LECTURE 17 – TEMPERATURE STABLE REFERENCES

LECTURE ORGANIZATION

Outline

- Principles of temperature stable references
- Examples of temperature stable references
- Design of bias voltages for a chip
- Summary

***CMOS Analog Circuit Design*, 3rd Edition Reference**

Pages 156-172

PRINCIPLES OF TEMPERATURE STABLE REFERENCES

Temperature Stable References

- The previous reference circuits failed to provide small values of temperature coefficient although sufficient power supply independence was achieved.
- This section introduces a temperature stable reference that cancels a positive temperature coefficient with a negative temperature coefficient. The technique is sometimes called the *bandgap reference* although it has nothing to do with the bandgap voltage.

Principle

$$V_{REF}(T) = V_{PTAT}(T) + K \cdot V_{CTAT}(T)$$

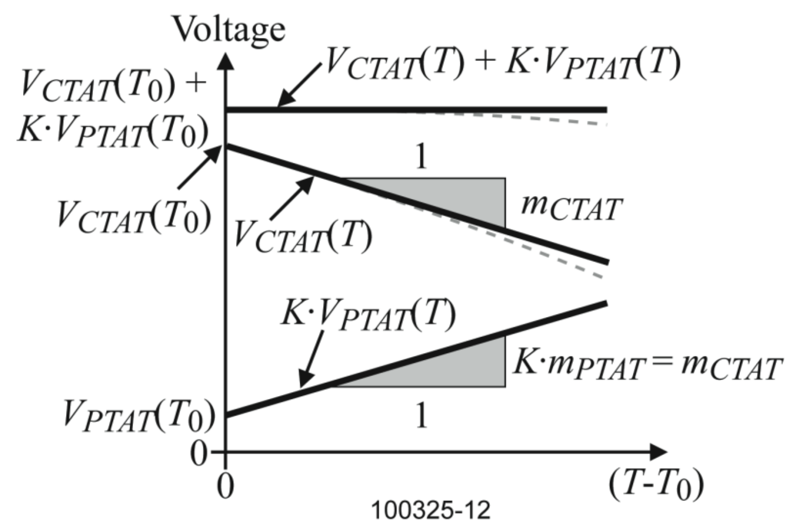
where

$V_{PTAT}(T)$ is a voltage that is *proportional to absolute temperature* (PTAT)

$V_{CTAT}(T)$ is a voltage that is *complimentary to absolute temperature* (CTAT)

and

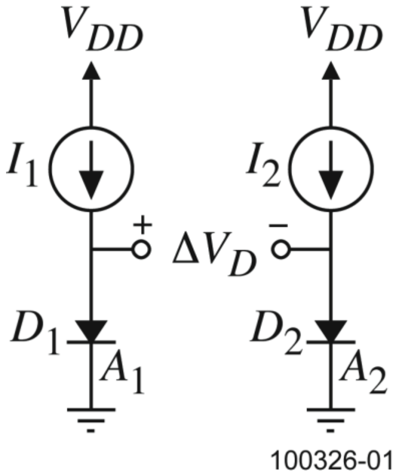
K is a temperature independent constant that makes $V_{REF}(T)$ independent of temperature



PTAT Voltage

The principle illustrated on the last slide requires perfectly linear positive and negative temperature coefficients to work properly. We will now show a technique of generating PTAT voltages that are linear with respect to temperature.

Implementation of a PTAT voltage:



$$V_{PTAT} = \Delta V_D = V_{D1} - V_{D2} = V_t\, ln\left(\frac{I_1}{I_{s1}}\right) - V_t\, ln\left(\frac{I_2}{I_{s2}}\right)$$

$$= V_t\, ln\left(\frac{I_1}{I_2}\,\frac{I_{s2}}{I_{s1}}\right) = V_t\, ln\left(\frac{I_{s2}}{I_{s1}}\right) = V_t\, ln\left(\frac{A_2}{A_1}\right) = \frac{kT}{q}\, ln\left(\frac{A_2}{A_1}\right)$$

if $I_1 = I_2$.

