Chapter 7

Bandgap Reference Circuit

Reference voltages or currents that exhibit little dependence on temperature prove essential in many analog circuits. It is interesting to note that, since most process parameters vary with temperature, if a reference is temperature-independent, then it is usually process-independent as well.

In order to generate a quantity that remains constant with temperature, we postulate that if two quantities having opposite temperature coefficients (TCs) are added with proper weighting, the result displays a zero TC. For example, for two voltages V_1 and V_2 that vary in opposite direction with temperature, we choose α_1 and α_2 such that $\alpha_1 \frac{\partial V_1}{\partial T} + \alpha_2 \frac{\partial V_2}{\partial T} = 0$, obtaining a reference voltage, $V_{REF} = \alpha_1 V_1 + \alpha_2 V_2$, with zero TC.

7.1 Negative-TC Voltage

The base-emitter voltage of bipolar transistors or, more generally, the forward voltage of a *pn*-junction diode exhibits a negative TC. For a bipolar device, we can write $I_C = I_S \exp(V_{BE}/V_T)$, where $V_T = KT/q$. The saturation current I_S is proportional to $\mu k T n_i^2$, where μ denotes the mobility of minority carriers and n_i is the intrinsic minority carrier concentration of silicon. The temperature dependence of these quantities is represented as $\mu \propto \mu_0 T^m$, where $m \approx -3/2$, and $n_i^2 \propto T^3 \exp[-E_g/(kT)]$, where $E_g \approx 1.12 eV$ is the Bandgap energy of silicon. Thus,

$$I_S = bT^{4+m} \exp\left(\frac{-E_g}{kT}\right) \tag{7.1}$$

where b is a proportionality factor. Writing $V_{BE} = V_T \ln\left(I_C / I_S\right)$, we can now compute the TC of the base-emitter voltage. In taking the derivative of V_{BE} with respect to T, we must know the behaviour of I_C as a function of temperature. To simplify the analysis, we assume that I_C is held constant. Thus,

$$\frac{\partial V_{BE}}{\partial T} = \frac{\partial V_T}{\partial T} \ln \frac{I_C}{I_S} - \frac{V_T}{I_S} \frac{\partial I_S}{\partial T} \tag{7.2}$$

From (7.1), we have

$$\frac{\partial I_S}{\partial T} = b(4+m)T^{3+m} \exp\left(\frac{-E_g}{kT}\right) + bT^{4+m}\left(\exp\frac{-E_g}{kT}\right)\left(\frac{E_g}{kT^2}\right) \tag{7.3}$$

Therefore,

$$\frac{V_T}{I_S} \frac{\partial I_S}{\partial T} = (4+m)\frac{V_T}{T} + \frac{E_g}{kT^2} V_T \tag{7.4}$$

From equations (7.2) and (7.4), we can write

$$\frac{\partial V_{BE}}{\partial T} = \frac{V_T}{T} \ln \frac{I_C}{I_S} - (4+m)\frac{V_T}{T} - \frac{E_g}{kT^2} V_T$$

$$= \frac{V_{BE} - (4+m)V_T - E_g / q}{T} \tag{7.5}$$

Equation (7.5) gives the temperature coefficient of the base-emitter voltage at a given temperature T, revealing dependence on the magnitude of V_{BE} itself. With $V_{BE} \approx 750mV$ and $T = 300K, \dfrac{\partial V_{BE}}{\partial T} \approx -1.5mV / K$.

We note that the temperature coefficient of V_{BE} itself depends on the temperature, creating error in constant reference generation if the positive-TC quantity exhibits a *constant* temperature coefficient.

7.2 Positive-TC Voltage

If two bipolar transistors operate at unequal current densities, then the difference between their base-emitter voltages is directly proportional to the absolute temperature. As shown in Fig. 7.2.1, if two identical transistors ($I_{S1} = I_{S2}$) are biased at collector currents of nI_0 and I_0 and their base currents are negligible, then

$$\begin{aligned}\Delta V_{BE} &= V_{BE1} - V_{BE2} \\ &= V_T \ln\left(\frac{nI_0}{I_{S1}}\right) - V_T \ln\left(\frac{I_0}{I_{S2}}\right) \\ &= V_T \ln n\end{aligned}$$

Thus, the V_{BE} difference exhibits a positive temperature coefficient, given by:

$$\frac{\partial \Delta V_{BE}}{\partial T} = \frac{k}{q} \ln n$$

Interestingly, this TC is independent of the temperature or behaviour of the collector currents.

