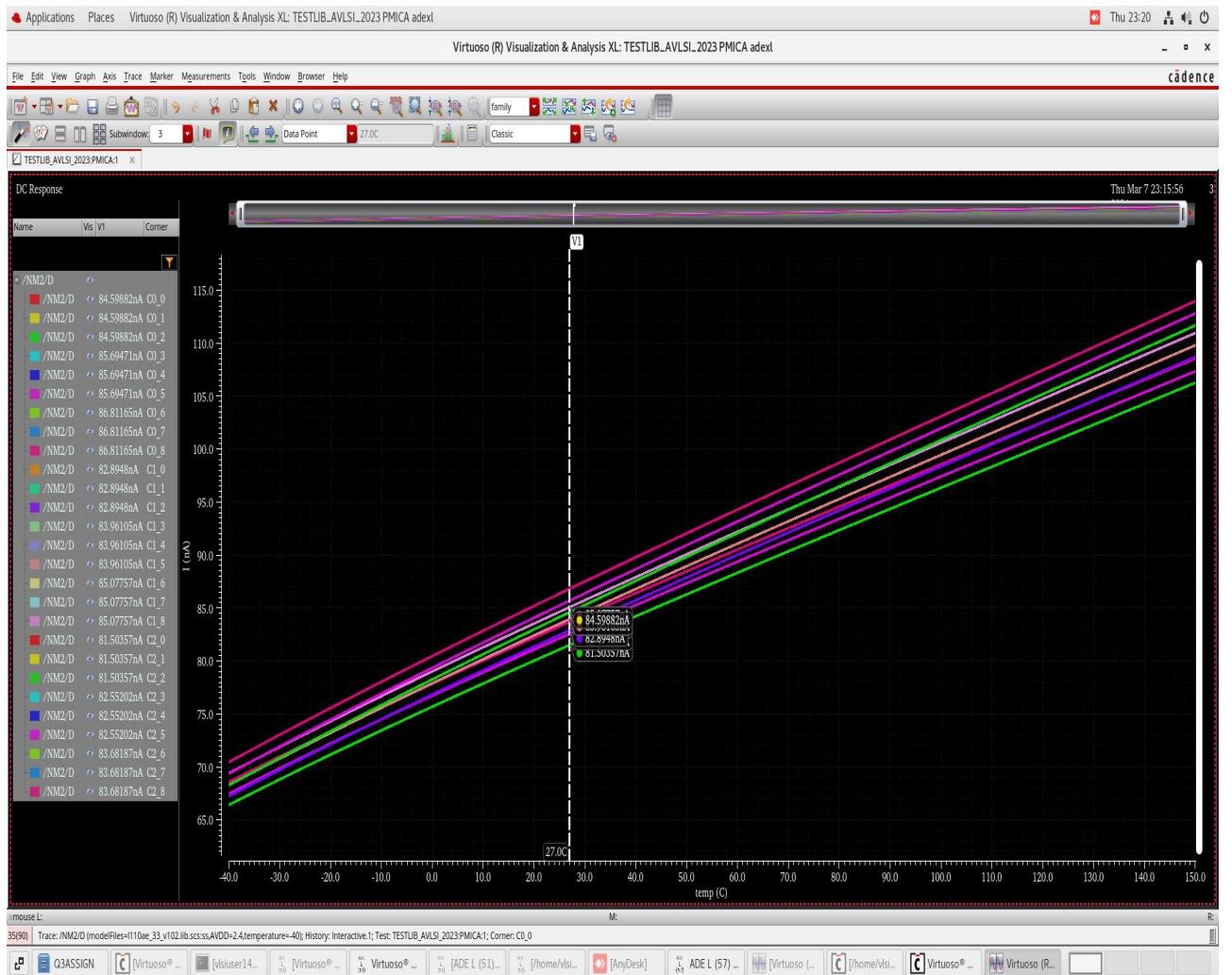
- **gm vs Temperature Sweep at 3 different Corner(ss, tt, ff)**



- Vth vs Temperature Sweep at 3 different Corner(ss, tt, ff)



- **I_{BIAS} at 2.4V,3V,3.6V and 3 Different Corner(ss, tt, ff) Temperature Sweep**

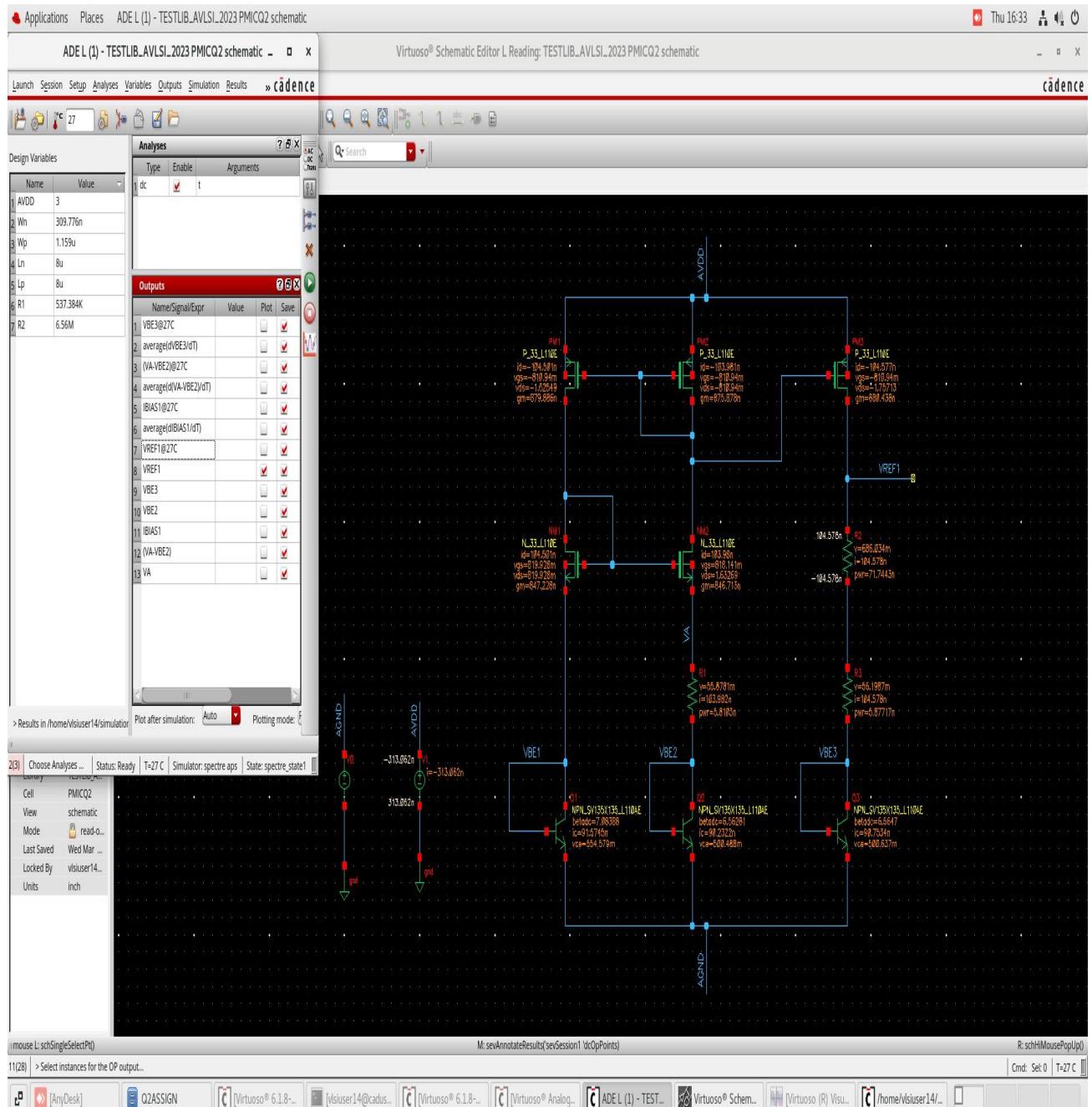


- OBSERVATION TABLE:

<u>Q1 B-MULTIPLIER CIRCUIT</u>										
		Slow			Typical			Fast		
AVDD		2.4 V	3.0 V	3.6 V	2.4 V	3.0 V	3.6 V	2.4 V	3.0 V	3.6 V
VTH_NM1(mV)	@ -40 C	703.29	703.29	703.29	664.022	664.022	664.022	623.862	623.862	623.862
	@ 27 C	703.29	703.29	703.29	664.022	664.022	664.022	623.862	623.862	623.862
	@ 125 C	703.29	703.29	703.29	664.022	664.022	664.022	623.862	623.862	623.862
Gm_NM1(uS)	@ -40 C	1.24361	1.26183	1.28045	1.25775	1.27626	1.29571	1.27025	1.28912	1.30942
	@ 27 C	1.24361	1.26183	1.28045	1.25775	1.27626	1.29571	1.27025	1.28912	1.30942
	@ 125 C	1.24361	1.26183	1.28045	1.25775	1.27626	1.29571	1.27025	1.28912	1.30942
I _{BIAS} (nA)	@ 27 C	84.5988	85.6947	86.8116	82.8948	83.9611	85.0776	81.5036	82.552	83.6819
average (dIBIAS/dT)	pA/C	228.282	228.565	228.822	218.015	218.23	218.527	209.526	209.703	210.09

(Q3) BANDGAP VOLTAGE REFERENCE (CIRCUIT 1)

