LECTURE 4 - HOW TO DESIGN ULTRA-STABLE TEMPERATURE INDEPENDENT BIAS CIRCUITS

Topics:

- Temperature stable bias currents
- Issues with ultra-precision bandgap references
- Curvature corrected bandgap with V_{DD} independence
- Design procedure
- Trimming and influence of process

What will I learn?

- How to design temperature independent voltage sources with a temperature coefficient of 1ppm/°C or less over -50°C to 125°C.

Dr. Phillip Allen
Prof. Emeritus, ECE, Georgia Tech

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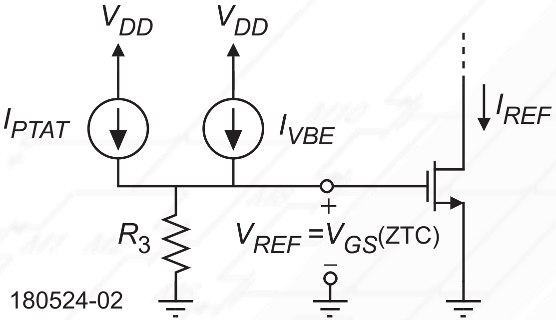
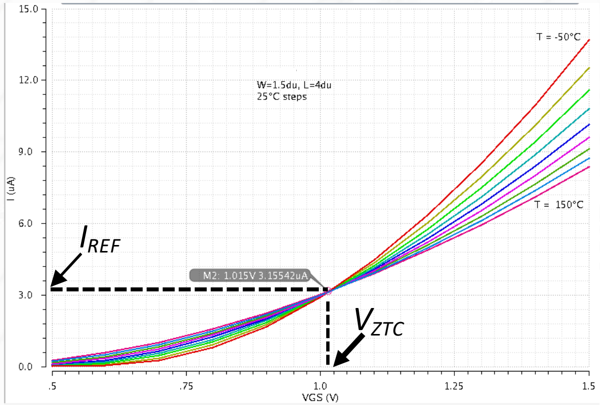
Temperature Stable Bias Currents

Principle

Use a MOSFET in ZTC operation and design the parallel form of the bandgap voltage reference equal to the value of V_{ZTC}.





Comments

- Ability of the ZTC point not to drift with temperature will restrict the temperature range
- The reference voltage must be equal to the ZTC voltage
- The voltage V_{REF} will suffer the bandgap curvature problem which will be translated onto I_{REF}.

PTAT and CTAT Voltages

Bandgap Curvature

PTAT is perfectly linear with respect to *T*

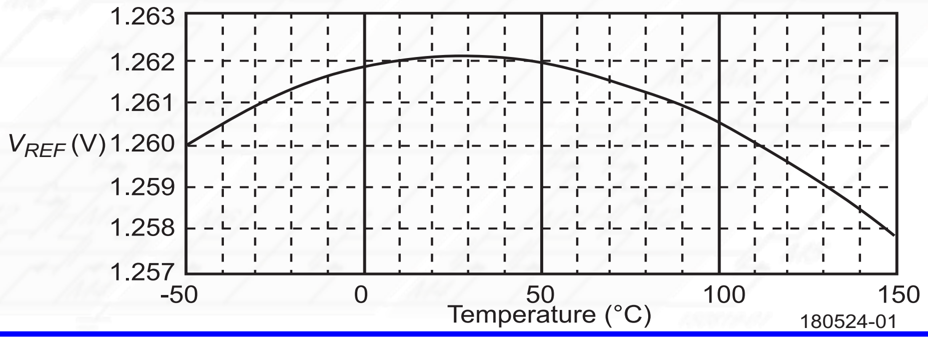
$$V_{PTAT} = V_t ln(N) \text{ if } I_1 = I_2$$

CTAT has a term that is not linear with respect to *T* that causes the bandgap curvature.

$$V_{CTAT} = V_{BG} - V_t(\gamma - \alpha)ln(T) - V_t ln\left(\frac{A}{B}\right)$$

where $I_s = AT^{\gamma} exp\left(\frac{-V_{BG}}{V_t}\right)$ and $i_{PTAT} = BT^{\alpha}$