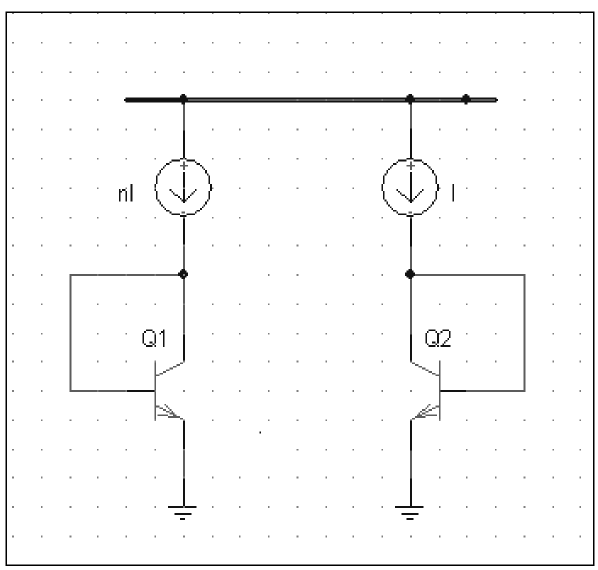

Fig. 7.2.1 Generation of PTAT voltage

7.3 Bandgap Reference

With the negative- and positive- TC voltages obtained above, we can now develop a reference having nominally zero temperature coefficient. To generate a Bandgap reference voltage, we use the circuit shown in fig 7.3.1.

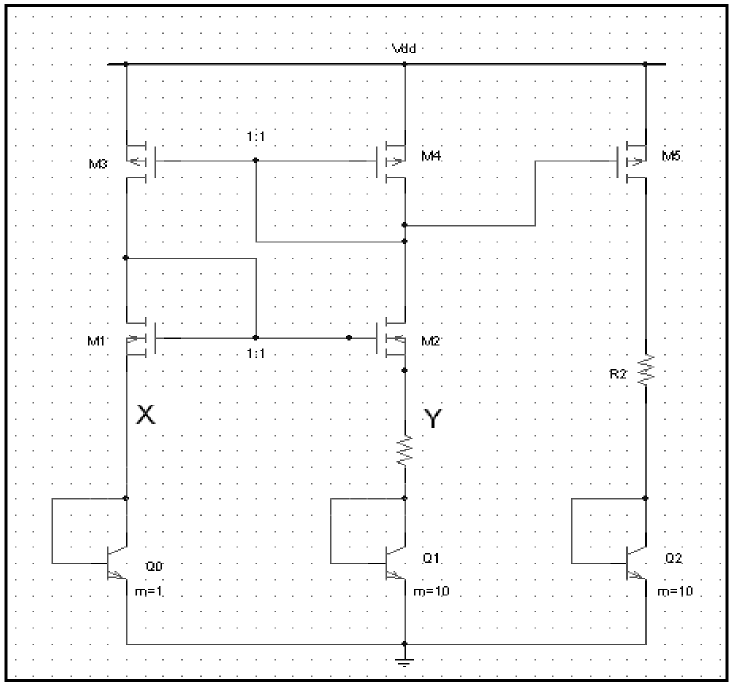

Fig. 7.3.1 Bandgap Reference Voltage Circuit

In our circuit, the transistor pairs M1-M2 and M3-M4 are identical. This makes $I_{D1}=I_{D2}$ and hence $\mathbf{V_x=V_Y}$.

Using suitable transistor sizes, we obtain a current of approximately 10.5 µA in each branch. To be more accurate, the current values obtained after simulation are: - $\mathbf{I_{D1} = 10.5\ \mu A}$

$\mathbf{I_{D2} = 10.68\ \mu A}$

Size of transistor M5 is 3 times that of M3 and M4.

Therefore, $\mathbf{I_{D5} \approx 3I_{D2}}$

On simulation, we obtain $\mathbf{I_{D5} = 31.78\ \mu A}$

Since, voltages at X and Y are approximately equal to

$\mathbf{V_X = 749.5\ mV}$ and $\mathbf{V_Y = 742.6\ mV}$

We assume that $V_X \approx V_Y = V_{BE0}$

Therefore, Voltage across R_1, $V_{R1} = V_{BE0} - V_{BE1}$

$$= \Delta V_{BE}$$

$$= V_T \ln n$$

Here n=10, since m=10 for Q1 and m=1 for Q0.