- Schematic and DC Operating Point



● Calculation of Width W_n and W_p and R₁ and R₂

Given; AVDD = 3V ; V_{ov} = 0.2V ; L = 8μm ; I_{Bias} = 100nA @ 27°C

NMOS:

$$K_{fit} = 0.7733$$

$$\mu_n = 0.0363 \text{ M}^2/\text{V.s}$$

$$C_{ox} = 4.6 \times 10^{-3} \text{ F/m}^2$$

PMOS: K_{fit} = 0.7733

$$\mu_p = 0.0097 \text{ M}^2/\text{V.s}$$

$$C_{ox} = 4.6 \times 10^{-3} \text{ F/m}^2$$

NMOS

• In saturation;

$$\rightarrow I_{Bias,n} = \frac{K_{fit} \mu_n C_{ox}}{2} \left(\frac{W}{L}\right)_n V_{ov}^2$$

$$\therefore \frac{10^{-7} \times 2}{0.7733 \times 0.0363 \times 4.6 \times 10^{-3} \times (0.2)^2} = \left(\frac{W}{L}\right)_n$$

$$\therefore \left(\frac{W}{L}\right)_n = 387.21978 \mu\text{m}$$

$$W_n = 387.21978 \times 8 \times 10^{-6} \times 10^{-3}$$

$$\boxed{W_n = 309.776 \text{ nm}}$$

PMOS

In saturation,

$$\rightarrow I_{Bias,p} = \frac{K_{fit} \mu_p C_{ox}}{2} \left(\frac{W}{L}\right)_p V_{ov}^2$$

$$\frac{10^{-7} \times 2 \times 8 \times 10^{-6}}{0.7733 \times 0.0097 \times 4.6 \times 10^{-3} \times (0.2)^2} = \left(\frac{W}{L}\right)_p$$

$$\left(\frac{W}{L}\right)_p = 144.908 \times 10^{-3}$$

$$\boxed{W_p = 1.159 \mu\text{m}}$$

$$\beta_n = \mu_n C_{ox} \left(\frac{W}{L}\right)_n K_{fit}$$

$$= 0.7733 \times 0.0363 \times 4.6 \times 10^{-3} \times 38.7219 \times 10^{-3}$$

$$\boxed{\beta_n = 5 \times 10^{-6}}$$

Soln | Q2

$$\rightarrow R_2 = \frac{V_T \ln(8)}{I_{BIAS}}$$

$$= \left(\frac{kT}{q}\right) \frac{\ln(8)}{I_{BIAS}}$$

$$= \frac{1.38 \times 10^{-23} \times 300}{1.602 \times 10^{-19}} \frac{\ln(8)}{100 \times 10^{-9}}$$

~~$R_2 = 537.384 \text{ k}\Omega$~~

$$\rightarrow \text{Here, } V_T = \frac{kT}{q_{ZTC}} = \frac{1.38 \times 10^{-23} \times 300}{1.602 \times 10^{-19}} = 25.843 \text{ mV}$$

$$\rightarrow V_{be} = V_T \ln\left(\frac{I_C}{I_S}\right)$$

$$= 25.875 \times 10^{-3} \ln\left(\frac{100 \times 10^{-9}}{10^{-16}}\right)$$

$$\underline{V_{be} = 0.5362 \text{ V}}$$

$$\rightarrow \frac{\partial V_{BE3}}{\partial T} = \frac{V_{be} - (1+n)V_T - E_g}{T}$$

Here E_g for Si is given, $E_g = 1.12 \text{ eV} = 1.12 \times 1.602 \times 10^{19} \text{ V}$
 $= 1.82 \times 10^9 \text{ V}$

$$n = -\frac{3}{2};$$

$$\frac{\partial V_{BE3}}{\partial T} = \frac{0.5362 - (1 - \frac{3}{2}) \times 25.875 \times 10^{-3} - 1.12}{300}$$

$$\frac{\partial V_{BE3}}{\partial T} = -2.3658 \times 10^{-3}$$

$$\rightarrow \text{By KVL, Now, } V_{REF} = I_{BIA} (R_1 + R_2) + V_{be3}$$

$$\frac{\partial V_{REF}}{\partial T} = \frac{\partial I_{BIA}}{\partial T} (R_1 + R_2) + \frac{\partial V_{be3}}{\partial T}$$

$$\text{Here Consider, } \frac{\partial V_{REF}}{\partial T} = 0$$

$$\frac{\partial V_{be3}}{\partial T} = -\left(\frac{\partial I_{BIA}}{\partial T}\right)(R_1 + R_2)$$

$$= -\frac{\partial}{\partial T} \left(\frac{V_A - V_{be2}}{R_1} \right) (R_1 + R_2)$$

$$\text{By KVL; } V_{be2} - V_{as} + V_{as} - V_A = 0$$

$$V_A = V_{be2} \Rightarrow V_A - V_{be2} = V_{be1} - V_{be2} = \Delta V_{be}$$

$$\frac{\partial V_{be3}}{\partial T} = -\left[\frac{\partial}{\partial T} \left(\frac{\Delta V_{be}}{R_1} \right)\right] [R_1 + R_2]$$

$$= -\left(1 + \frac{R_2}{R_1}\right) \frac{\partial}{\partial T} [V_T \ln(m)]$$

$$= -\left(1 + \frac{R_2}{R_1}\right) \left[\frac{k}{q} \ln(m) \right]$$

$$\rightarrow \frac{\partial V_{be3}}{\partial T} = - \left(1 + \frac{R_2}{R_1} \right) \left[\frac{k}{q} \ln(\varepsilon) \right]$$

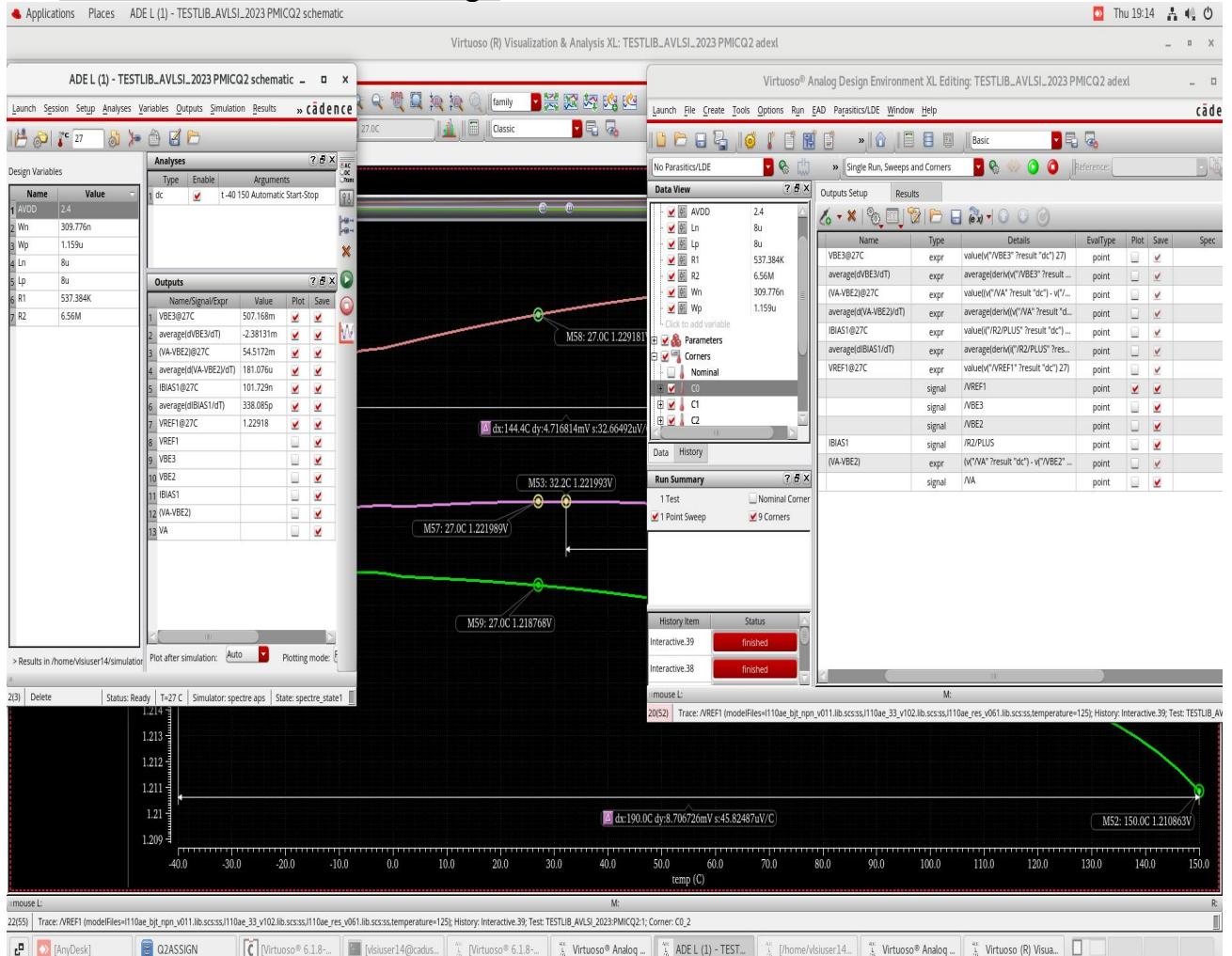
$$-2.3658 \times 10^{-3} = - \left(1 + \frac{R_2}{R_1} \right) \left(\frac{k}{q} \right) \ln(\varepsilon)$$

$$\frac{1 + R_2}{R_1} = \frac{2.3658 \times 10^{-3} \times 2.602 \times 10^{-19}}{\ln(\varepsilon) \times 1.38 \times 10^{-23}}$$

