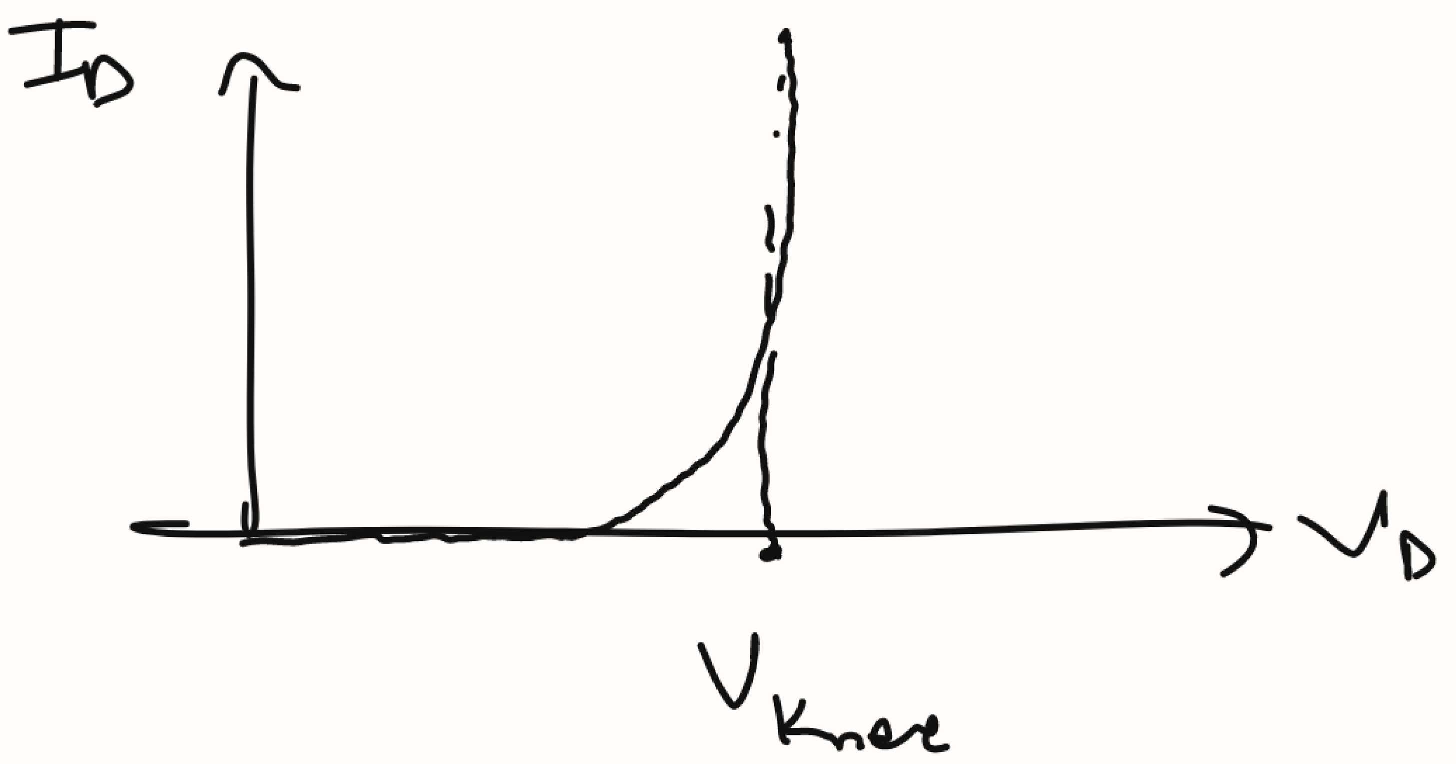
Voltage Mode BGR

⇒ (I) The basic Idea :-

→ The basic concept behind a BGR is, we need a Reference voltage / current which is constant with temperature. And the first thing that comes in mind is a diode. Let's look at the characteristics of a diode;



→ As we can see that I_D does not vary much with respect to voltage around V_{knee}. Let's analyse the diode through its equations.

$$I_D \cong I_S \, e^{V_{be}/V_T} \quad ; \text{ In forward bias.}$$

$$\therefore V_{be} = V_T \ln\left(\frac{I_D}{I_S}\right)$$

$$\rightarrow \quad V_{be} = \frac{K_b T}{q} \ln\left(\frac{I_D}{I_S}\right)$$

$\rightarrow$ Now, $I_s \propto \mu K_b T n_i^2$

$\rightarrow \mu \propto T^{-m}$, $n_i^2 \propto T^3 e^{-E_g/K_b T}$

$\therefore I_s \propto T^{(4-m)} e^{-E_g/K_b T}$

$\therefore$ Let $I_s = C e^{-E_g/K_b T} T^{(4-m)}$

$$\therefore V_{be} = \frac{K_b T}{q} \ln\left(\frac{I_D}{C e^{-E_g/K_b T} T^{(4-m)}}\right)$$

$$\therefore V_{be} = \frac{K_b T}{q} \left\{ \ln(I_D) - \ln(C) + \frac{E_g}{K_b T} - (4-m)\ln(T) \right\}$$

$$\therefore V_{be} = \frac{1}{q} \left\{ K_b T \ln(I_D) - K_b T \ln(C) + E_g - (4-m) K_b T \ln(T) \right\}$$

$$\therefore V_{be} = \frac{1}{q} \left\{ K_b T \ln\left(\frac{I_D}{C}\right) - (4-m) K_b T \ln(T) + E_g \right\}$$