Therefore, current across R_1 can be indicated as:

$$I_{R1} = \frac{V_T \ln 10}{R_1}$$

Current through M5 is: $I_{D5} \approx 3I_{R1} = \dfrac{3V_T \ln 10}{R_1}$

Therefore, Voltage output, $V_{REF} = V_{BE2} + I_{D5}R_2$

$$= V_{BE2} + 3\left(\frac{V_T \ln 10}{R_1}\right)R_2 \qquad (7.6)$$

Differentiating with respect to temperature, we get:

$$\frac{\partial V_{REF}}{\partial T} = \frac{\partial V_{BE2}}{\partial T} + R_2 \frac{\partial I_{D5}}{\partial T}$$

Here, we assume that the temperature coefficient of R_2 is zero.

For zero TC of the Bandgap reference voltage, we need

$$\frac{\partial V_{REF}}{\partial T} = 0$$

Therefore, $$\frac{\partial V_{BE2}}{\partial T} + R_2 \frac{\partial I_{D5}}{\partial T} = 0 \qquad (7.7)$$

From simulation plots shown in fig.7.4.2, we obtain $\dfrac{\partial V_{BE2}}{\partial T} = -1.27763 mV/K$

Now, $$R_2 \frac{\partial I_{D5}}{\partial T} = \left(\frac{3k \ln 10}{q}\right)\left(\frac{R_2}{R_1}\right)$$

$$= \left(5.9505 \times 10^{-4}\right)\left(\frac{R_2}{R_1}\right) \text{ V/K}$$

From equation (7.7), we get $$\frac{R_2}{R_1} = \frac{1.27763 \times 10^{-3}}{5.9505 \times 10^{-4}} = 2.147$$

From equation (7.6), we get: $V_{REF} = V_{BE2} + I_{D5}R_2 = 1.2V$

or, $0.7179 + 31.78 \times 10^{-6} R_2 = 1.2$

or, $R_2 \approx 15k\Omega$

From equation (7.7), we get: $R_1 \approx 7k\Omega$

On selecting these values of R_1 and R_2, the simulation results showed the following discrepancies:

1. Voltages V_X and V_Y were very different.
2. V_{REF} had a slightly negative temperature coefficient.

To solve the above two problems, the value of R_1 is reduced and following several iterations we obtain zero TC for V_{REF} at 300K for **R_1 = 5 KΩ** & **R_2 = 12 KΩ**.

The plot in Fig.7.4.3 shows that though the voltage reference obtained is around 1.1112 V, it has nearly zero TC at T = 300K. In the curve shown in Fig. 7.4.3, we notice a finite curvature which may be due to many reasons, some of which are listed below:

1. Temperature variations of base-emitter voltages.
2. Temperature variations of collector currents.
3. Temperature variations of offset voltages.