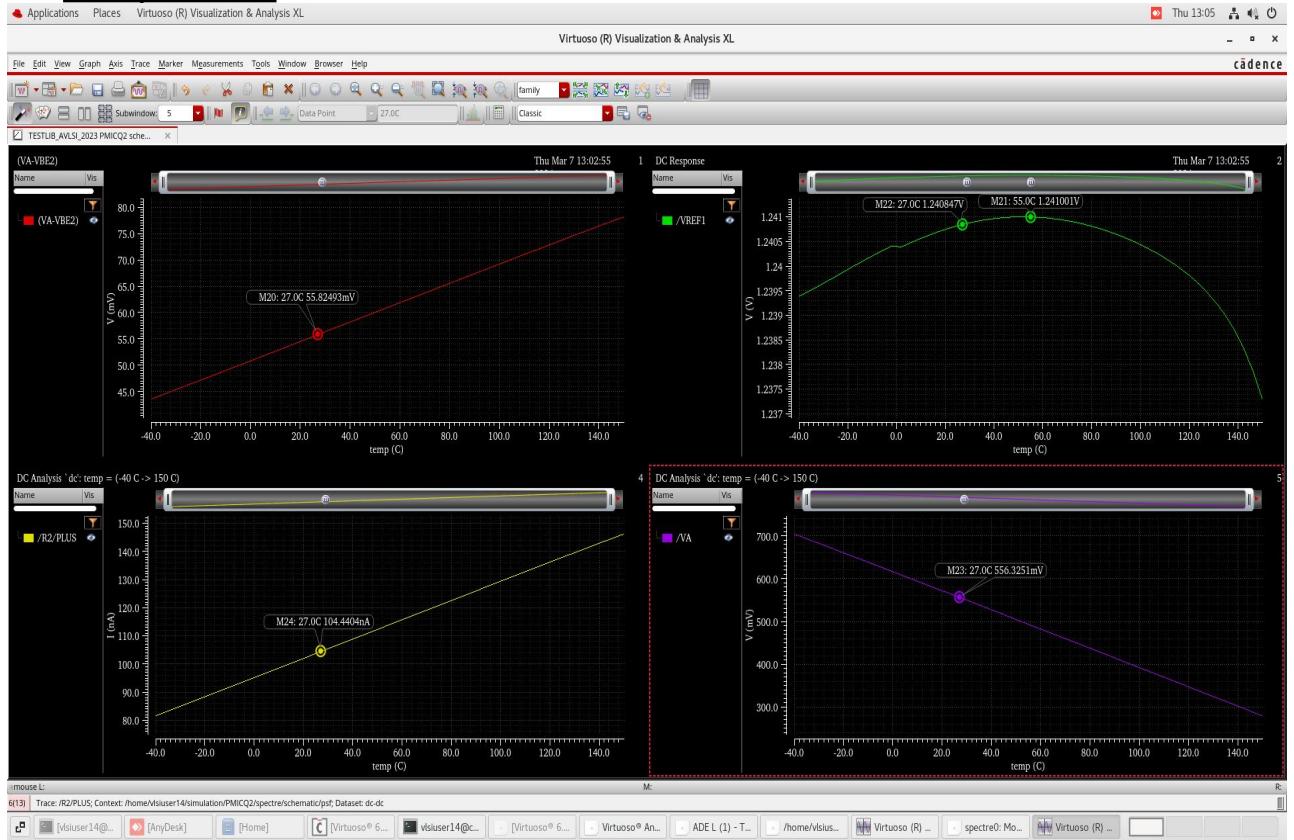
$$13.2076 = 1 + \frac{R_2}{R_1}$$

$$R_2 = 6.56 \text{ M}\Omega$$
~~$$R_2 = 537.384 \text{ k}\Omega$$~~

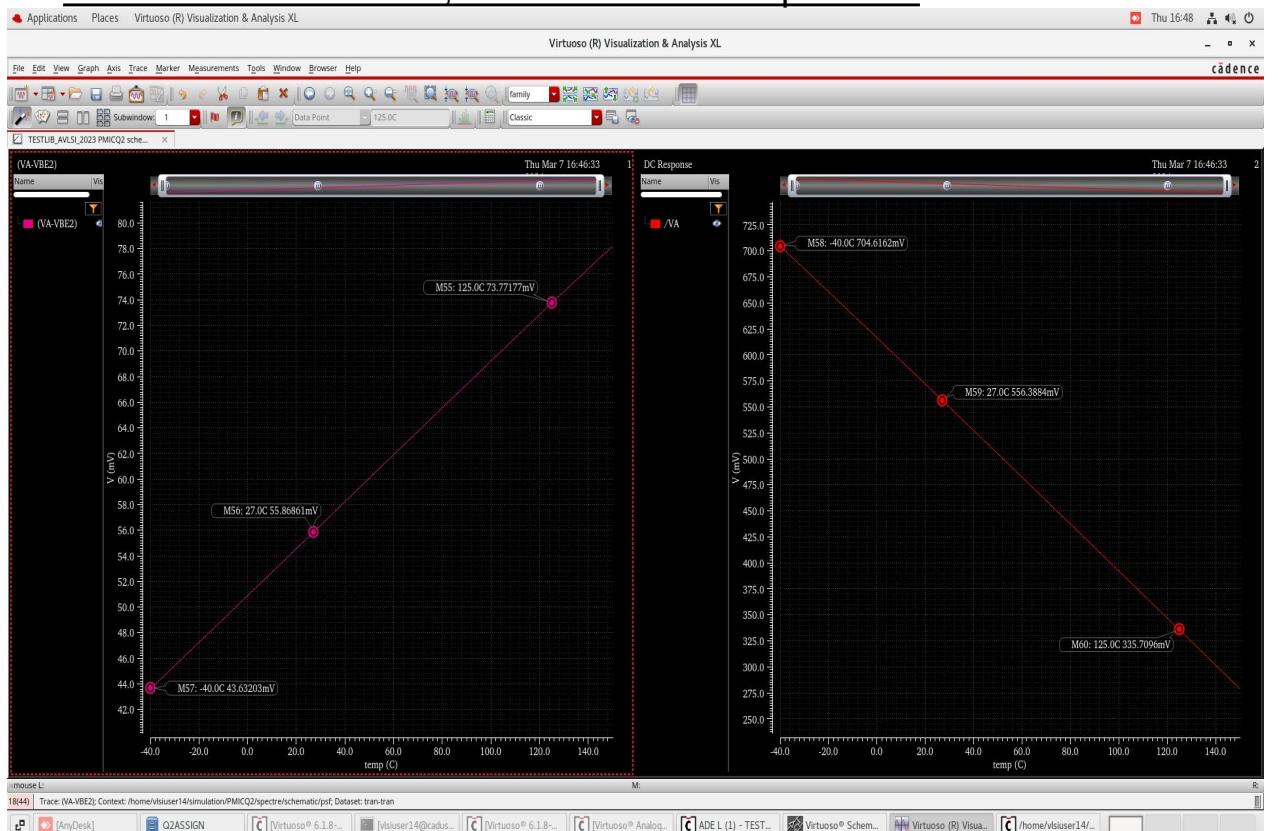
● ADE XL and ADE L Settings



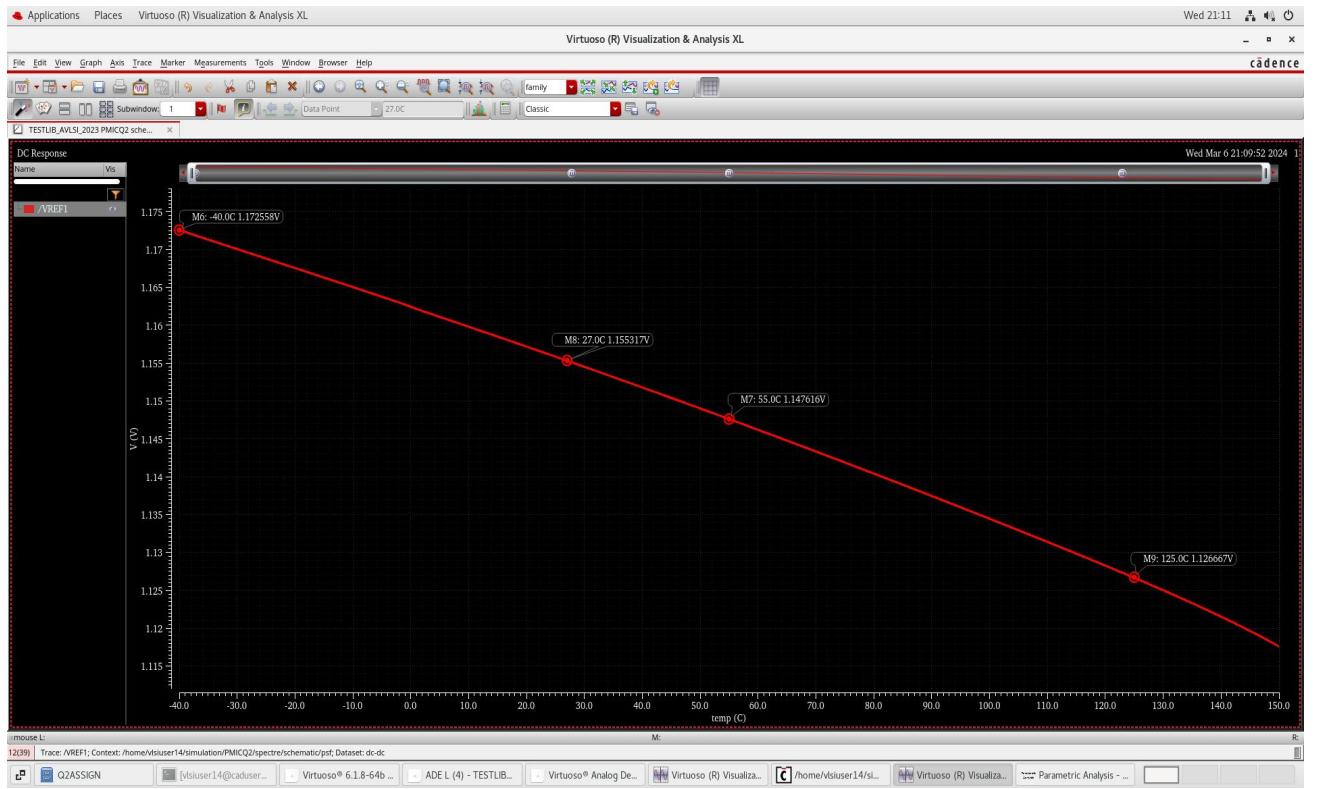
● Waveform of VA,IBIAS,VREF,VA-VBE2 at Different Temperature