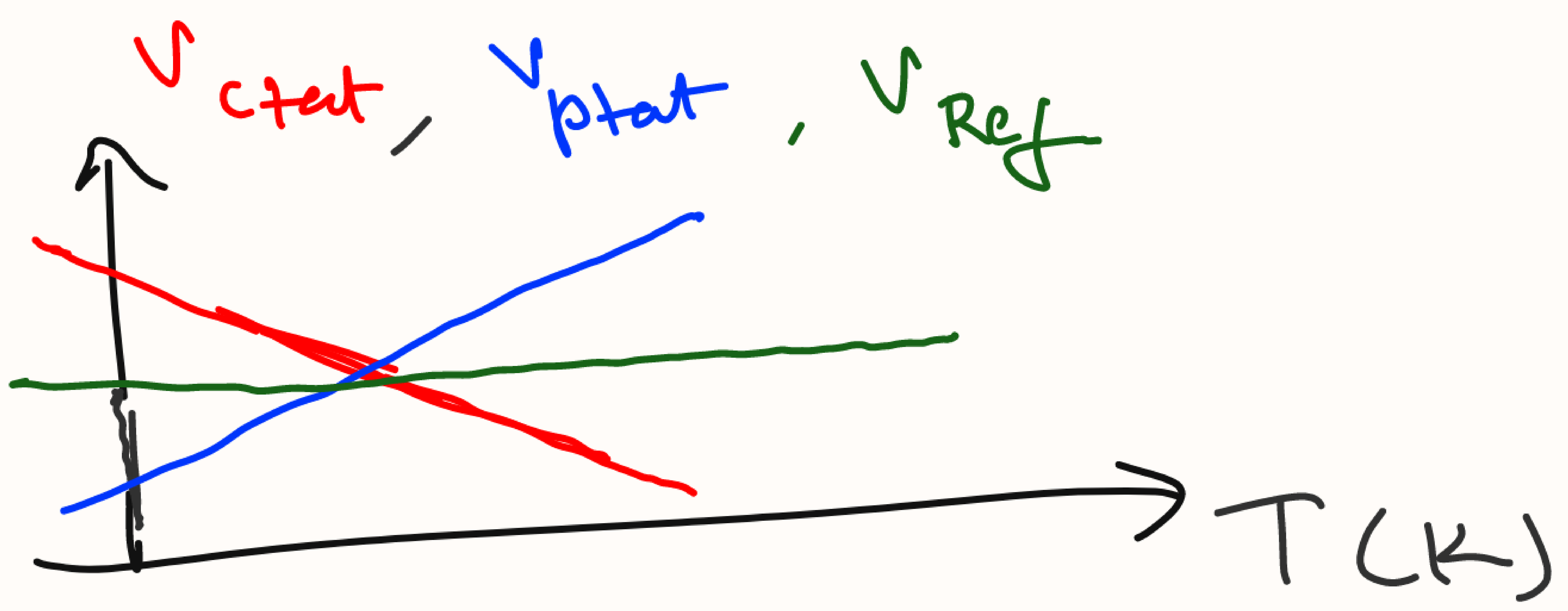
$\rightarrow E_g = E_{g_0} - \alpha T$

$$\therefore V_{be} = \frac{1}{q} \left\{ K_b T \ln\left(\frac{I_D}{C}\right) - (4-m) K_b T \ln(T) + E_{g_0} - \alpha T \right\} \quad \text{— (1)}$$

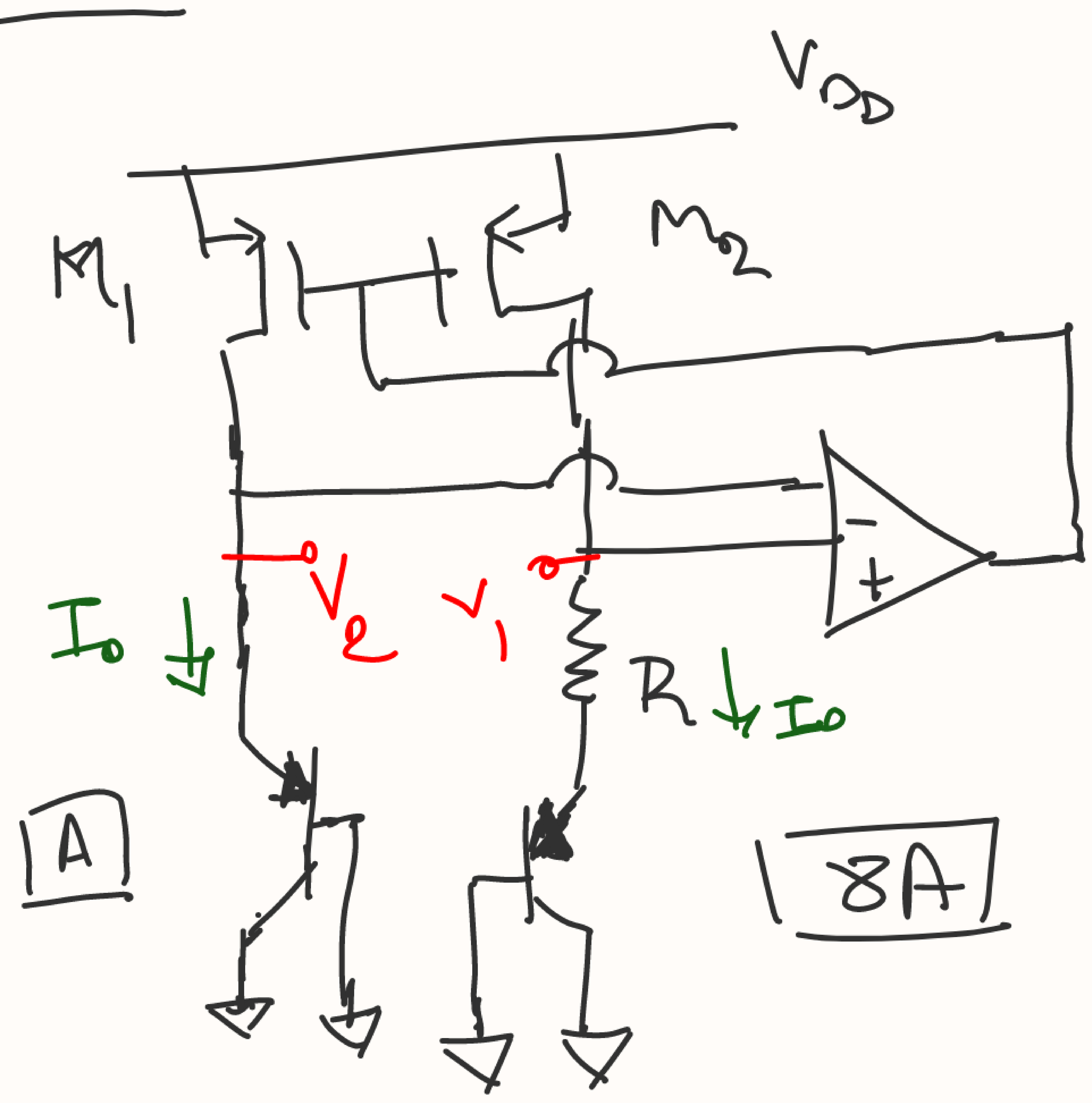
→ Clearly V_{be} is a CTAT (Complementary with absolute temperature) i.e. V_{be} reduces as temperature increases.

→ Also note that it is mostly a linear fashion of decrease with some amount of non-linearity.

→ Now to get a constant voltage reference the idea is to add a PTAT voltage (Proportional to absolute temperature) which has same slope.



⇒ Schematic :



→ Note that due to op-amp $V_1 = V_2$. Also V_{gs} of M_1 & M_2 are same so current flowing through both the branch is same.