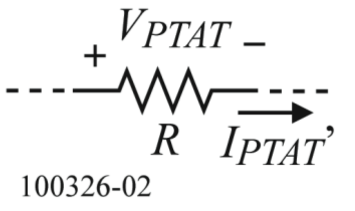
Therefore, if $A_2 = 10A_1$, ΔV_D at room temperature becomes,

$$\Delta V_D = \left[\frac{k}{q}\, ln\left(\frac{A_2}{A_1}\right)\right]T = \left[\frac{1.381\text{x}10^{-23}\text{J/°K}}{1.6\text{x}10^{-19}\text{ Coul}}\, ln(10)\right]T = (+\,0.086\text{mV/°C})T$$

$$\therefore \quad V_{PTAT} = V_t\, ln\left(\frac{A_2}{A_1}\right)$$

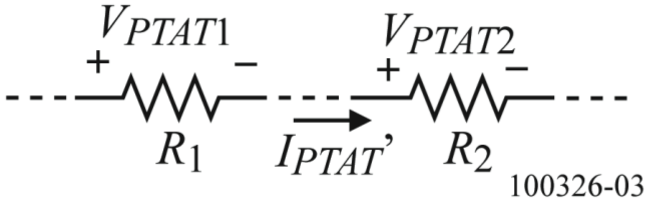
Psuedo-PTAT Currents

In developing temperature independent voltages, it is useful to show how to generate PTAT currents. A straight-forward method is to superimpose V_{PTAT} across a resistor as shown:



Because R is always dependent on temperature, this current is called a *pseudo-PTAT current* and is designated by I_{PTAT}'.

When a pseudo-PTAT current flows through a second resistor with the *same* temperature characteristics as the first, it creates a new V_{PTAT} voltage.



The new V_{PTAT} voltage, V_{PTAT2} is equal to,

$$V_{PTAT2} = \frac{R_2}{R_1} V_{PTAT1}$$

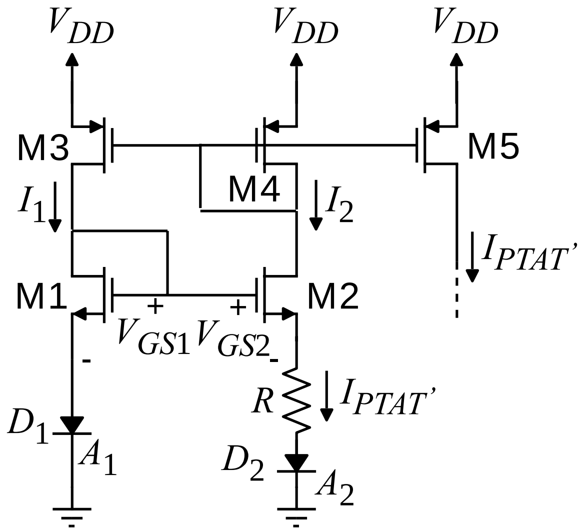
Differentiating with respect to temperature gives

$$\frac{dV_{PTAT2}}{dT} = \frac{R_2}{R_1}\left(\frac{dR_2}{R_2 dT} - \frac{dR_1}{R_1 dT}\right) + \frac{dV_{PTAT1}}{dT}$$

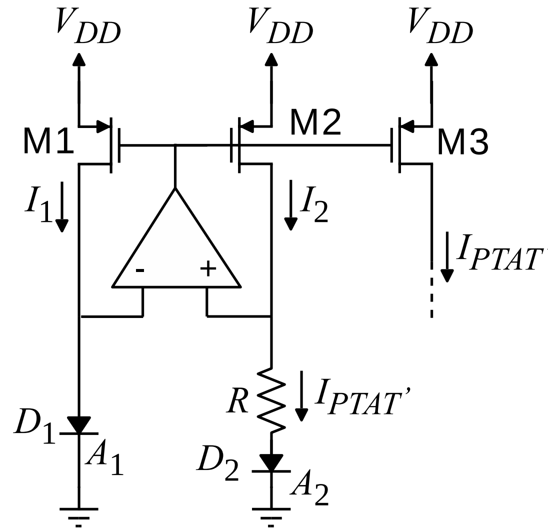
Therefore, if the temperature coefficient of R_1 and R_2 are equal, then the temperature dependence of V_{PTAT2} is the same as V_{PTAT1}.

Pseudo-PTAT Currents - Continued

Pseudo-PTAT currents can be generated through the circuits below which use only MOSFETs and *pn* junctions or MOSFETs, an op amp, and *pn* junctions.