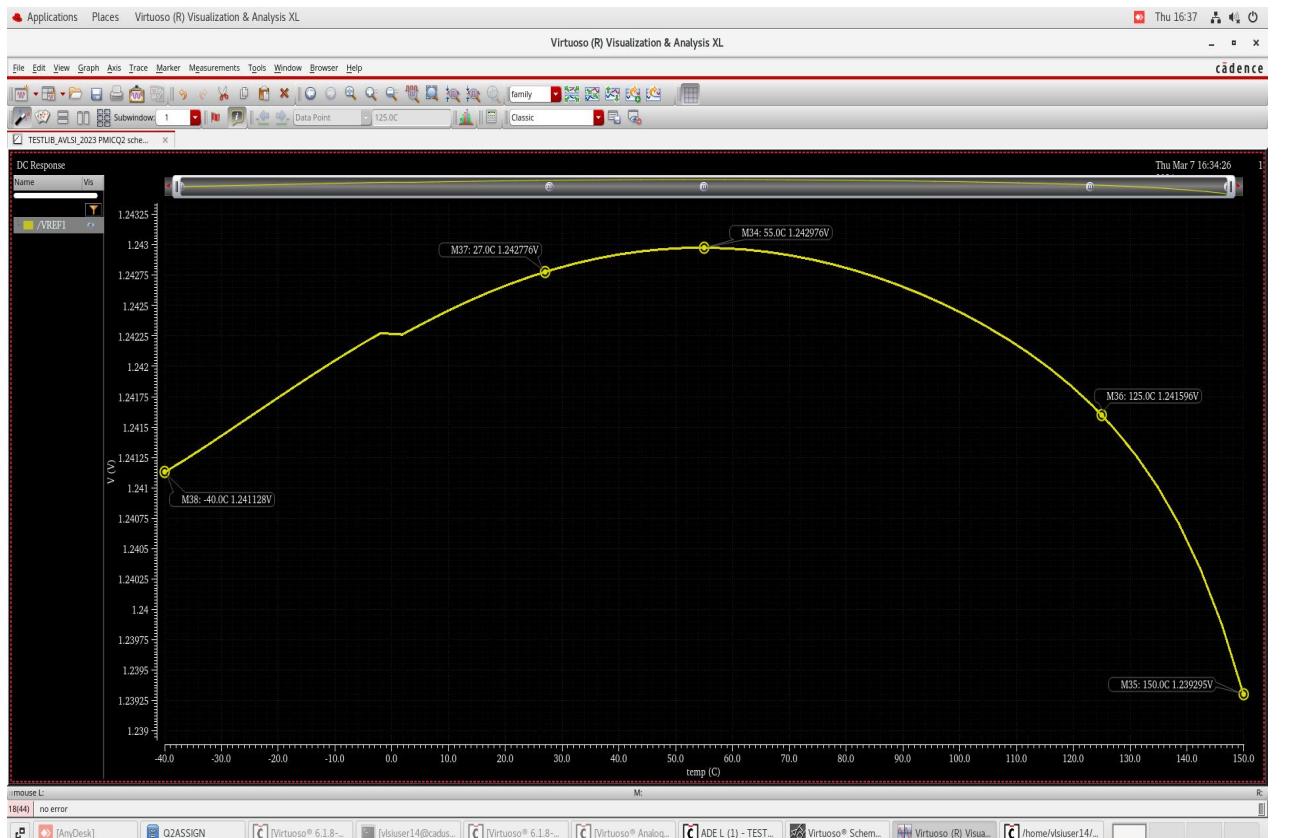
● Waveform of VA-VBE2,VA at Different Temperature



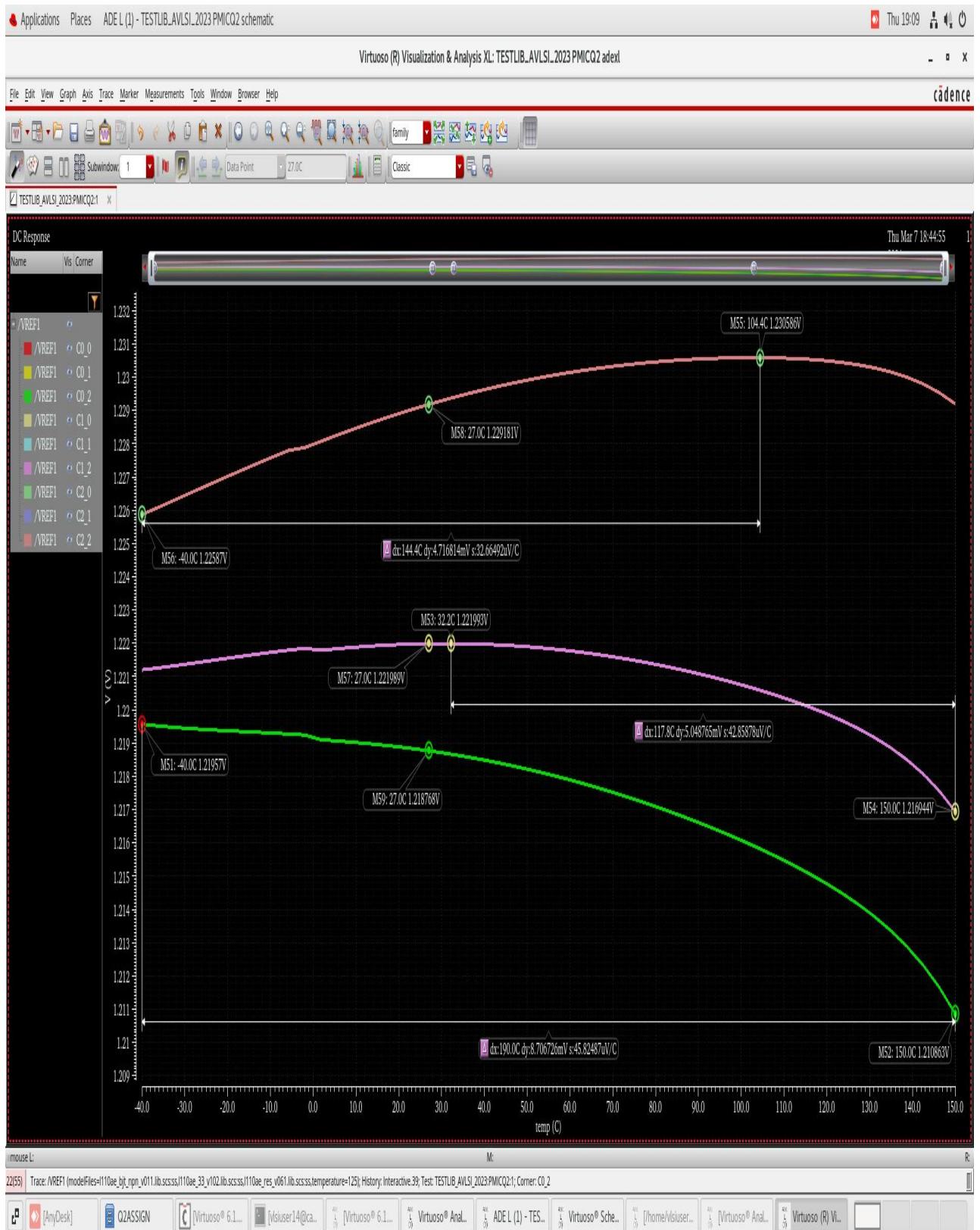
● Waveform at VREF=3V for R2 =5.7MOhm



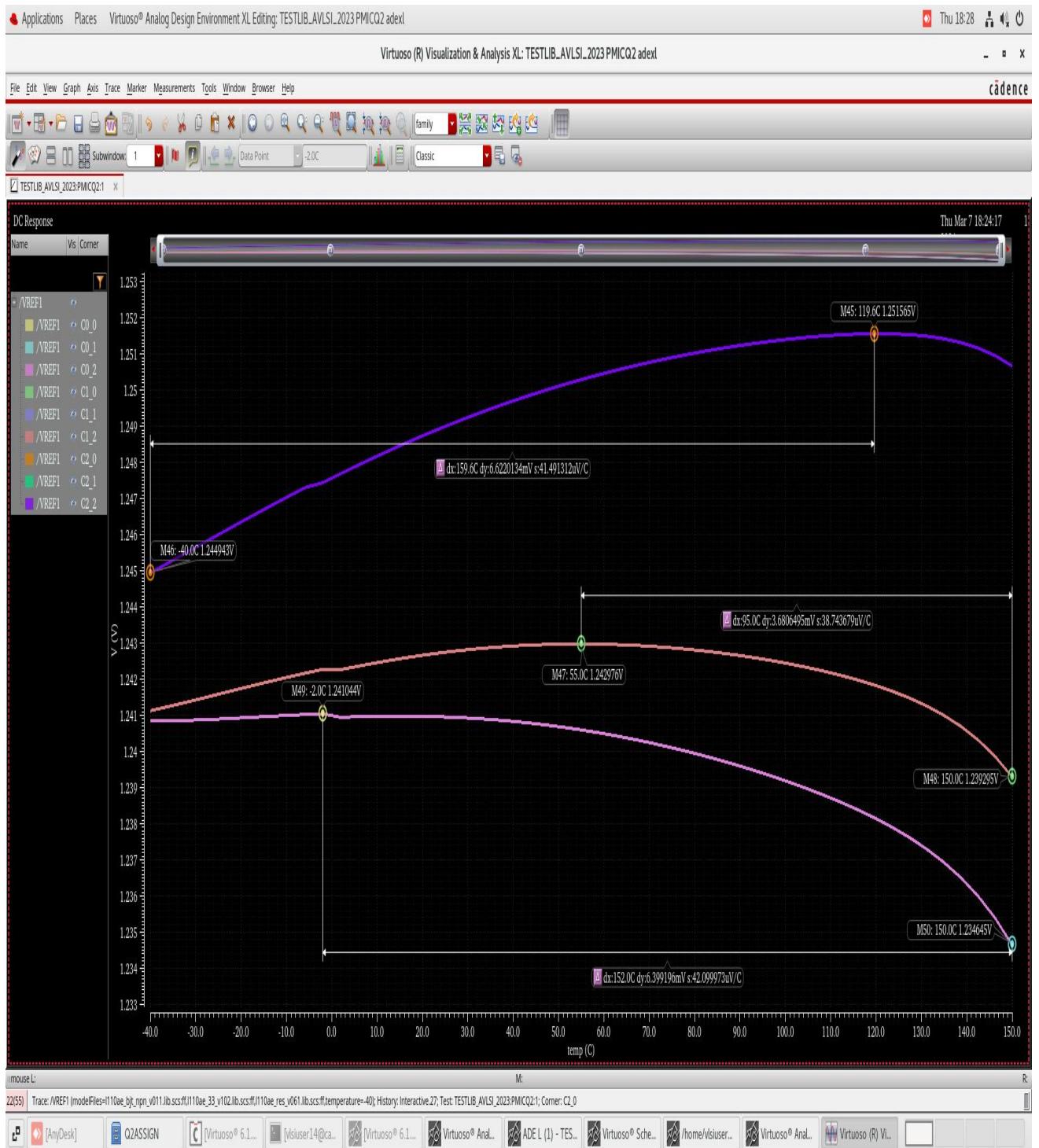
● Waveform of VREF=3V at TT Corner Different Temperature