Result of adding V_{PTAT} to V_{CTAT}:



Cancellation of Nonlinear CTAT Term

Principle:

Eliminate the nonlinear term of the following CTAT expression:

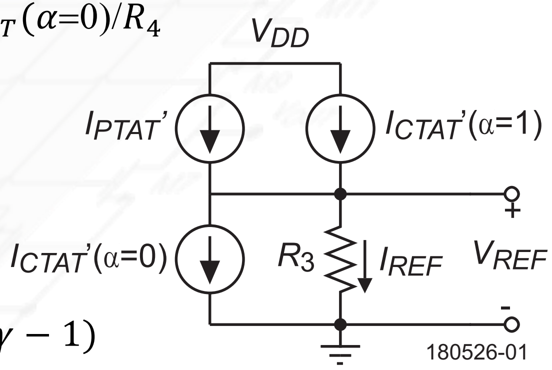
$$V_{CTAT}(\alpha) = V_{BG} - (\gamma - \alpha)V_t \ln(T) - V_t \ln(A/B)$$

Generate the following:

$$V_{CTAT}(\alpha = 1) = V_{BG} - (\gamma - 1)V_t \ln(T) - V_t \ln(A/B) \rightarrow I_{CTAT}'(\alpha{=}1) = V_{CTAT}(\alpha{=}1)/R_2$$

and

$$V_{CTAT}(\alpha = 0) = V_{BG} - \gamma \ln(T) - V_t \ln(A/B) \rightarrow I_{CTAT}'(\alpha{=}0) = V_{CTAT}(\alpha{=}0)/R_4$$



Combine the psuedo PTAT and 2 CTAT currents as follows,

$$V_{REF} = K_1 \cdot I_{PTAT}' + K_2 \cdot I_{CTAT}'(\alpha{=}1) - K_3 \cdot I_{CTAT}'(\alpha{=}0)$$

and

$$V_{REF} = \frac{R_3}{R_1} V_{PTAT} + \frac{R_3}{R_2} V_{CTAT}(\alpha = 1) - \frac{R_3}{R_4} V_{CTAT}(\alpha = 0)$$

To cancel the nonlinear terms requires that:

$$(R_3/R_2)(\gamma - 1)V_t \ln(T) = (R_3/R_4)\gamma\, V_t \ln(T) \text{ or } R_4/R_2 = \gamma/(\gamma - 1)$$

Therefore we can write,

$$V_{REF} = (R_3/R_1)V_{PTAT} + (R_3/\gamma R_2)V_{CTAT} \quad \text{where } V_{CTAT} = V_{BG} - V_t \ln(A/B)$$

Ultra-Stable Temperature Reference

Design Equations

From last slide,

$$V_{REF} = (R_3/R_1)V_{PTAT} + (R_3/\gamma R_2)V_{CTAT} \quad \text{where } V_{CTAT} = V_{BG} - V_t\ln(A/B)$$

Differentiate with respect to temperature to get,

$$\frac{dV_{REF}}{dT} = \frac{R_3}{R_1}\frac{V_{PTAT}}{T} + \frac{R_3}{\gamma R_2}\frac{dV_{CTAT}}{dT} = 0 \Rightarrow \quad \frac{R_2}{R_1} = \frac{-T(dV_{CTAT}/dT)}{\gamma\times V_{PTAT}}$$

Substituting back into V_{REF} gives,

$$V_{REF} = \frac{R_3}{\gamma\times R_2}\left[\frac{\gamma R_2}{R_1}V_{PTAT} + V_{CTAT}\right] = \frac{R_3}{\gamma\times R_2}\left[-T\frac{dV_{CTAT}}{dT} + V_{CTAT}\right]$$

But,

$$\frac{dV_{CTAT}}{dT} = -\frac{V_t}{T}\ln(A/B) \rightarrow V_{REF} = \frac{R_3}{\gamma\times R_2}[V_t\ln(A/B) + V_{BG} - V_t\ln(A/B)] = \frac{R_3}{\gamma\times R_2}V_{BG}$$

The design equations are:

1.) $R_1 = V_{PTAT}/I_{PTAT}$

2.) $R_2 = [-T(dV_{CTAT}/dT)/\gamma\times V_{PTAT}]R_1 \approx [T(2mV/°C)/\gamma\times V_{PTAT}]R_1$

3.) $R_4 = (\gamma/\gamma - 1)R_2$

4.) $R_3 = [\gamma\times V_{REF}/V_{BG}]\,R_2$

PTAT Linearity Issues

Problem with canceling the nonlinear term

In order for the previous principle to work, V_{PTAT} must be linear with temperature.

