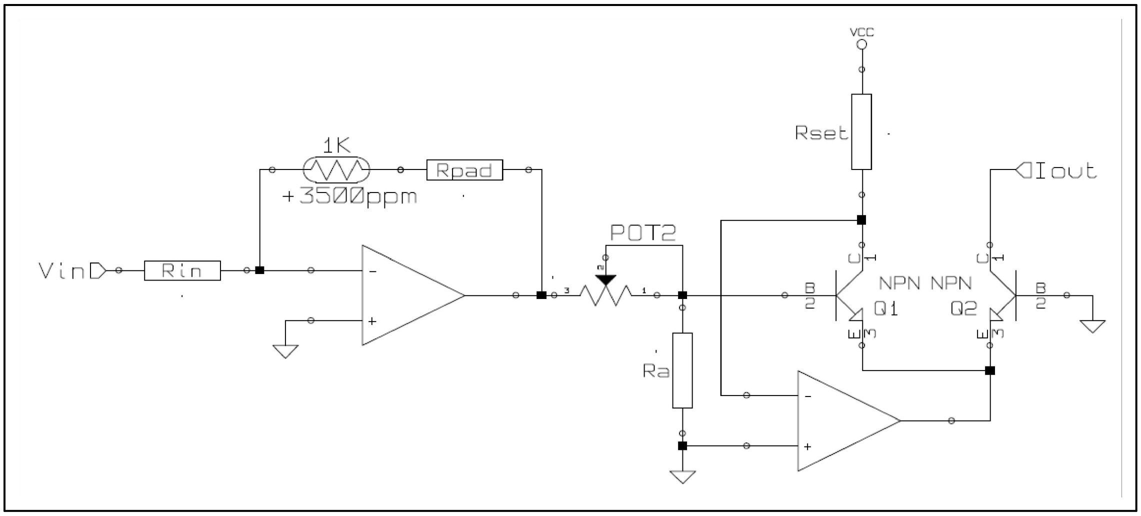
# Tempco Calculations Part 1

Ryan Williams

**Temperature Compensating Resistors (PT146)**

The following calculations show the design and analysis of the common exponential current sink using a tempco resistor for compensation. The format of the output current equations is as shown by Ian Fritz (see reference) on his "Tempco Equations" web page. I have made this note to verify the correct operation and to see the error (drift) when using a non-ideal tempco resistor. Besides, I was required to write a paper on a topic of interest and these calculations were part of it.

The tempco resitor used as an example is the PT146 from Precision Resistor Co. I have used the 1K +3500ppm version. The actual coefficient of the PT146 changes slightly with temperature. At room temperature (25C, 298K) it is about +3369, and at (100C, 373K) it will be about +3430ppm. At room temperature, it is very close to the required coefficient. Note that I have not actually taken measurments on the VCOs that I built with the PT146. They do seem to work fairly well though.




definitions:

$ppm := \frac{1}{10^6}$ $\quad$ $Kohm := 10^3 ohm$ $\quad$ $R_{set} := 1000Kohm$

$uA := 10^{-3} mA$ $\quad$ $nA := 10^{-3} uA$ $\quad$ $V_{cc} := 15V$

$k := 1.38 \cdot 10^{-23} \cdot \frac{J}{K}$ $\quad$ $q := 1.60 \cdot 10^{-19} coul$ $\quad$ $t_0 := 298$ room temp.

$V_t(t) := \frac{k \cdot (t\,K)}{q}$ $\quad$ $V_{t0} := V_t(t_0)$ thermal voltage for BJT

$$I_{c1} := \frac{V_{cc}}{R_{set}} \qquad R_0 := 1\text{Kohm}$$

0V output current, nominal TCR

The provided data on the tempco resistor shows a graph which matches the following equation. I would expect that actually measuring this data would help because there is some tolerance on the specs given. I also extend this function beyond the given table so this analysis is not exact.

$$TCR(t) := \left(t - t_0\right)\cdot\frac{3430ppm - 3369ppm}{75} + 3369ppm \qquad TCR\left(t_0\right) = 3369\,ppm$$

This curve needs to be in the form A*t/t0 + B. For the perfect tempco resistor (3355ppm), the value of B will be 0. If a 3355ppm/C tempco is not available, then a larger TCR can be used with a small series resistor of value B. To calculate this value, we simply put the provided curve into the correct form. Since the TCR changes, this value should be calculated at an temperature near that of normal operation. Here we calculated the pad resistor at room temperature (298K). The value of B is the y axis offset at absolute zero.