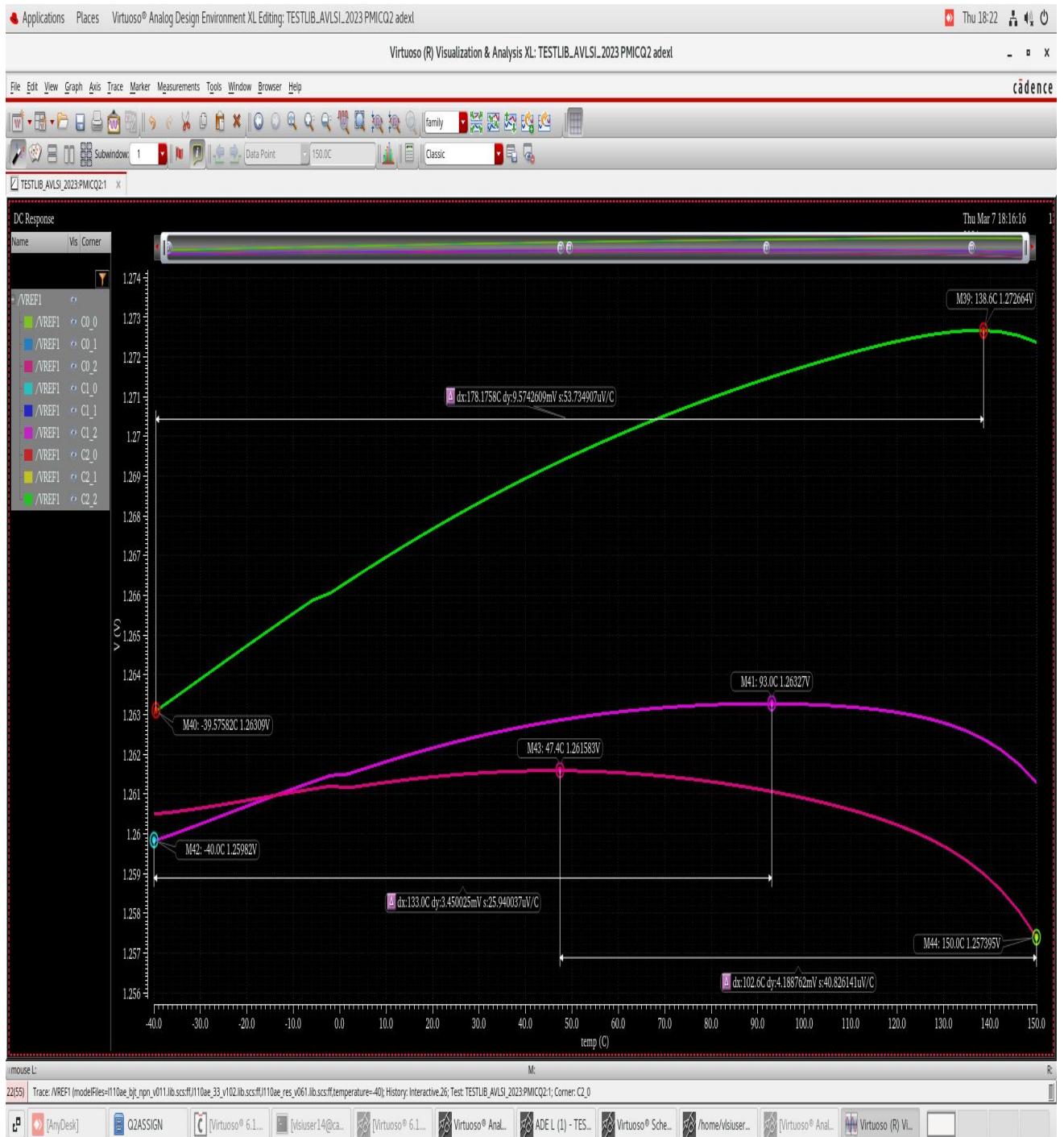
- Waveform of VREF=2.4V with Temperature Sweep at SS,TT,FF Corner and VMAX and VMIN Calculation



- Waveform of VREF=3V with Temperature Sweep at SS,TT,FF Corner VMAX and VMIN Calculation



- Waveform of VREF=3.6V with Temperature Sweep at SS,TT,FF Corner and VMAX and VMIN Calculation



- Observation Table

Q2 BANDGAP VOLTAGE REFERENCE (CIRCUIT 1)

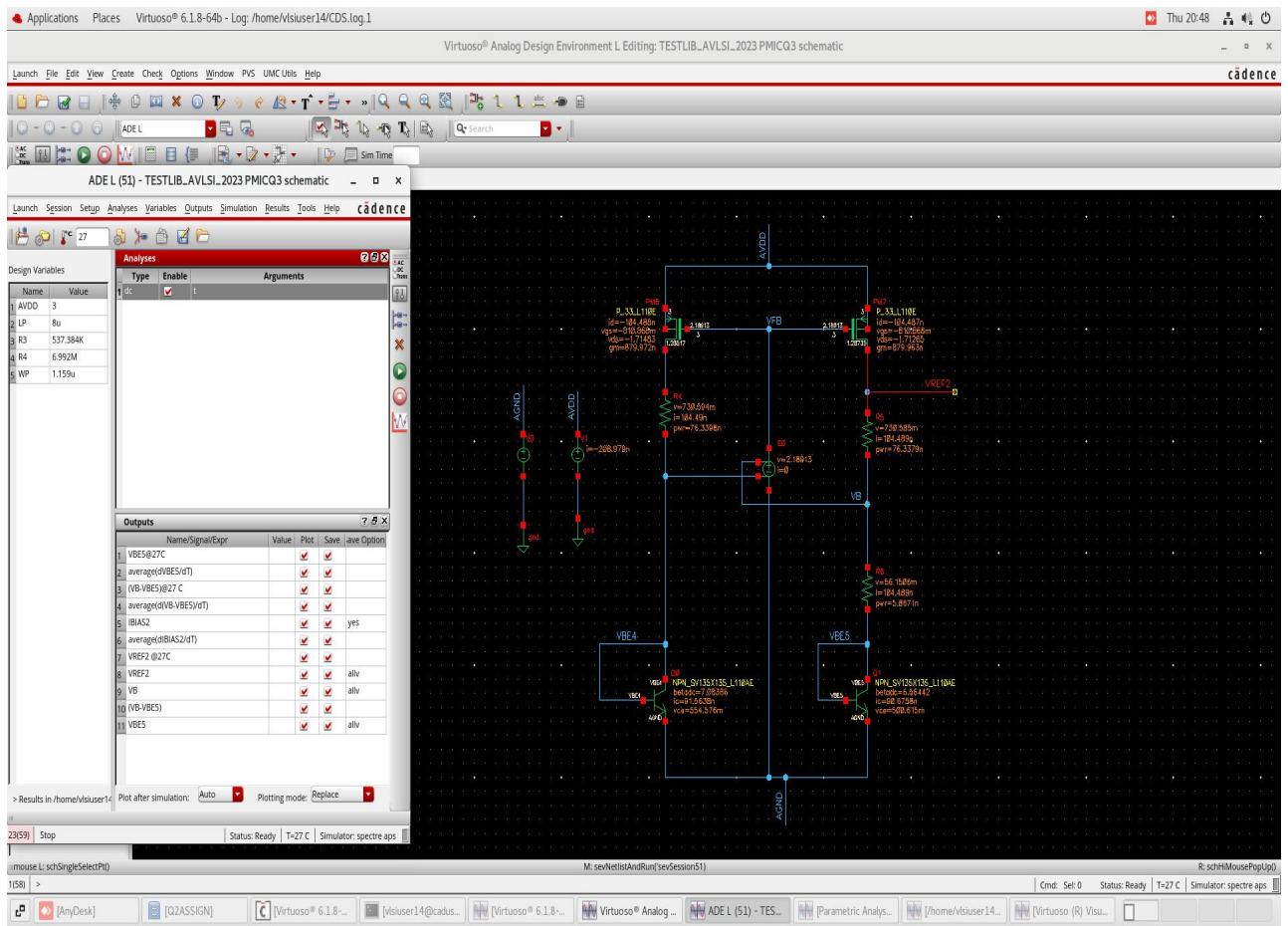
		Slow			Typical			Fast		
AVDD		2.4V	3.0V	3.6 V	2.4V	3.0V	3.6V	2.4 V	3.0 V	3.6 V
VBE3	@ 27°C (mV)	496.9	497.665	498.355	499.955	500.669	501.324	507.168	507.848	508.482
average (dVBE3/dT)	mV/C	-2.44732	-2.44696	-2.44646	-2.42167	-2.42132	-2.42079	-2.38131	-2.38095	-2.38035
(VA - VBE2)	@ 27°C (mV)	54.5389	55.9631	57.2701	54.5358	55.8686	57.1152	54.5172	55.7918	57.0028
average d(VA - VBE2)/dT	uV/°C	181.477	182.293	183.405	181.222	182.005	183.18	181.076	181.842	183.114
R1	kOhm	537.369								
R2	kOhm	6560								
IBIAS1 (nA)	@ 27°C (nA)	101.709	104.726	107.525	101.732	104.561	107.229	101.729	104.44	107.033
average (dIBIAS1/dT)	pA/C	338.557	340.356	342.584	338.2	339.945	342.309	338.085	339.813	342.376
VREF1 (V)	@ 27°C	1.21877	1.24094	1.2615	1.22199	1.24278	1.26237	1.22918	1.2491	1.26814
VREF1_Max (V)	(V)	1.21957	1.241044	1.261583	1.221993	1.242976	1.26327	1.230586	1.251565	1.272664
VREF1_Min (V)	(V)	1.210863	1.234645	1.257395	1.216944	1.239295	1.25982	1.22587	1.244943	1.26309
(VREF1_Max - VREF1_Min)	(mV)	8.71	6.399	4.188	5.049	3.68	3.45	4.716	6.622	9.574
VREF1 Temp Co	ppm/°C	37.5887	27.1376	17.4718	21.7462	15.5823	14.3737	20.1701	27.8472	39.5937