→ Now, $V_2 = V_T \ln\left(\frac{I_o}{I_s}\right)$, and $V_1 = V_T \ln\left(\frac{I_o}{8I_s}\right) + I_o R$

→ Thus let V_d = difference voltage be defined as

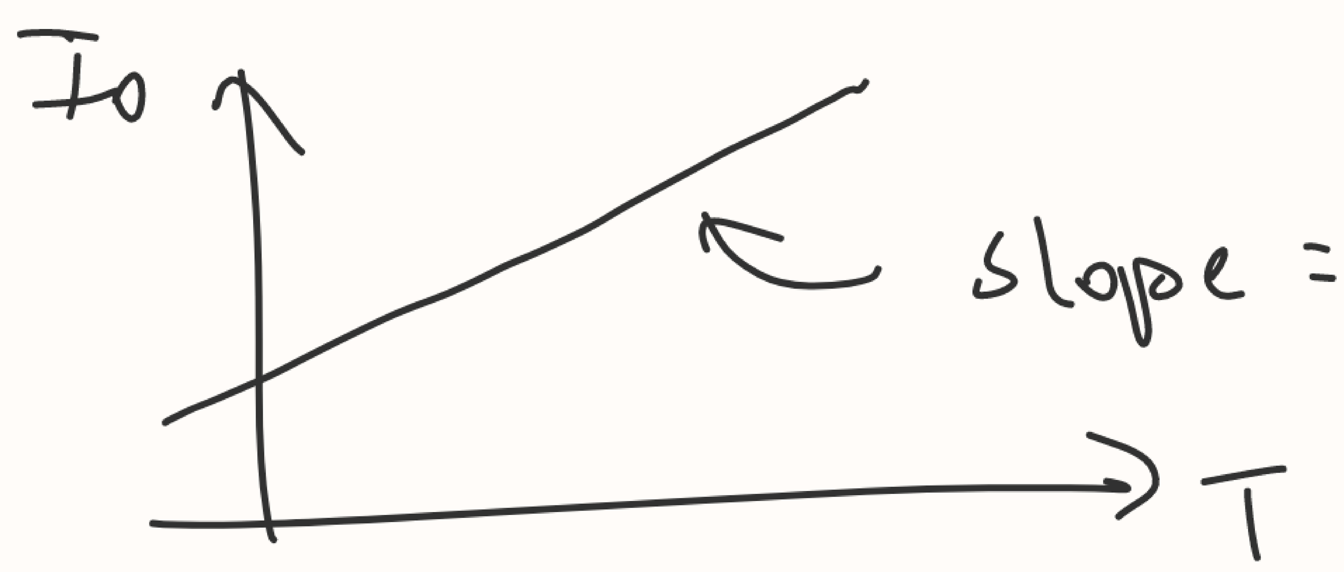
$\boxed{V_d = V_1 - V_2}$. For $V_d = 0$, we get

$$V_T \ln\left(\frac{I_o}{I_s}\right) = V_T \ln\left(\frac{I_o}{8I_s}\right) + I_o R$$

$$\therefore I_o R = V_T \ln(8)$$

$$\therefore \boxed{I_o = \frac{V_T \ln(8)}{R} = \frac{KT}{q}\frac{\ln(8)}{R}} \quad \text{— (2)}$$

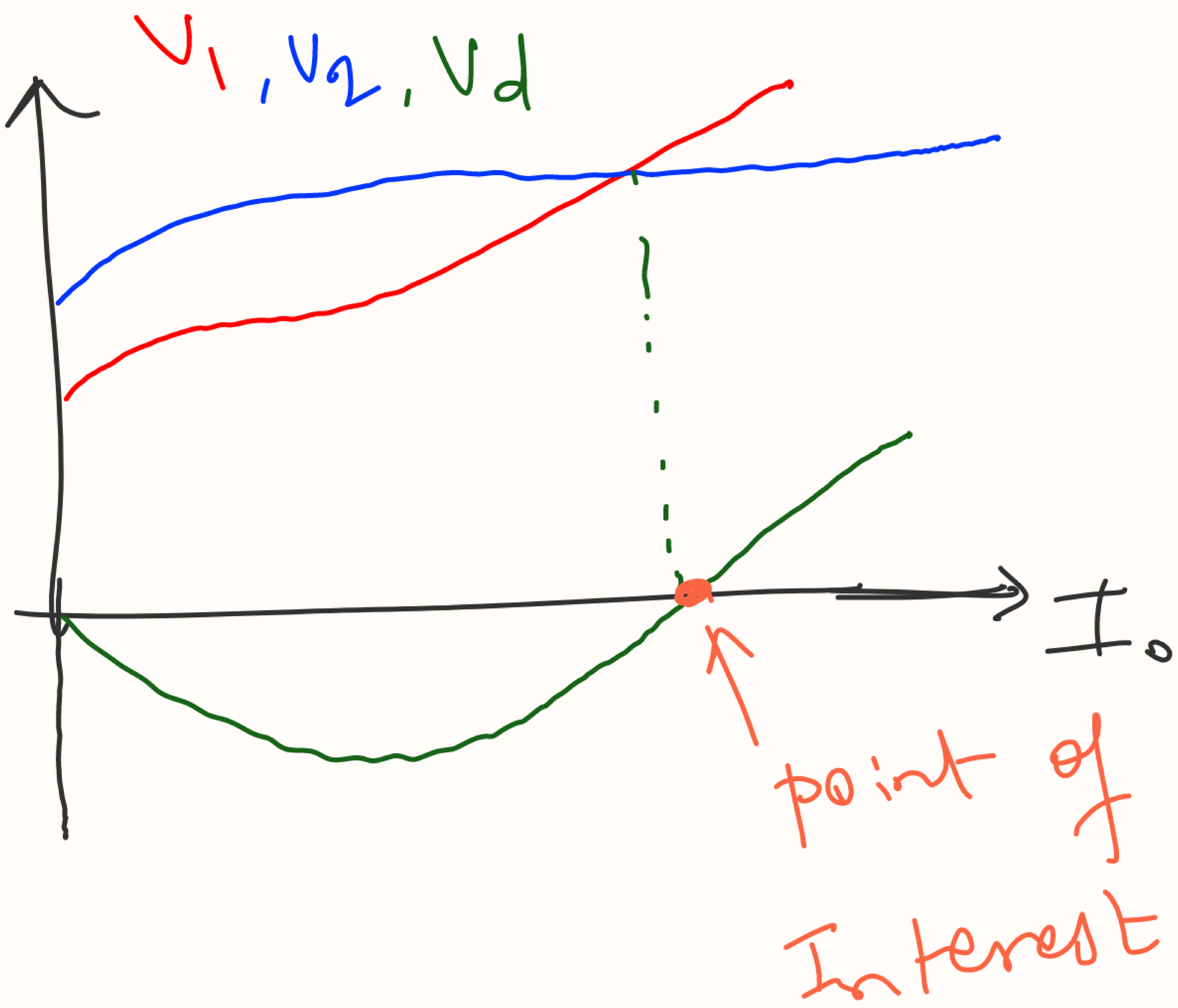
→ Thus I_o is a PTAT current.



slope = $\frac{K}{q}\frac{\ln(8)}{R}$

→ Now this PTAT current passes through our diode (i.e. diode connected BJT's), even though our analysis of V_{be} to be a CTAT voltage for a constant current one can substitute PTAT I_o in the equation and still the nature of diode voltage will be CTAT.