$$b := 1\text{Kohm} - TCR\left(t_0\right)\cdot R_0\cdot t_0 \qquad R_{pad} := -b \qquad R_{pad} = 3.962\ \Omega$$

$$a(t) := TCR(t)\cdot R_0\cdot t_0 \qquad a\left(t_0\right) = 1003.962\ \Omega$$

$$R_{temp}(t) := b + \frac{t}{t_0}\cdot a(t)$$

Putting Rtemp in a useable form

$$R_{temp}\left(t_0 + 75\right) = 1.275\,\text{Kohm}$$

that checks out with the PT146 data

$$R_{temp}\left(t_0\right) = 1\ \text{Kohm}$$

The pad resistor calculated for the PT146 is so tiny that I would omit it from the circuit. A spot on the PCB might be reserved for a resistor anyway. This would allow someone to adjust the compensator after the entire circuit is built. The opamp gain is now temperature dependent. As the temperature increases, the gain will decrease. This effect counteracts the change in the BJT gain. Of course, they need to be at the same temperature. This is usually done by gluing the resistor to the differential pair. I have used heat sink compound as well. The value of Rin is calculated afer the correct 1V/Oct scaling is determined. The input voltage should be scaled by ln(2) in order to double for each 1V increase.

$$V_b\left(V_{in}, t\right) := V_{in}\cdot\ln(2)\cdot V_{t0}\cdot\frac{\frac{t}{t_0}\cdot a(t)}{\left(R_0 + R_{pad}\right)\cdot V}$$

$$e^{0\cdot\ln(2)} = 1$$

$$e^{1\,\ln(2)} = 2$$

$$e^{2\cdot\ln(2)} = 4$$

$$I_{out}\left(V_{in}, t\right) := I_{c1}\cdot e^{\frac{-V_b\left(V_{in}, t\right)}{V_{t0}}\cdot\frac{t_0}{t}}$$

The value of Rin is now calculated. This would normally be chosen slightly smaller than required. Then a resistive attenuator with a trim pot would be placed as shown in the schematic diagram.

$$R_{in} := \frac{(R_0 + R_{pad})V}{\ln(2)\cdot V_{t0}} \qquad R_{in} = 56.353\,\mathrm{Kohm}$$

$$I_{out.s}(V_{in}, t) := I_{c1}\cdot e^{\frac{-V_{in}}{V_t(t)}\cdot\frac{R_{temp}(t)+R_{pad}}{R_{in}}}$$

simplified output current

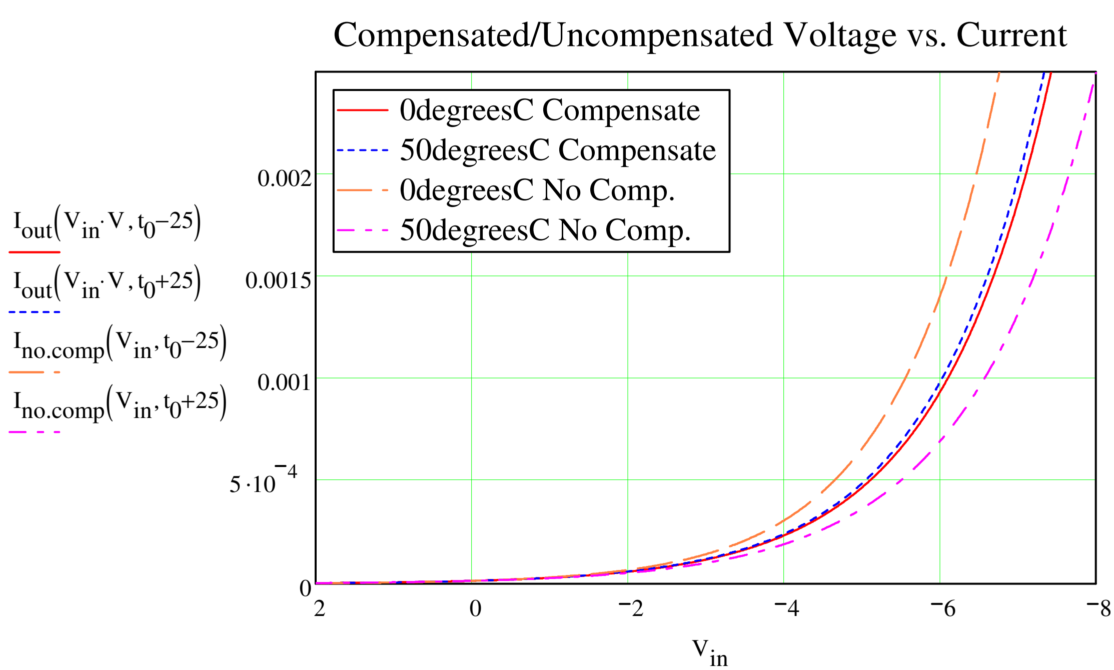
$$I_{out.s}(0V, t_0) = 15\,\mathrm{uA}$$