Psuedo-PTAT current generator using only MOSFETs and pn junctions.



Psuedo-PTAT current generator using MOSFETs, an op amp and pn junctions.

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In these circuits, $I_1 = I_2$ and the voltage across D_1 is made equal to the voltage across the series combination of R and D_2 to create the pseudo-PTAT current,

$$I_{PTAT}' = \frac{V_{D1} - V_{D2}}{R} = \frac{kT}{Rq}\ ln\left(\frac{A_2}{A_1}\right)$$

where $V_{GS1} = V_{GS2}$ for the MOSFET only version.

CTAT Voltage

This becomes more challenging because a true CTAT voltage does not exist. The best approach is to examine the *pn* junction (can be a diode or BJT).

The diode voltage can be written as

$$v_D = V_t \ln\left(\frac{i_D}{I_s}\right) = V_t \ln(i_D) - V_t \ln(I_s)$$

where

$$I_s = AT^{\gamma} \exp\left(\frac{V_{BG}}{V_t}\right) \quad \text{and} \quad i_D = BT^{\alpha}$$

and where A and B are temperature independent constants, γ is the temperature coefficient for I_s ($\gamma \approx 3$), α is the temperature coefficient for i_D (α =1 for PTAT), and V_{BG} is the bandgap voltage of silicon (1.205V at 27°C).

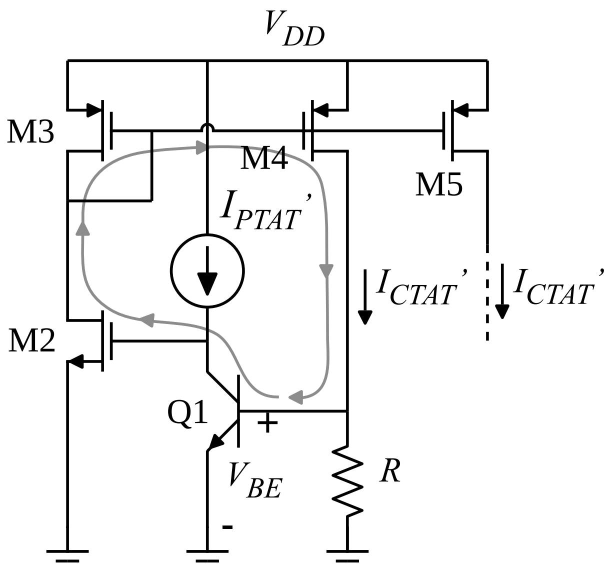
The diode voltage as a function of temperature is,

$$v_D(T) = V_{CTAT} = V_t \ln(BT^{\alpha}) - V_t \ln\left[AT^{\gamma} \exp\left(-\frac{V_{BG}}{V_t}\right)\right] = V_{BG} - V_t(\gamma - \alpha)\ln(T) - V_t \ln(A/B)$$

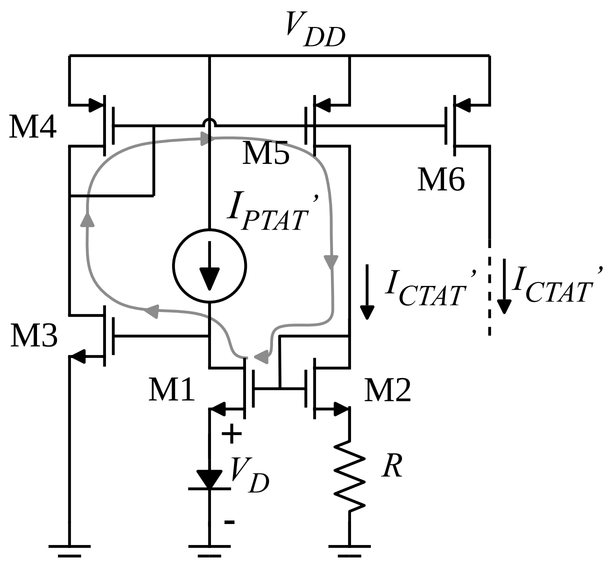
Note that the term $V_t(\gamma\text{-}\alpha)\ln(T)$ is not linear with temperature and cannot completely cancel the perfectly linear PTAT voltage.