- Formula

$$\text{VREF1 Temp-Co} = [\text{VREF1}_\text{Max} - \text{VREF1}_\text{Min}] * 10^6 / [\text{Tmax} - \text{Tmin}] / \text{VREF1}_\text{Max}$$

(Q3) BANDGAP VOLTAGE REFERENCE (CIRCUIT 2)

Schematic and DC Operating Point



Calculation of Width Wn and Wp and R3 and R4

Given; $A V_{DD} = 3V$; $V_{ov} = 0.2V$; $L = 8\mu m$; $I_{BIAS} = 100nA$
 $\text{NMOS: } K_{fit} = 0.7733$ $\text{PMOS: } K_{fit} = 0.7733$
 $\text{at } 27^\circ C$

$$\begin{aligned}\text{NMOS: } K_{fit} &= 0.7733 \\ \mu_n &= 0.0363 \text{ M}^2/\text{V/s} \\ C_{ox} &= 4.6 \times 10^{-3} \text{ F/m}^2\end{aligned}$$

$$\begin{aligned}\text{PMOS: } K_{fit} &= 0.7733 \\ \mu_p &= 0.0097 \text{ M}^2/\text{V/s} \\ C_{ox} &= 4.6 \times 10^{-3} \text{ F/m}^2\end{aligned}$$

NMOS
• In saturation;

$$\rightarrow I_{Bias_n} = K_{fit} \frac{\mu_n}{2} C_{ox} \left(\frac{W}{L}\right)_n V_{ov}^2$$

$$\therefore \frac{10^{-7} \times 2}{0.7733 \times 0.0363 \times 4.6 \times 10^{-3} \times (0.2)^2} = \left(\frac{W}{L}\right)_n$$

$$\therefore \left(\frac{W}{L}\right)_n = 38721.978 \mu m$$

$$W_n = 38721.978 \times 8 \times 10^6 \times 10^{-6}$$

$$\boxed{W_n = 309.776 nm}$$

PMOS
In saturation,

$$\rightarrow I_{Bias_p} = K_{fit} \frac{\mu_p}{2} C_{ox} \left(\frac{W}{L}\right)_p V_{ov}^2$$

$$\frac{10^{-7} \times 2 \times 8 \times 10^{-6}}{0.7733 \times 0.0097 \times 4.6 \times 10^{-3} \times (0.2)^2} = \left(\frac{W}{L}\right)_p$$

$$\left(\frac{W}{L}\right)_p = 144.908 \times 10^{-3}$$

$$\boxed{W_p = 1.449 \mu m}$$

$$\beta_n = \mu_n C_{ox} \left(\frac{W}{L}\right)_n K_{fit}$$

$$= 0.7733 \times 0.0363 \times 4.6 \times 10^{-3} \times 38.7219 \times 10^{-3}$$

$$\boxed{\beta_n = 5 \times 10^{-6}}$$

SOLⁿ Q3

$$\rightarrow R_3 = \frac{V_T \ln(8)}{I_{BIAS2}}$$

$$= \left(\frac{kT}{q}\right) \frac{\ln(8)}{I_{BIAS2}}$$

$$= \frac{1.38 \times 10^{-23} \times 300 [\ln(8)]}{2.602 \times 10^{-19} \times 200 \times 10^9}$$

R₃ = 537.384 kΩ

$$\Rightarrow R_4 = R_3 \left[\left(\frac{\partial V_{BE5}}{\partial T} \right) \frac{Q}{k \ln(8)} - 1 \right]$$

$$\& V_{REF} = I_T (R_3 + R_4) + V_{BE5}$$

$$= \frac{V_T (R_3 + R_4) \ln(8)}{R_3} + V_{BE5}$$

$$\therefore V_{REF} = \left(1 + \frac{R_4}{R_3} \right) V_T \ln(8) + V_{BE5}$$

$$\rightarrow \frac{\partial V_{REF}}{\partial T} = \left(1 + \frac{R_4}{R_3}\right) \frac{k}{q} \ln(8) + \frac{\partial V_{BEs}}{\partial T}$$

Here $V_{BEs} = V_T \ln\left(\frac{I_C}{n I_S}\right)$ & $\frac{\partial V_{REF}}{\partial T} = 0$ (Given)

$$0 = \left(1 + \frac{R_4}{R_3}\right) \frac{k}{q} \ln(8) + \frac{V_{BEs} - (1+n)T + E_g}{T}$$

$$\therefore \left[1 + \frac{R_4}{R_3}\right] = \frac{-0.4818 + \left(h - \frac{3}{2}\right)(300) + \frac{1.129}{2}}{\frac{2.38 \times 10^{-23}}{2.602 \times 10^{-19}} \times \ln(8) \times 3}$$

~~$1 + \frac{R_4}{R_3} = 24.01118$~~

$$\therefore R_4 = 6.992 \text{ M}\Omega$$

~~$\text{Given; } V_{BEs} = V_T \ln\left(\frac{I_C}{n I_S}\right)$~~

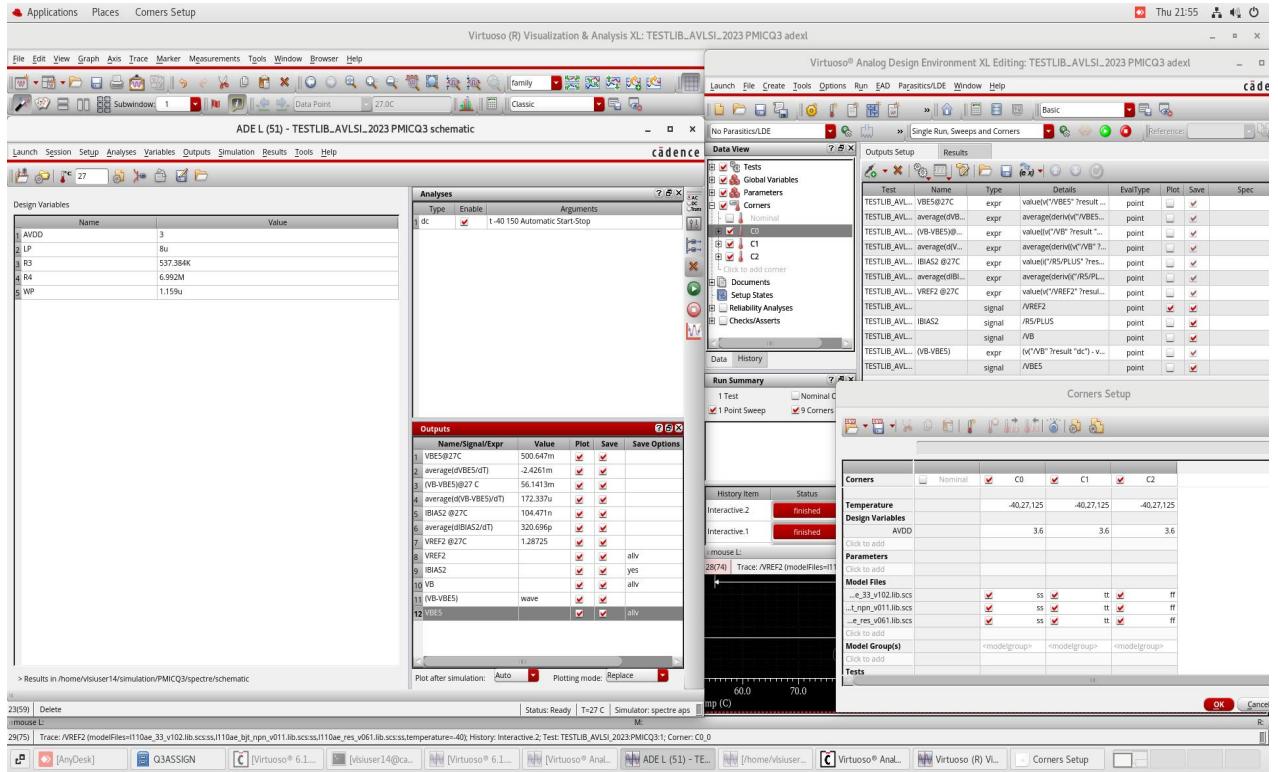
$$= \frac{kI}{q} \ln\left(\frac{10^{-7}}{8 \times 10^{-16}}\right)$$

$$= \frac{2.38 \times 10^{-23} \times 300}{2.602 \times 10^{-19}} \ln\left(\frac{10^{-7}}{8 \times 10^{-16}}\right)$$