7.4 Observations and Results

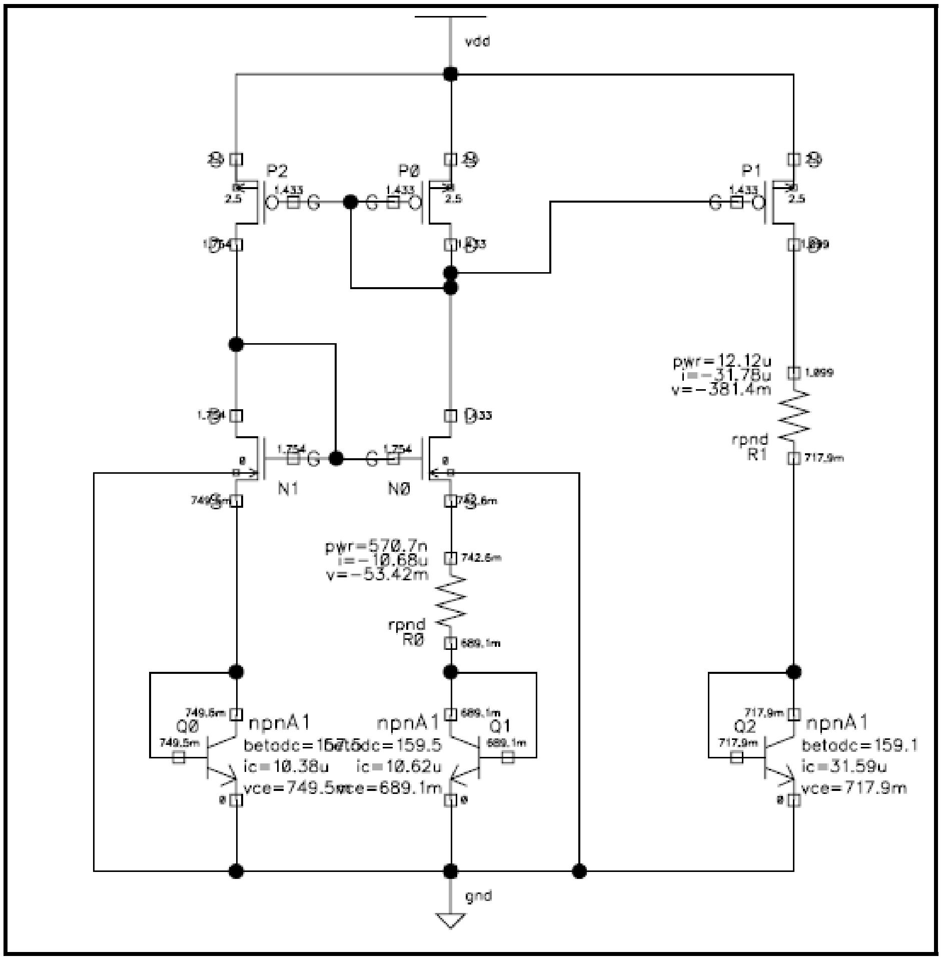

Fig.7.4.1 Schematic for 1.1 V Band-gap Voltage Reference Circuit

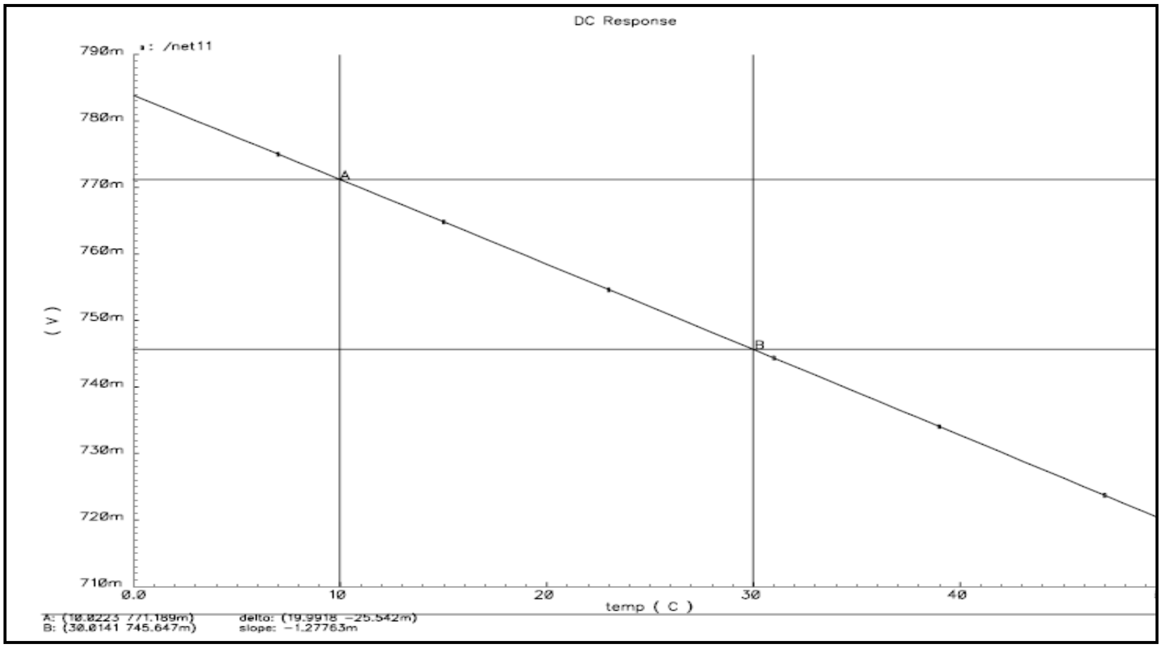