Pseudo CTAT Currents

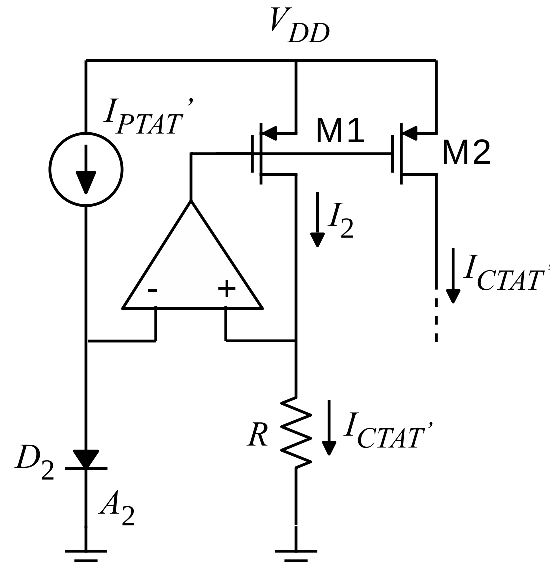
The circuits below show three ways of creating a pseudo CTAT current using negative feedback:†



Generation of a pseudo CTAT current using a bipolar transistor.



Generation of a pseudo CTAT current using a diode.



Generation of a pseudo CTAT current using MOSFETs, an op amp and pn junctions.

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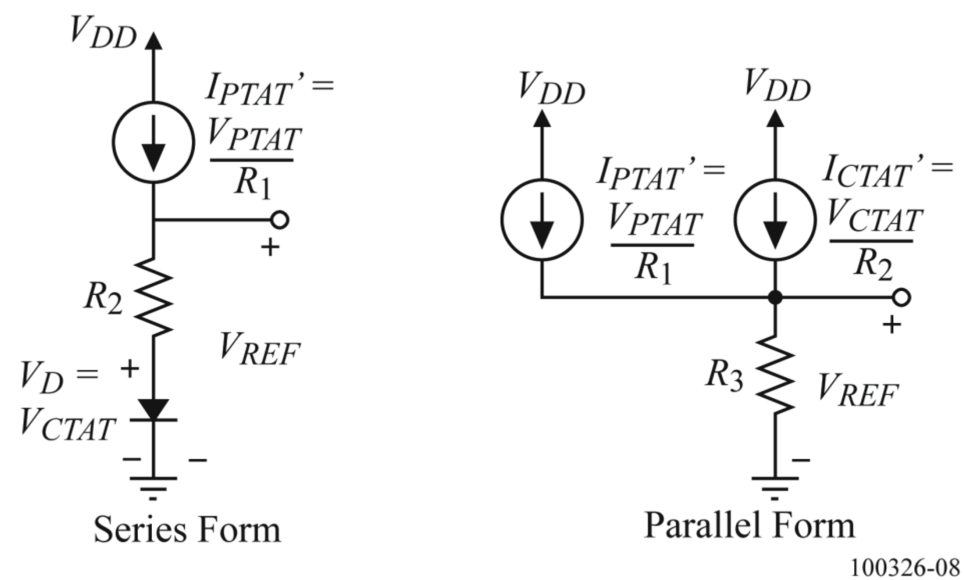
The negative feedback loop shown causes the current designated as I_{CTAT}' to be,

$$I_{\mathrm{CTAT}}' = \frac{V_{BE}}{R} = \frac{V_D}{R}$$

† I.M. Gunawan, G.C.M. Jeijer, J. Fonderie, and J.H. Huijsing, “A Curvature-Corrected Low-Voltage Bandgap Reference, *IEEE J. Solid-state Circuits*, vol. SC-28, No. 6, June 1993, pp. 677-670.

Temperature Independent Voltage References

Basic structures:



Series form:

$$V_{REF} = I_{PTAT}'R_2 + V_D = \left(\frac{R_2}{R_1}\right)V_{PTAT} + V_{CTAT}$$

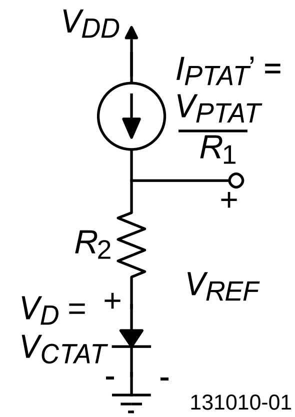
Parallel form:

$$V_{REF} = (I_{PTAT}' + I_{CTAT}')R_3 = \left(\frac{R_3}{R_1}\right)V_{PTAT} + \left(\frac{R_3}{R_2}\right)V_{CTAT} = \left(\frac{R_3}{R_2}\right)\left[\left(\frac{R_2}{R_1}\right)V_{PTAT} + V_{CTAT}\right]$$

To achieve temperature independence, V_{REF} must be differentiated with respect to temperature and set equal to zero. The resistor ratios and other parameters can be used to achieve temperature independence.