$$I_{out.s}(-1V, t_0) = 30\,\mathrm{uA}$$

Verification that it has a 1V/Oct response

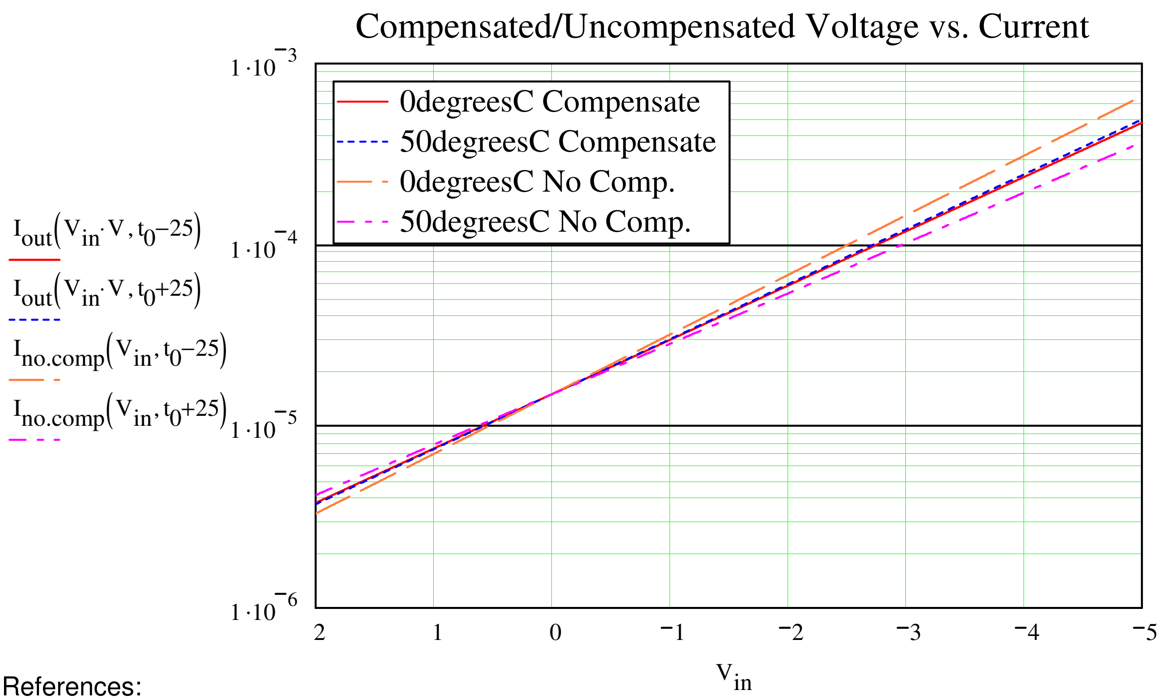
To see how well the the tempco compensates, an uncompensated version (using normal resistors) is plotted against the compensated version. The uncompensated current is scaled to the compensated current at room temperature.

$$I_{no.comp}(V_{in}, t) := I_{c1}\cdot e^{\frac{-V_{in}}{V_t(t)}\cdot\frac{R_0+R_{pad}}{R_{in}}}$$



Even in the compensated output, a small drift can be seen over the 50 degreeC temperature difference. This is due to the changing coefficient of the tempco resistor. Some additional circuity, and trim pots can be used to reduce the temperature dependence further (see Ian's page). Even if a perfect tempco resistor is used, there will be drift caused by other components in the circuit. This compensation is not perfect, however the circuit shown here is good enough for most people.

The plot above is now shown again using a log scale for the y axis. This shows that the current error caused by drift increases as the input voltage is farther away from 0V. So, the drift can be minimized by setting the 0V current to the center of the usable range.





References:

Ian Fritz, "Tempco Equations" & "Dial a Tempco" : http://home.earthlink.net/~ijfritz/

René Schmitz,  "Whats that exp and tempco stuff?" : http://www.uni-bonn.de/~uzs159/