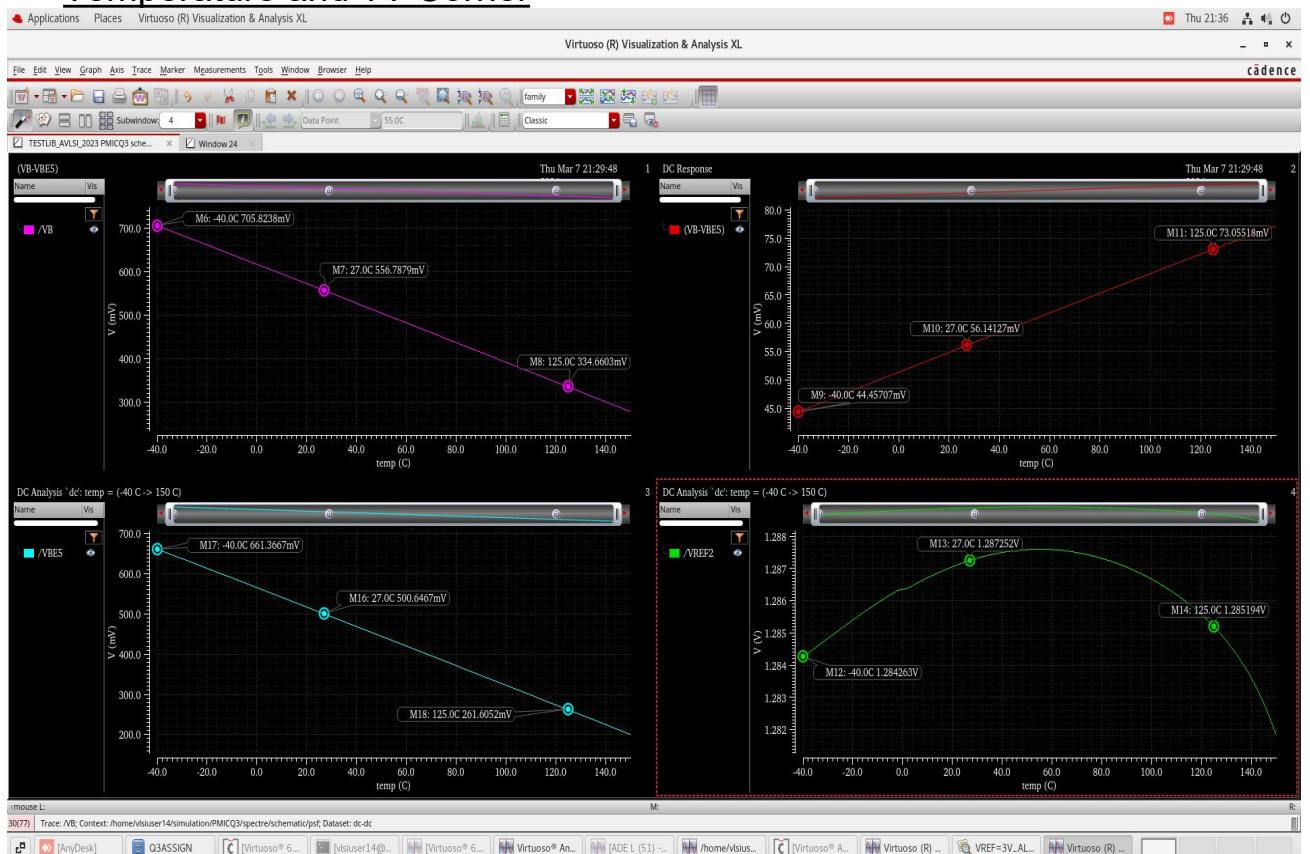
$$V_{BEs} = 0.4818$$

$$\text{So, } R_4 = 6.992 \text{ M}\Omega \quad \& \quad R_3 = 537.384 \text{ k}\Omega$$

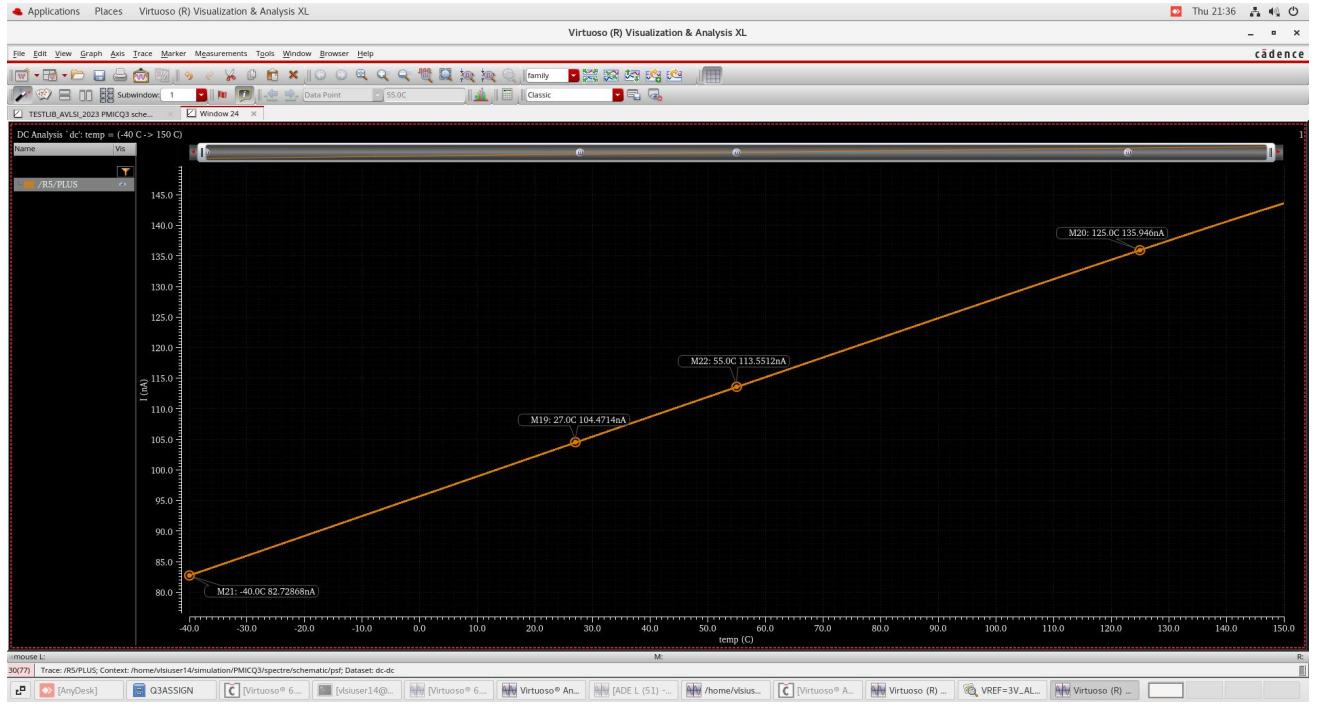
● ADE XL and ADE L Settings



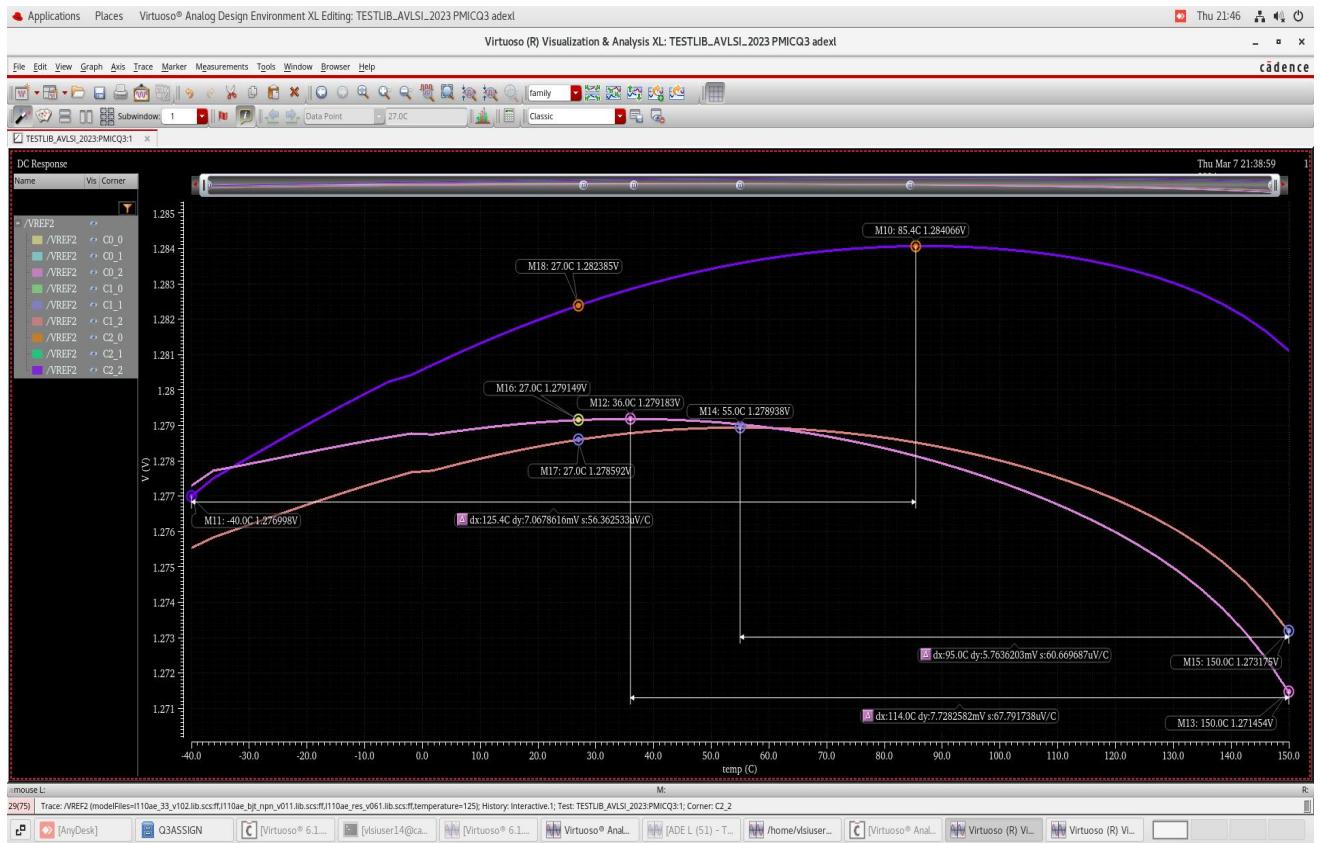
● Waveform of VB,VBE5,VB-VBE5,VREF2 at Different Temperature and TT Corner