Consider the following model for a BJT:

$$V_{PTAT} = V_1 - V_2 = V_{BE1} + R_{B1}I_{B1} - V_{BE2} + R_{B2}I_{B2}$$

$$= V_t \ln\left(\frac{I_1}{I_{S1}}\right) + R_{B1}I_{B1} - V_t \ln\left(\frac{I_2}{I_{S2}}\right) - R_{B2}I_{B2}$$

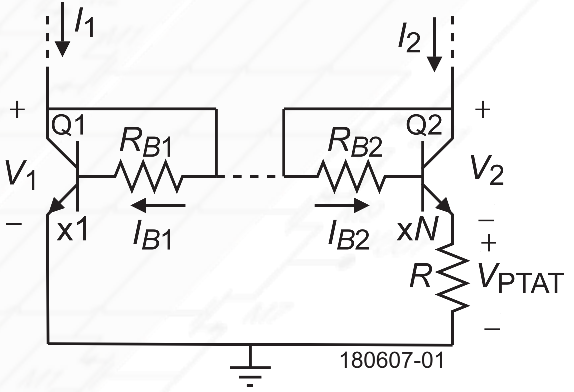
Assume $I_1 = I_2$ and $I_{B1} = I_{B2}$ gives,

$$V_{PTAT} = V_t \ln(N) + I_{B1}(R_{B1} - R_{B2})$$

But $R_B \propto {}^1/_{N\times A}$ where A is the area of the emitter.

Therefore, since $R_{B1} = N \times R_{B2}$,

$$V_{PTAT} \propto V_t \ln(N) + \frac{I_B R_B}{A}\left(1 - \frac{1}{N}\right)$$



To linearize V_{PTAT} we must make A large, I_B small, and $N \approx 1$

However, as A becomes large, the leakage current at high temperatures causes V_{PTAT} to be nonlinear.

To cancel the nonlinear term, *I* should be less than 1μA, *N* ≈ 2-6, and emitter area as large as possible without experiencing high temperature leakage.

Configuration Issues

Preserving I_{PTAT}

I_{PTAT} generated in the resistor R_{PTAT} must be the same I_{PTAT} (I_{PTATX}) going to the upper current mirror.

- For base-connected PTAT circuit,

  $$I_{PTATX} = I_C = \alpha \times I_E = \alpha \times I_{PTAT}$$

- For base-disconnected PTAT circuit,

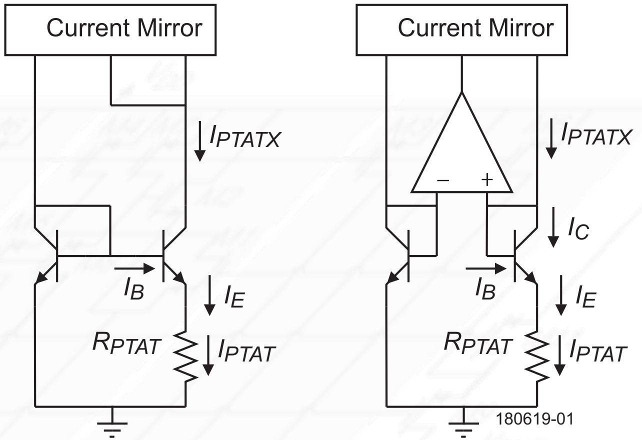
  $$I_{PTATX} = I_C + I_B = I_E = I_{PTAT}$$