→ Plot of V_1, V_2 & V_d vs. I_o



→ As for a PTAT current we need $V_d = 0$ and this happens at a particular I_o, i.e $I_o = \frac{V_t \ln(8)}{R}$.

→ Now for feedback we can see that if

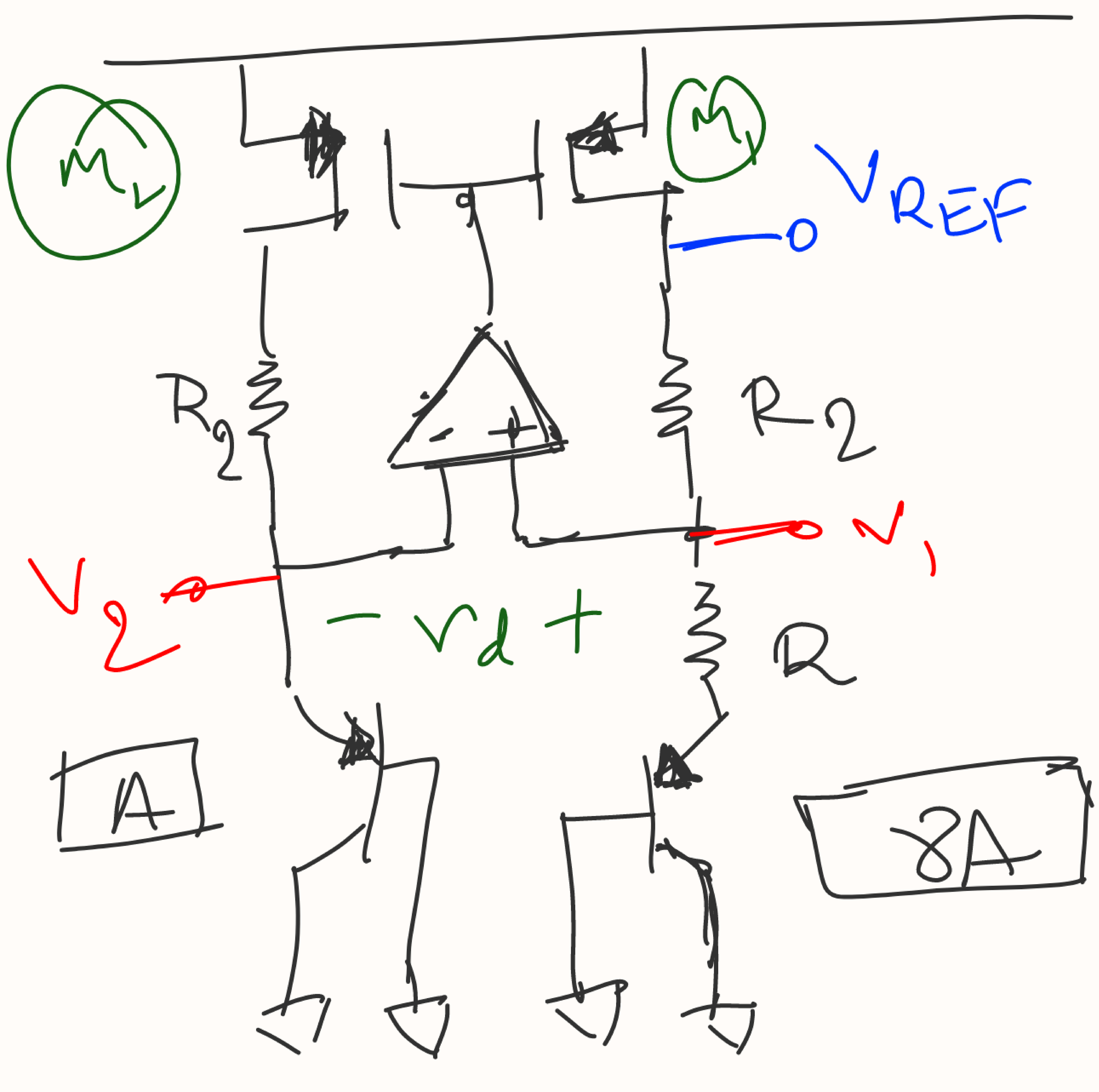
- $V_d > 0 \boxed{\Rightarrow}$ we must decrease I_o.
- $V_d < 0 \boxed{\Rightarrow}$ we must increase I_o.

→ As $V_d = V_1 - V_2$, thus V_1 must be at "+" terminal of op-amp and V_2 must be at "−" terminal of op-amp.

→ M_1 & M_2 works as current source which will drive same current through both branches.

→ Now as we got a PTAT & CTAT quantities Voltage mode BGR we have to add PTAT & CTAT voltages. As we already have a CTAT Voltage we need to generate a PTAT Voltage and this can be easily done by passing PTAT current through a resistor. So from simulation we can find slope of CTAT voltage and PTAT current and then accordingly decide the value of resistor. Let's say the value of resistor is R_2. Thus our ckt will be,

→



→ Note that we put R_2 on both the sides so that V_{sd} of both M_1 and M_2 are same and thus the difference in the currents of both the branches will be less.

(*) Design of Voltage Mode BGR :-

→ I selected the I_o of $5\,\mu A$ and the diode on Right branch has a multiplier of "8".

→ For $I_o = 5\,\mu A$, $I_o = \dfrac{V_T \ln(8)}{R}$, at room temperature $V_T = 25.9\,mV$ we get R as