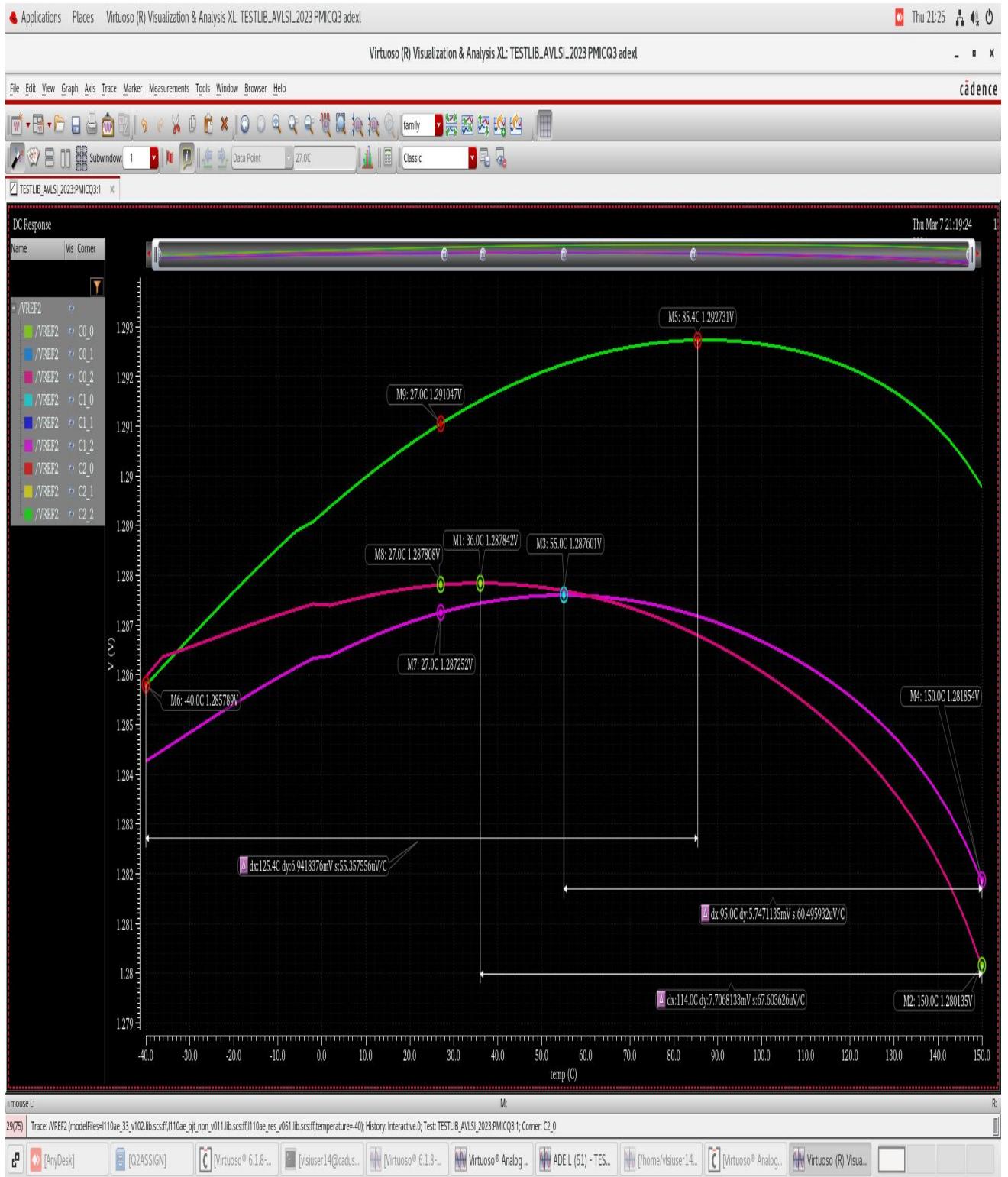
● Waveform of IBIAS at Different Temperature and TT Corner



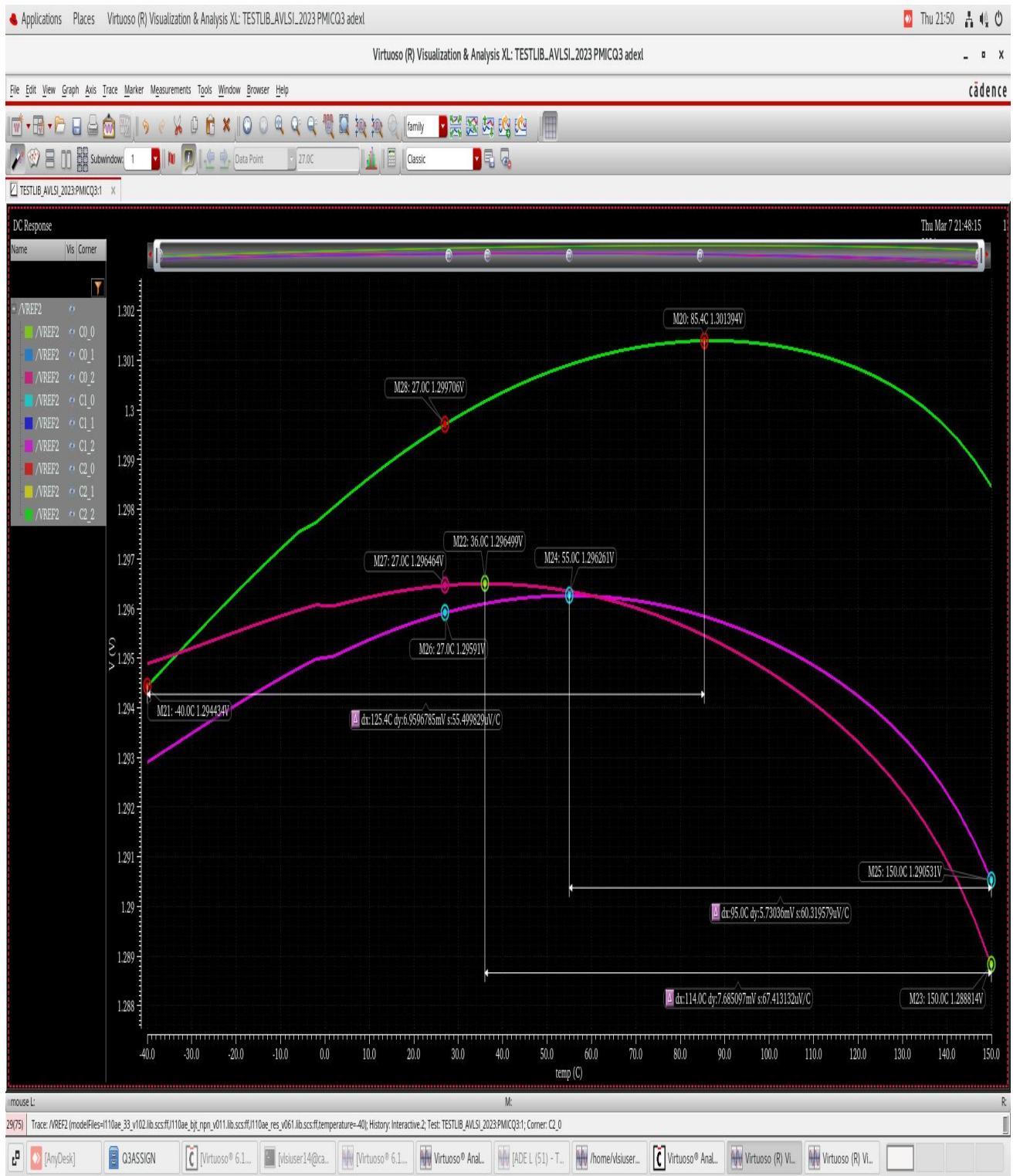
● Waveform of VREF=2.4V with Temperature Sweep at SS,TT,FF Corner and VMAX and VMIN Calculation



- Waveform of VREF=3.0V with Temperature Sweep at SS,TT,FF Corner and VMAX and VMIN Calculation



- Waveform of VREF=3.6V with Temperature Sweep at SS,TT,FF Corner and VMAX and VMIN Calculation



- Observation Table

Q3 BANDGAP VOLTAGE REFERENCE (CIRCUIT_2)

		Slow			Typical			Fast		
AVDD		2.4V	3.0V	3.6V	2.4V	3.0V	3.6V	2.4V	3.0V	3.6V
VBE5	@ 27°C(mV)	497.438	497.717	497.993	500.368	500.647	500.922	507.469	507.747	508.022
average (dVBE5/dT)	mV/C	-2.45171	-2.45169	-2.45162	-2.42613	-2.4261	-2.42607	-2.38595	-2.38591	-2.38588
(VB - VBE5)	mV@ 27C (V)	55.7919	56.39	56.9881	55.543	56.1413	56.7395	55.307	55.9053	56.5037
average d(VA - VBE5)/dT	uV/°C	172.841	172.849	172.802	172.343	172.337	172.347	171.87	171.849	171.857
R3	kOhm						537.384			
R4	kOhm						6992			
IBIAS2 (nA)	@ 27°C	103.821	104.934	106.047	103.358	104.471	105.585	102.919	104.032	105.146
average (dIBIAS2/dT)	pA/C	321.635	321.649	321.562	320.707	320.696	320.715	319.827	319.789	319.804
VREF2 (V)	@ 27°C	1.27915	1.28781	1.29646	1.27859	1.28725	1.29591	1.28239	1.29105	1.29971
VREF2_Max (V)		1.279183	1.287842	1.296499	1.278938	1.287601	1.296261	1.284066	1.292731	1.301394
VREF2_Min (V)		1.271454	1.280135	1.288814	1.273175	1.281854	1.290531	1.276998	1.285789	1.294434
(VREF2_Max - VREF2_Min) (mV)		7.729	7.707	7.685	5.763	5.747	5.73	7.068	6.942	6.96
VREF2 Temp CO	ppm/°C	31.8007	31.497	31.1974	23.7162	23.4912	23.2653	28.9705	28.2633	28.1479

- Formula

$$\text{VREF1 Temp-Co} = [\text{VREF1}_\text{Max} - \text{VREF1}_\text{Min}] * 10^6 / [\text{Tmax} - \text{Tmin}] / \text{VREF1}_\text{Max}$$