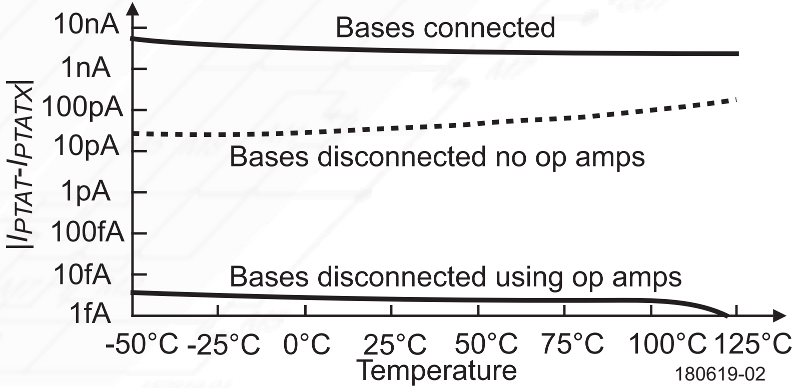
Result:

Temperature influence of α causes

$I_{PTAT} - I_{PTATX}$ to vary over temperature for base-connected PTAT circuits.

Unfortunately, techniques other than op amps do not achieve sufficient reduction of $|I_{PTAT} - I_{PTATX}|$.





Configuration Issues - Continued

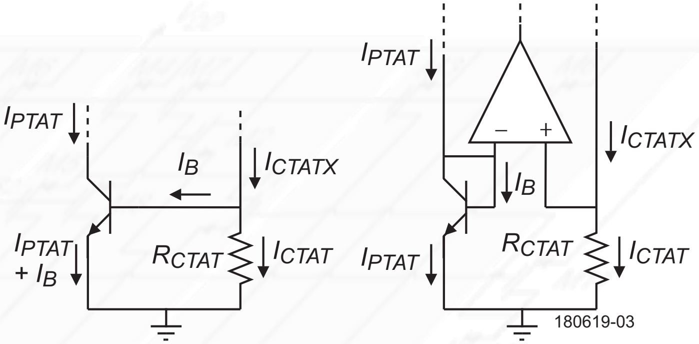
Preserving I_{CTAT}

I_{CTAT} generated in the resistor R_{PTAT} must be the same I_{PTAT} (I_{CTATX}) going to the upper current mirror.

- For base-connected CTAT circuit,

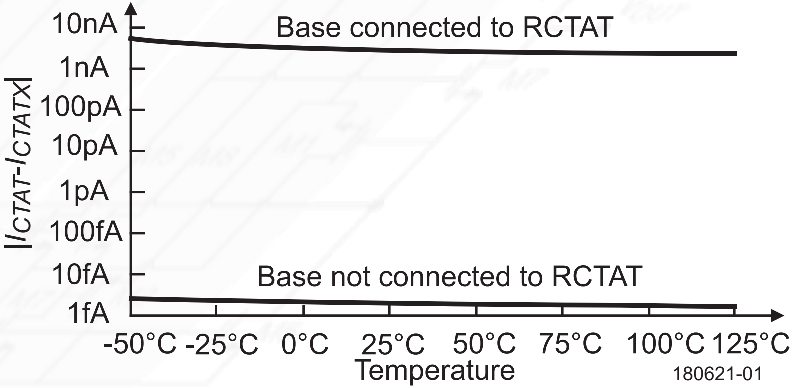
  $I_{CTATX} = I_B + I_{CTAT}$
- For base-disconnected CTAT circuit,

  $I_{PTATX} = I_{PTAT}$



Result:

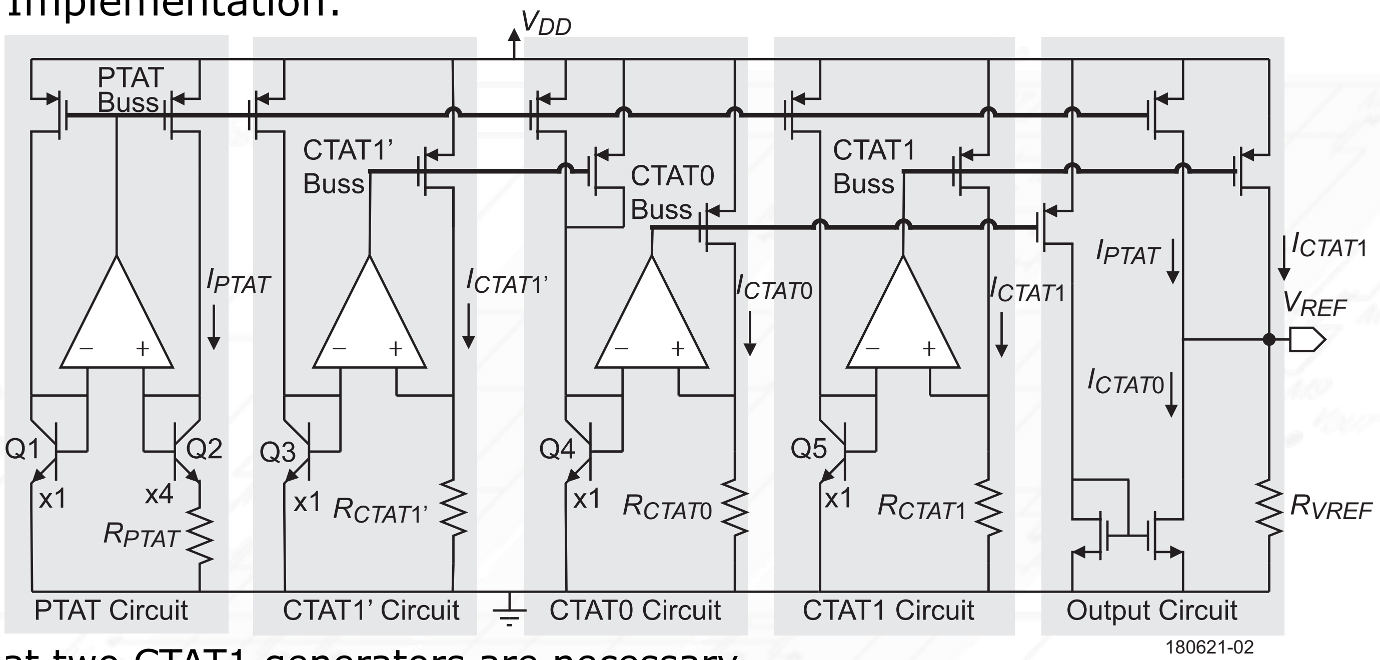
Temperature influence of α causes $I_{CTAT} - I_{CTATX}$ to vary over temperature for base-connected CTAT circuits.



Unfortunately, techniques other than op amps do not achieve sufficient reduction of $|I_{CTAT} - I_{CTATX}|$.

Temperature and V_{DD} Independent Sources

Circuit Implementation:



Note that two CTAT1 generators are necessary-

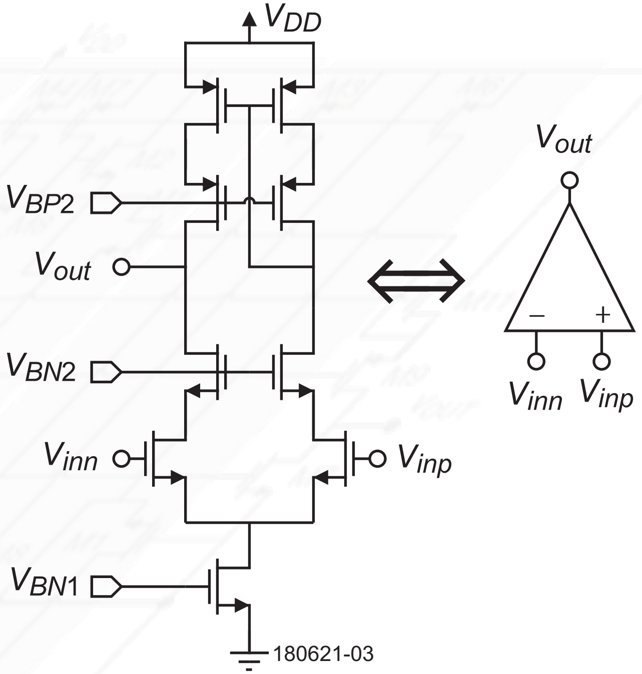
1. One is used to generate CTAT0 (CTAT1')
2. One is used to create V_{REF} (CTAT1)
3. Cannot cancel the nonlinear term if changing CTAT1 influences CTAT0

Op Amps?