Series Temperature Stable Voltage Source

Series Configuration:



From the circuit on the right, we get

$$V_{REF} = I_{PTAT}'R_2 + V_D = (R_2/R_1)V_{PTAT} + V_{CTAT} = \mathrm{K}V_{PTAT} + V_{CTAT}$$

Substituting for V_{PAT} and V_{CTAT} gives,

$$V_{REF} = \mathrm{K}V_t\ln(A_2/A_1) + V_{BG} - V_t(\gamma-\alpha)\ln(T) - V_t\ln(A/B)$$

Differentiating with respect to T and setting $T = T_0$ gives,

$$\frac{dV_{REF}}{dT}(T=T_0) = \mathrm{K}\ln(A_2/A_1)\frac{V_{t0}}{T_0} - \frac{V_{t0}}{T_0}\ln(\mathrm{A/B}) - \frac{V_{t0}}{T_0}(\gamma-\alpha)\ln(T_0) - (\gamma-\alpha)\frac{V_{t0}}{T_0}$$

Equating the derivative to zero gives,

$$\mathrm{K}\ln(A_2/A_1) - \ln(\mathrm{A/B}) = (\gamma-\alpha)[1+\ln(T_0)]$$

Substituting back gives,

$$V_{REF} = (\gamma-\alpha)V_t[1+\ln(T_0)] + V_{BG} - V_t(\gamma-\alpha)\ln(T) = V_{BG} + (\gamma-\alpha)V_t\left[1+\ln\left(\frac{T_0}{T}\right)\right]$$

At $T = T_0$, assuming $\gamma = 3.2$ and $\alpha = 1$, the reference voltage is

$$V_{REF} = V_{BG} + V_t(\gamma-\alpha) = 1.205\text{V} + 0.057\text{V} = 1.262\text{V}\ (T_0 = 27°\text{C})$$

Because $V_{REF} \approx V_{BG}$, this voltage reference is called the "bandgap reference".

Series Temperature Stable Voltage Source

Eliminating the constants ln(A/B):

Express the *pn* junction voltage at a reference temperature, T_o, and T

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

and

$$v_D(T_o) = V_{BG} - V_{to}(\gamma - \alpha)\ln(T_o) - V_{to}\ln(\mathrm{A/B})$$

Eliminating the ln(A/B) term gives,

$$v_D(T) = V_{BG} - \frac{T}{T_o}\left[V_{BG} - v_D(T_o)\right] - (\gamma - \alpha)V_t\ln\left(\frac{T}{T_o}\right)$$

Approximating the ln(T/T_o) term with a Taylor's series expansion gives,

$$\ln\left(\frac{T}{T_o}\right) \approx \left(\frac{T - T_o}{T}\right) + \frac{1}{2}\left(\frac{T - T_o}{T}\right)^2 + \frac{1}{3}\left(\frac{T - T_o}{T}\right)^3 + \cdots$$

Substituting this into the above gives

$$v_D(T) = V_{BG} - \frac{T}{T_o}\left[V_{BG} - v_D(T_o)\right] - (\gamma - \alpha)V_t\left(\frac{T - T_o}{T_o}\right) - \frac{(\gamma - \alpha)V_t}{2}\left(\frac{T - T_o}{T_o}\right)^2 - \frac{(\gamma - \alpha)V_t}{3}\left(\frac{T - T_o}{T_o}\right)^3 + \cdots$$

Series Temperature Stable Voltage Source

Tuning V_{REF} (solving for K):

From the previous slide, let V_{CTAT} be approximated as,

$$v_D(T) = V_{CTAT} \approx V_{BG} - \frac{T}{T_o}\left[V_{BG} - v_D(T_o)\right] - (\gamma-\alpha)V_t\left(\frac{T-T_o}{T_o}\right)$$