$$R = \frac{25.9\,mV \times \ln(8)}{5\,\mu A} = 10.77\,K\Omega$$

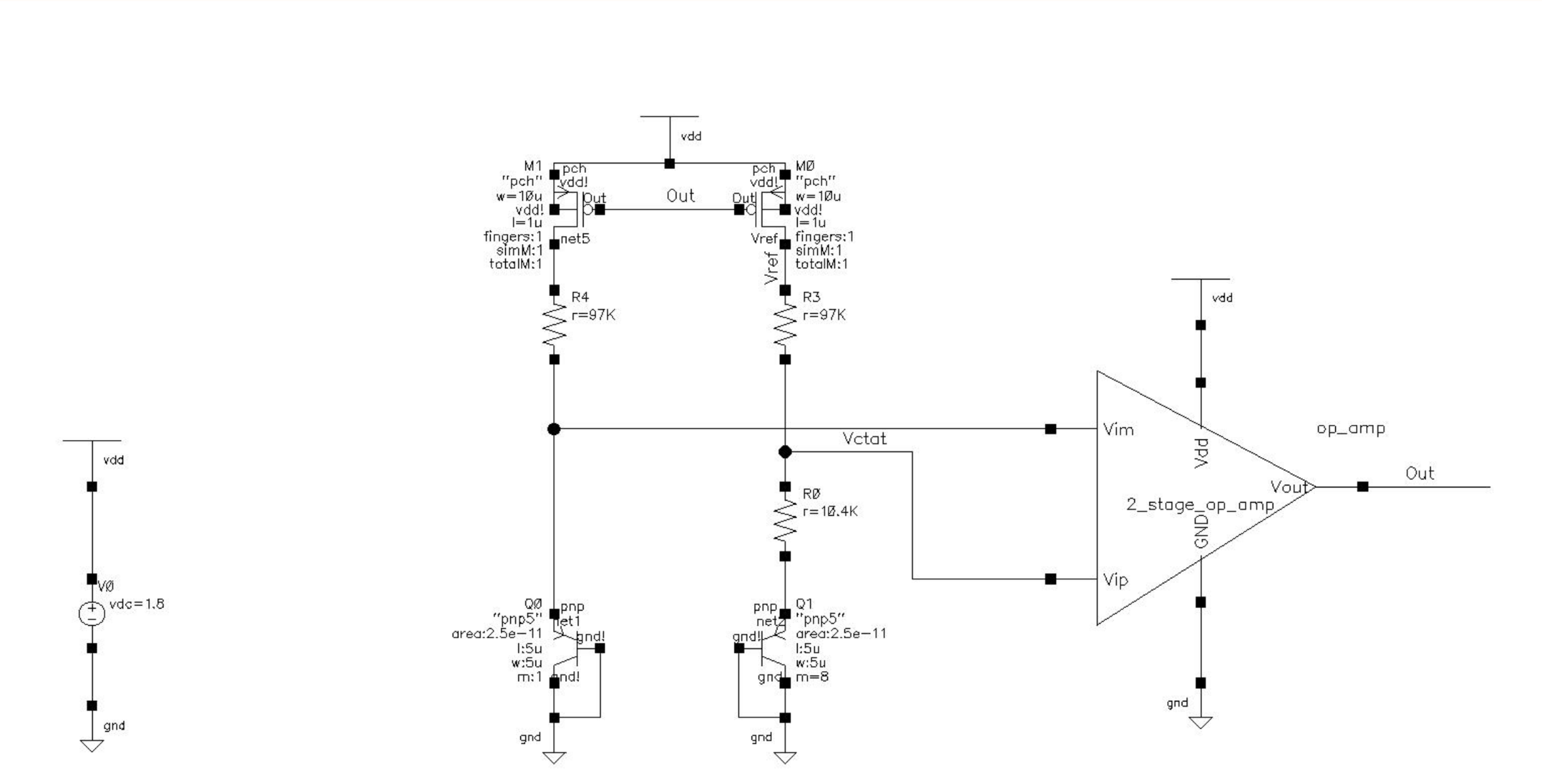
→ For M_1 & M_2 we selected the lengths such that channel length modulation effect is minimum, so the current is almost same in both branches.

→ The size of M_1 & M_2 are

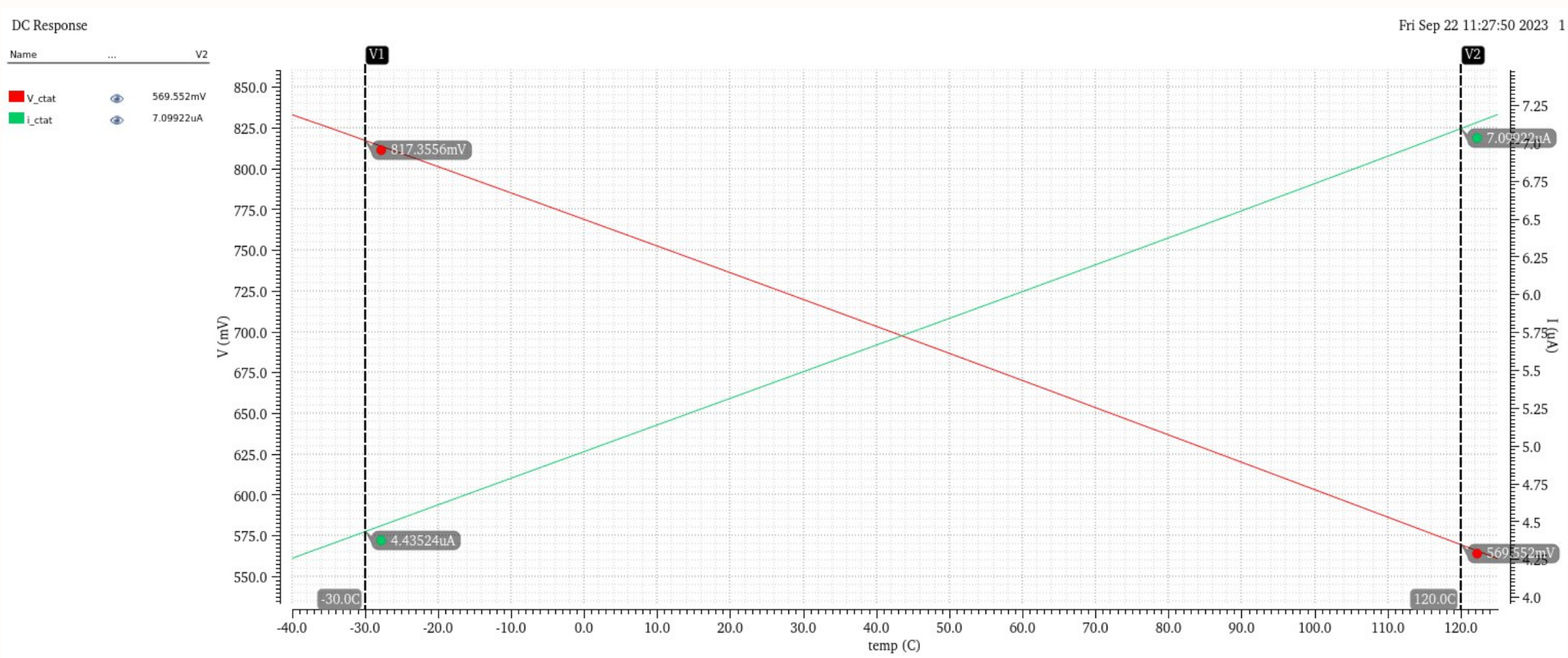
$$w_1 = w_2 = 10\,\mu m$$

$$L_1 = L_2 = 1\,\mu m.$$

⇒ Schematic :