Requirements

- Gain ≥ 60dB
- ≥45° phase margin
- Minimize the input offset voltage (should be less than 10 times the anticipated ΔV_{REF})

The op amps used in the curvature corrected bandgap design need only be one-stage because the current mirror and resistive load constitute a second stage.



For details on the design of the op amp see *How to Design Op Amps* in the *How to Design Analog IC Circuits Series*.

Ultra-Stable Temperature and V_{DD} Independent Source Design

Ultra-Stable Design Procedure BT4

Step	Design Equations	Comments
1	$R_{PTAT} = 1.386V_t/I_{PTAT}$	Choose $I_{PTAT} \lesssim 1\mu A$, N = Area of Q2/Area of Q1 = 4
2	$R_{CTAT1'} = \left(R_{PTAT}T(dV_{BE}/dT)\right)/(V_t \ln 4)$	Makes $dI_{CTAT0}/dT \approx 0$, need a good value for $\lvert dV_{BE}/dT\rvert$ or use 2mV/°C.
3	$R_{CTAT1} = \dfrac{R_{PTAT}T(dV_{BE}/dT)}{\gamma\, V_t \ln(4)}$	Makes $dV_{REF}/dT \approx 0$, need a good value for $\lvert dV_{BE}/dT\rvert$ or use 2mV/°C. Guess $\gamma \approx 2$ if not know and adjust later
4	$R_{CTAT0} = \gamma/(\gamma-1)R_{PTAT}$	If γ is not known guess $\gamma \approx 2$ and adjust later
5	$R_{VREF} = \dfrac{\gamma V_{REF}}{V_{BG}} R_{CTAT1}$	$V_{BG} \approx 1.205$V

Example 1

Let V_{DD} = 3V. Design V_{REF} = 1.0V

1.) Let N = 4 and choose I_{PTAT} = 0.25μA, therefore $R_2 = 1.386\times0.0259/2\mu A = 143.6k\Omega$

2.) Design $R_{CTAT1'}$= $R_{PTAT}T(dV_{BE}/dT)/(V_t\ln(4))$=143.6kΩx300°K(2mV/°C)/(0.0258x1.386)= 2.4MΩ

3.) Design R_{CTAT1}= $R_{PTAT}T(dV_{BE}/dT)/(\gamma V_t\ln(4))$=143.5kΩx300°K(2mV/°C)/(2x0.0258x1.386)= 1.2MΩ

4.) Design $R_{CTAT0} = \gamma/(\gamma-1)R_{CTAT1} = (2/1)\times1.2M\Omega$ = 2.4MΩ

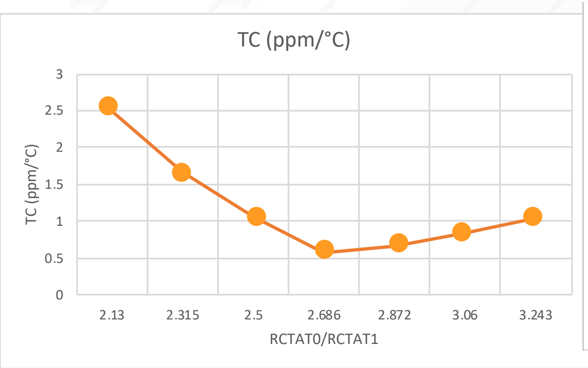
5.) Design $R_{VREF} = [\gamma\times V_{REF}/V_{BG}]\ R_{CTAT1} = (1\times2\times1.2M\Omega)/(1.205)$ = 2MΩ