V_{REF} can be written as,

$$V_{REF} = K\cdot V_{PTAT} + V_{CTAT} \approx KV_t\ln\left(\frac{A_2}{A_1}\right) + V_{BG} - \frac{T}{T_o}\left[V_{BG} - v_D(T_o)\right] - (\gamma-\alpha)V_t\left(\frac{T-T_o}{T_o}\right)$$

Differentiating V_{REF} with respect to temperature and setting $T = T_o$ gives,

$$\frac{dV_{REF}}{dT}(T=T_o) = \frac{KV_{to}}{T_o}\ln\left(\frac{A_2}{A_1}\right) - \frac{V_{BG} - v_D(T_o)}{T_o} - \frac{(\gamma-\alpha)V_{to}}{T_o} = 0$$

Solving for K gives,

$$K = \frac{V_{BG} - v_D(T_o) - (\gamma-\alpha)V_{to}}{V_{to}\ln\left(\frac{A_2}{A_1}\right)} \quad \Rightarrow \quad R_2 = \frac{V_{BG} - v_D(T_o) - (\gamma-\alpha)V_{to}}{I_{PTAT}}$$

Example 17-1 – Temp. Independent Constant for Series and Parallel References

(a.) Design the ratio of R_2/R_1 for the series configuration if V_{CTAT} = 0.6V and A_2/A_1 = 10 for room temperature (V_t = 0.026V). Assume γ = 3.2 and α = 1. Find the value of $V_{\rm REF}$.

$$\frac{R_2}{R_1} = \frac{V_{GO} - V_{CTAT} + (\gamma-\alpha)V_{t0}}{V_{PTAT}} = \frac{1.205 - 0.6 + 2.2(0.026)}{0.026(2.3026)} = 11.05$$

$$V_{\rm REF} = 1.205 + 2.2(0.026) = 1.262\text{V}$$

If R_1 = 1kΩ, then R_2 = 11.05kΩ

(b.) For the parallel configuration find the values of R_2/R_1 and R_3/R_2 if $V_{\rm REF}$ = 0.5V.

From (a.) we know that R_2/R_1 = 11.05. We also know that,

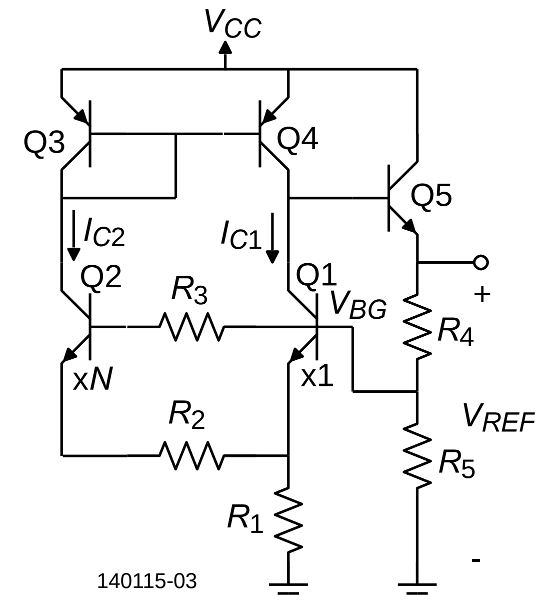
$$V_{\rm REF} = \left(\frac{R_3}{R_1}\right)V_{\rm PTAT} + \left(\frac{R_3}{R_2}\right)V_{\rm CTAT} = \left(\frac{R_3}{R_2}\right)\left[\left(\frac{R_2}{R_1}\right)V_{\rm PTAT} + V_{\rm CTAT}\right]$$

$$= (R_3/R_2)[11.05\,ln(10)(0.026) + 0.6] = (R_3/R_2)1.262 = 0.5$$

$$\therefore \quad (R_3/R_2) = 0.3963$$

If R_1 = 1kΩ, then R_2 = 11.05kΩ and R_3 = 4.378kΩ

Simple Brokaw Bandgap[†]



Circuit:

The voltage across R_2 is,

$$V_{R2} = V_{PTAT} = V_t \ln(N)$$

creating the PTAT current flowing through Q2.