⇒ Vctat and Iptat curves :



→ we varied the temperature from $-40°C$ to $125°C$ and we found the slopes as,

V_{ctat} slope $= -1.652 \left(\frac{mV}{°C}\right)$ and

I_{ptat} slope $= 0.01776 \left(\frac{\mu A}{°C}\right)$

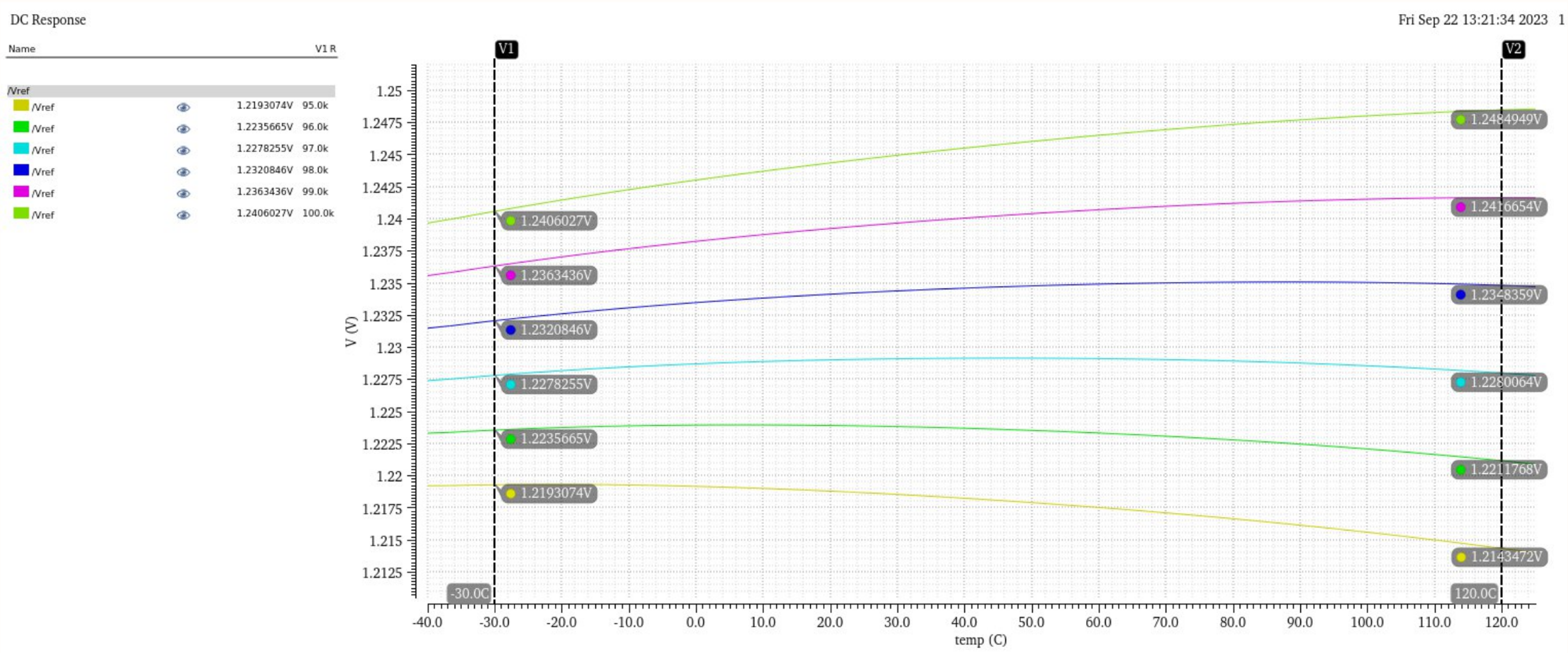
→ As we want a PTAT Voltage, thus

$$I_{ptat} \times R_2 = V_{ctat}$$

$$\therefore \boxed{R_2 = 93.018\ k\Omega}$$

→ But there can be a little deviation from our calculated value, thus we will do a parametric sweep, the result of parametric sweep is shown below.

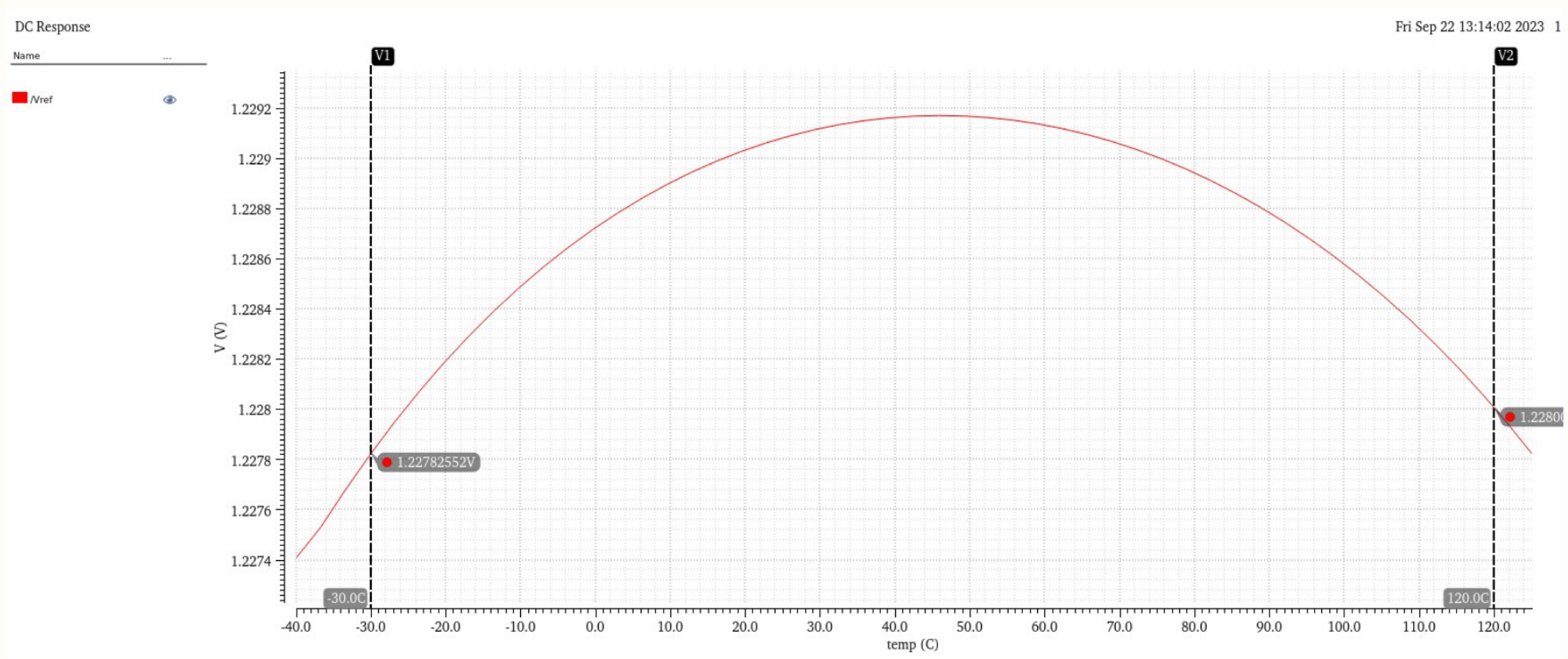
⇒ Parametric Sweep Result :-



→ From graphs the curve corresponding to $97K\Omega$ seems to have least variation along the temperature range.