Fig.7.4.2 Variation of V_{be} with Temperature

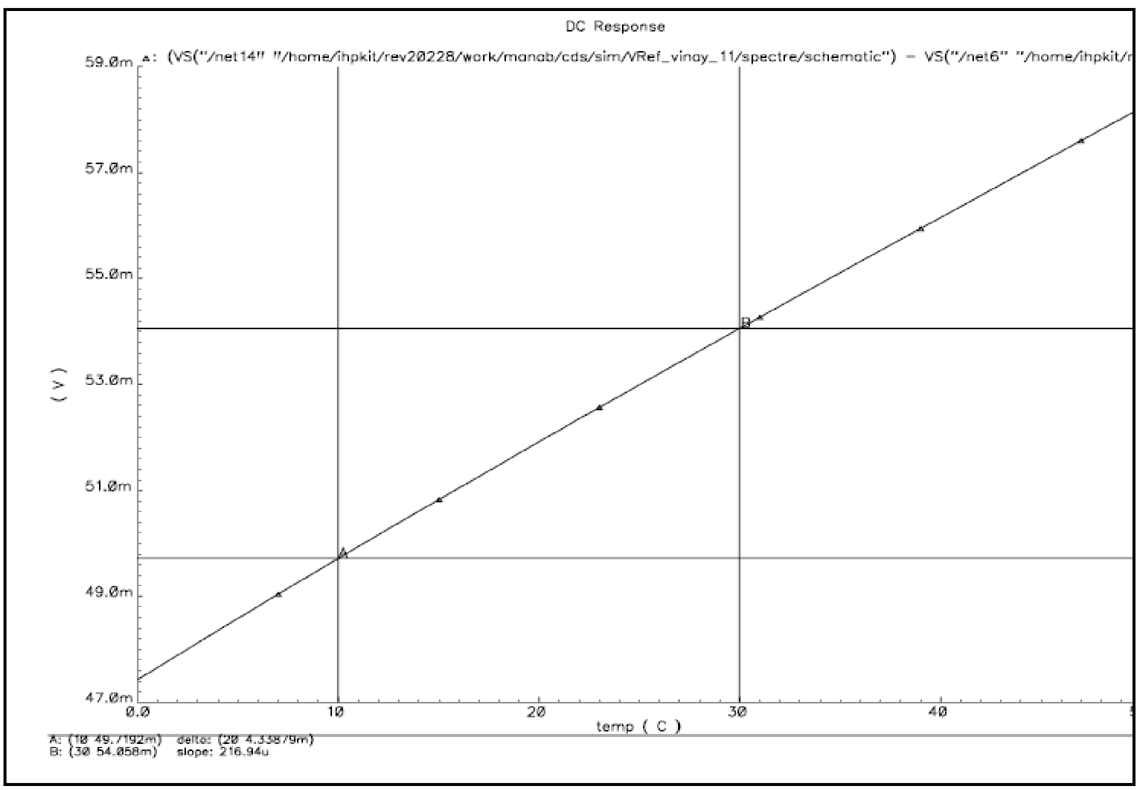

Fig.7.4.3 Variation of ΔV_{be} with Temperature

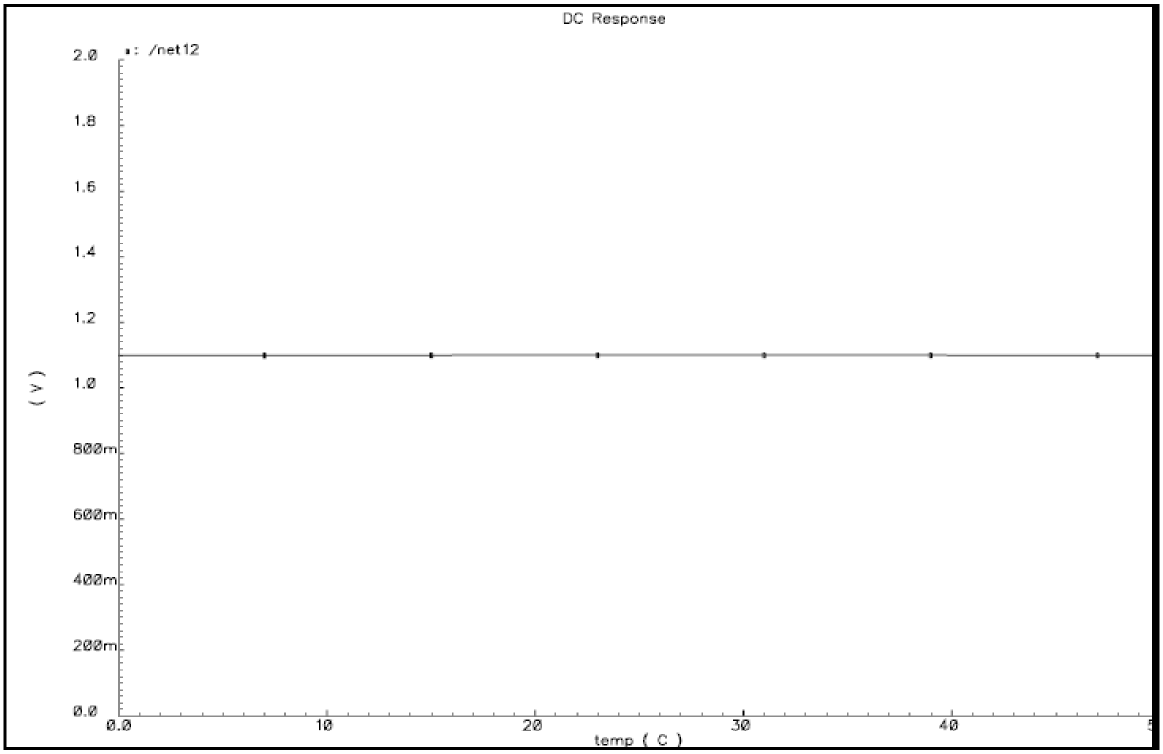