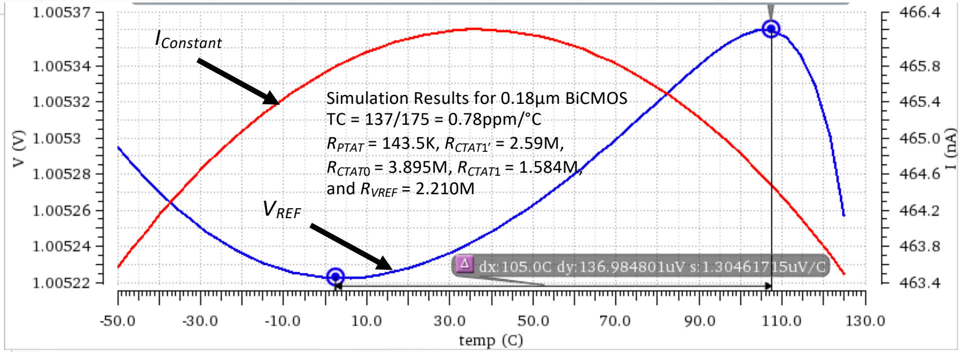
Ultra-Stable Temperature and V_{DD} Independent Sources

Design adjustment Procedure

Step	Adjustment
1	Adjust $R_{CTAT1'}$ to make I_{CTAT0} flat with respect to temperature (do not change R_{PTAT} in design step 1)
2	Adjust R_{CTAT1} to make V_{REF} flat as possible with respect to temperature (do not change R_{PTAT} in design step 1)
3	Select R_{CTAT0} that is less than that in design step 4 and repeat steps 1 and 2 above.
4	Select R_{CTAT0} that is greater than that in design step 4 and repeat steps 1 and 2 above.
5	Pick the value of R_{CTAT0} that gives minimum dV_{REF}/dT or TC

Design results





Process Dependence

Influence of Process

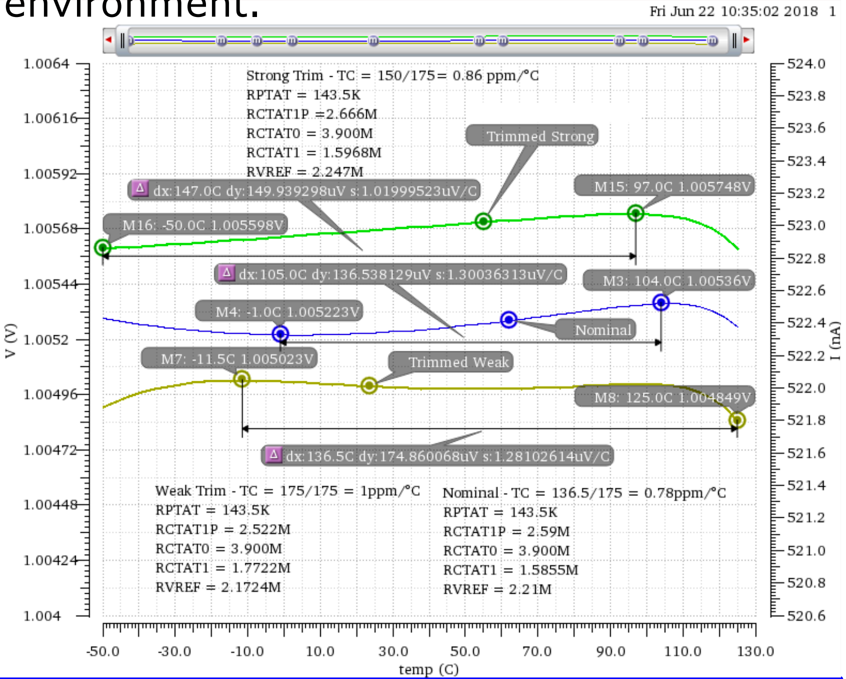
Unfortunately, the ultra-stable temperature reference is very sensitive to process.

Tuning will be necessary in a manufacturing environment.

Trimming Procedure

1. Assume nominal meets specs
2. Trim R_{CTAT0} to make I_{CTAT0} constant
3. Trim R_{CTAT1} and R_{VREF} to achieve desired TC

Example:



Summary – Ultra-stable temperature sources

Curvature-Corrected Bandgap Design

- How to create a temperature stable current from a temperature stable voltage
- CTAT curvature cancellation technique
- Issues with ultra-stable temperature sources
  - Base currents
  - Op amps versus no op amps
- Design procedures – BT4
- Example
- Influence of process and the need for trimming