→ Thus lets take $R_2 = 97K\Omega$ and plot the curve of Vref vs. Temp.

⇒ Vref vs. Temp :-



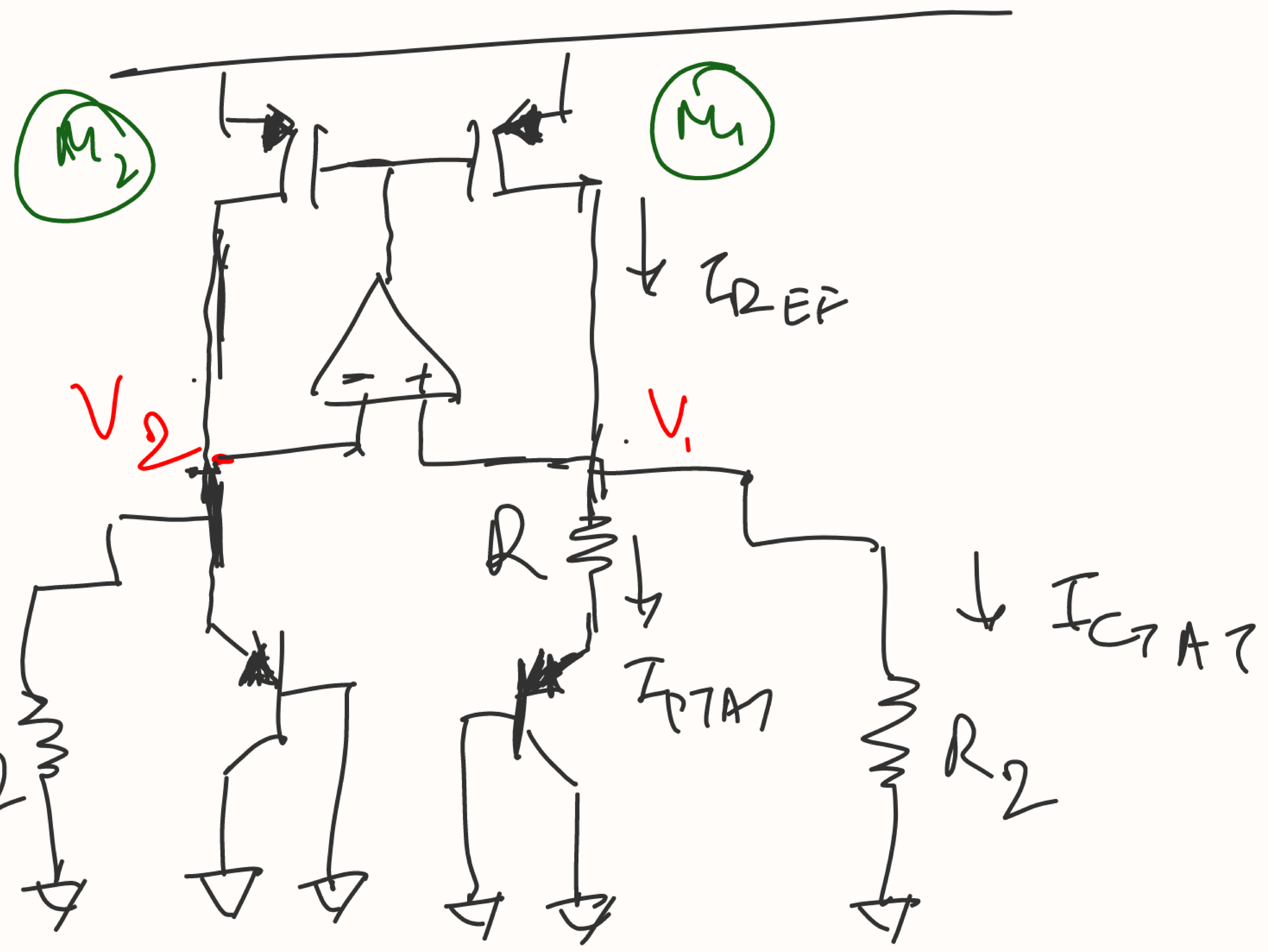
(*) Design of Current Mode BGR:

⇒ Introduction:

→ As we noticed from Voltage mode BGR the V_{ref} has value around 1.2 V which is coming due to bandgap of silicon. But as we are stacking voltages thus the supply voltage requirement is increased. Also if we need a reference Voltage level other than 1.2 V then it is very difficult to get. Thus instead of stacking PTAT and CTAT Voltages to get a temperature independent Voltage we can add PTAT and CTAT currents to get a temperature independent current. As we already have a PTAT current, we just need a CTAT current. Now we have a CTAT Voltage thus if we put a resistor across V_1 & V_2, thus we get a CTAT current. And due to adding of resistor we are adding PTAT and CTAT currents thus current through M_1 & M_2 is temperature independent.