Fig.7.4.4 Variation of Output Reference voltage with Temperature

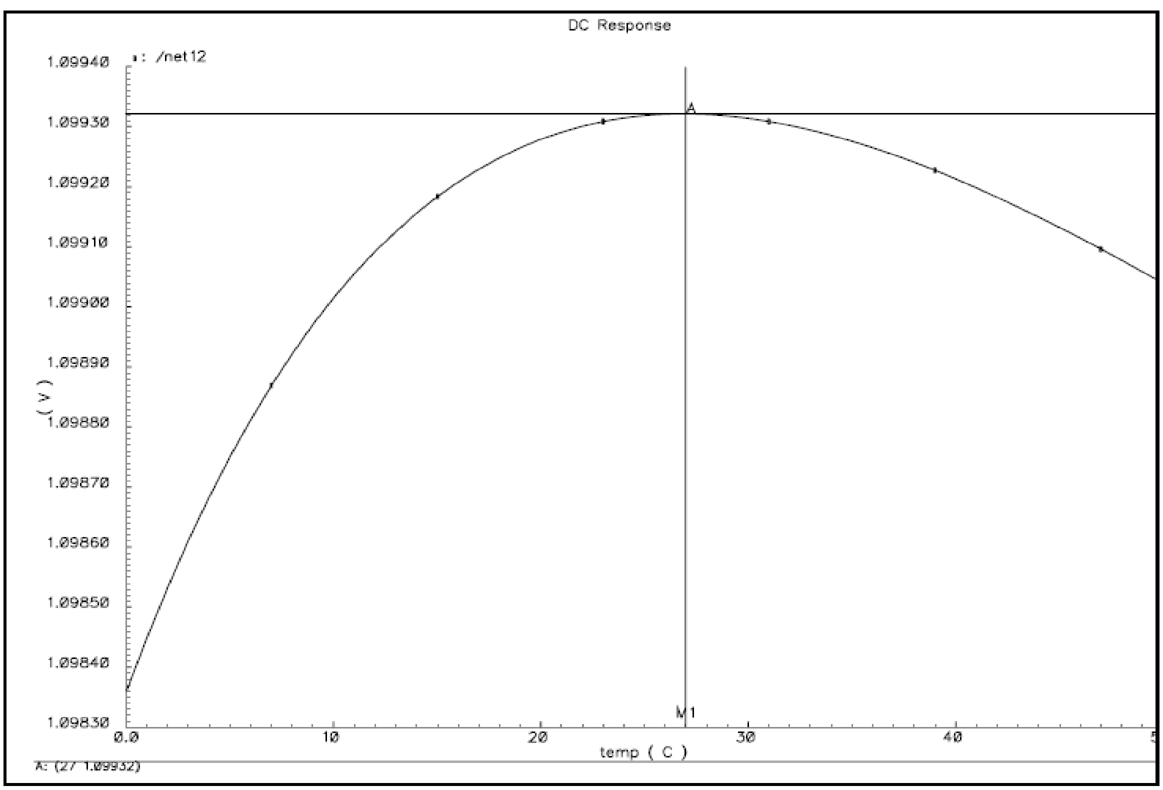

Fig.7.4.5 Magnified look into the variation of output reference voltage with Temperature