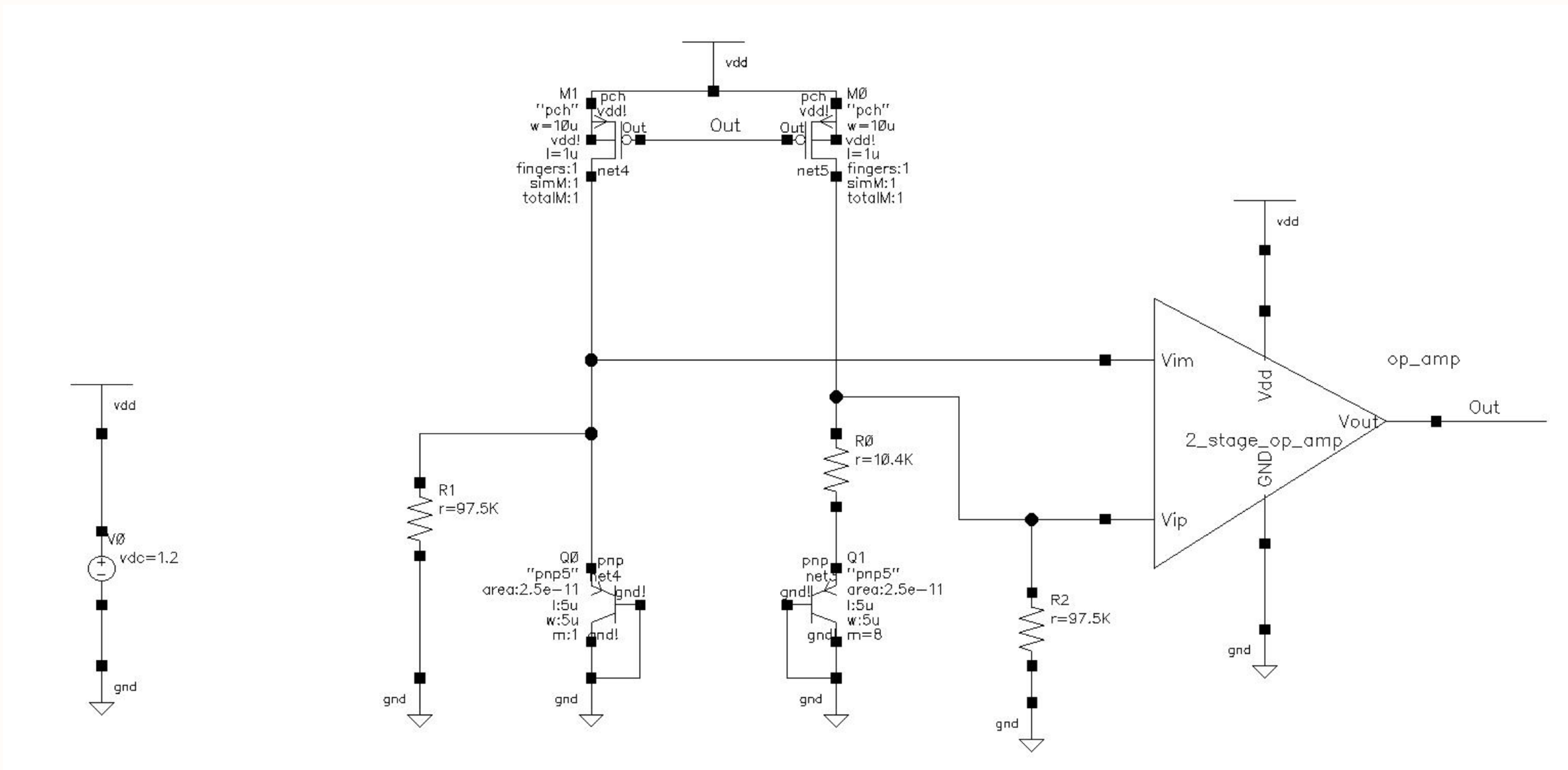
$\boxed{\Rightarrow}$ Schematic:-

→



→ The value of R_2 is found from V_{CTAT} & I_{PTAT} slope values.

$$\frac{V_{CTAT}}{R_2} = I_{PTAT} \quad \boxed{\Rightarrow} \quad R_2 = \frac{1.652\ (mV/^\circ C)}{0.01776\ (uA/^\circ C)} = \underline{\underline{93.018\ k\Omega}}$$



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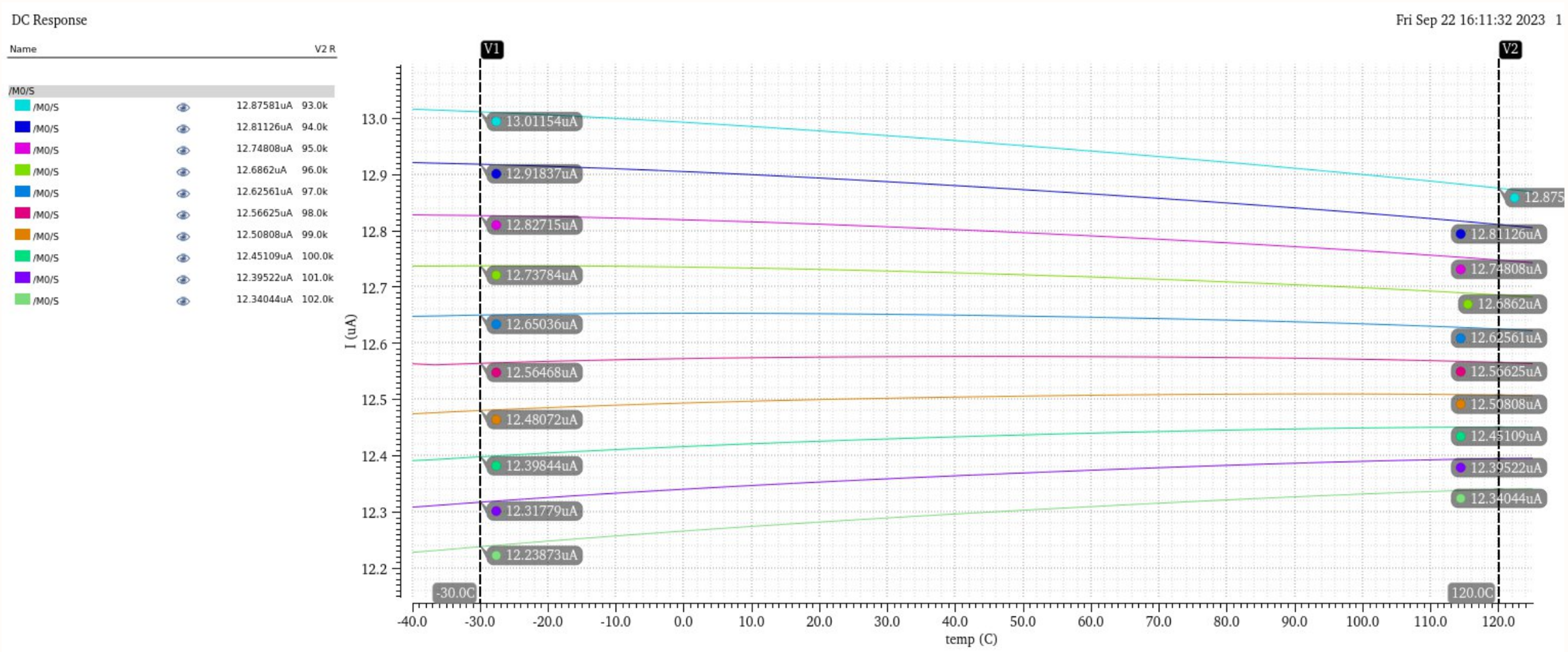
→ But the actual value of R_2 may differ than 93.018 kΩ. Thus we will do parametric analysis for different values of R_2 around 93 kΩ.

⇒ Parametric sweep Results:-



→ From this we selected $R_2 = 97.5\,K\Omega$, for this the Iref simulated result is as shown,

⇒ I_{REF} Vs. Temperature.