The bandgap voltage, V_{BG}, is,

$$V_{BG} = \frac{2R_1 V_t \ln(N)}{R_2} + V_{BE1}$$

The resistor divider R_4-R_5 "gains up" this voltage to

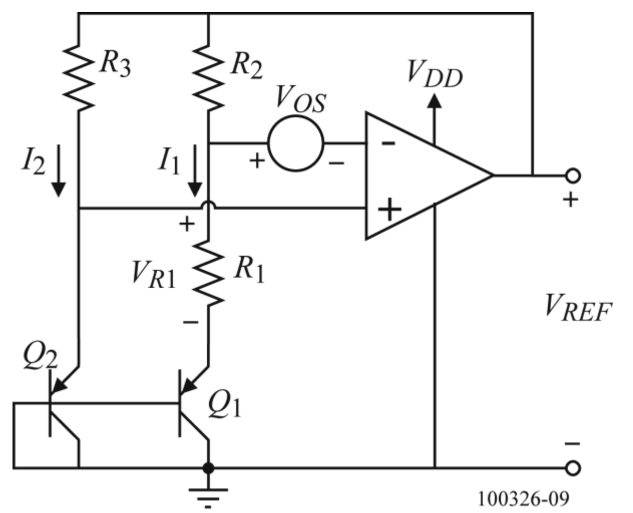
$$V_{REF} = \left(\frac{R_4 + R_5}{R_5}\right)\left[\frac{2R_1 V_t \ln(N)}{R_2} + V_{BE1}\right]$$

The resistor R_3 eliminates the impact of the base currents of Q1 and Q2

$$V'_{REF} = V_{REF} + R_4(I_{B1} + I_{B2}) - I_{B2} R_3 \frac{2(R_4 + R_5)R_1}{R_2 R_5} \quad \rightarrow \quad R_3 = \frac{R_2 R_4 R_5}{R_1(R_4 + R_5)}$$

[†] A.P. Brokaw, "A Simple Three-Terminal IC Bandgap Reference," *IEEE J. Solid-State Circuits*, Vol. SC-6, No. 1, 1971, pp. 2-7.

A Series Temperature Independent Voltage Reference



An early realization of the series form is shown below[†]:

Assuming $V_{OS} = 0$, then V_{R1} is

$$V_{R1} = V_{EB2} - V_{EB1} = V_t \ln\left(\frac{J_2}{J_{s2}}\right) - V_t \ln\left(\frac{J_1}{J_{s1}}\right)$$

$$= V_t \ln\left(\frac{I_2 A_{E1}}{I_1 A_{E2}}\right) = V_t \ln\left(\frac{R_2 A_{E1}}{R_3 A_{E2}}\right)$$

The op amp forces the relationship $I_1 R_2 = I_2 R_3$

$$\therefore V_{REF} = V_{EB2} + I_2 R_3 = V_{EB2} + V_{R1}\left(\frac{R_2}{R_1}\right) = V_{EB2} + \left(\frac{R_2}{R_1}\right) V_t \ln\left(\frac{R_2 A_{E1}}{R_3 A_{E2}}\right) = V_{CTAT} + \left(\frac{R_2}{R_1}\right) \ln\left(\frac{R_2 A_{E1}}{R_3 A_{E2}}\right) V_t$$

Differentiating the above with respect to temperature and setting the result to zero, gives

$$\left(\frac{R_2}{R_1}\right) \ln\left(\frac{R_2 A_{E1}}{R_3 A_{E2}}\right) = \frac{V_{GO} - V_{CTAT} + (\gamma - \alpha) V_{t0}}{V_t}$$

If $V_{OS} \neq 0$, then V_{REF} becomes,

$$V_{REF} = V_{EB2} - \left(1 + \frac{R_2}{R_1}\right) V_{OS} + \frac{R_2}{R_1} V_t \ln\left[\frac{R_2 A_{E1}}{R_3 A_{E2}}\left(1 - \frac{V_{OS}}{I_1 R_2}\right)\right]$$

† K.E. Kujik, "A Precision Reference Voltage Source," *IEEE Journal of Solid-State Circuits*, Vol. SC-8, No. 3 (June 1973) pp. 222-226.

Example 17-2 – Design of the Previous Temperature Independent Reference

Assume that $A_{E1} = 10\ A_{E2}$, $V_{EB2} = 0.7$ V, $R_2 = R_3$, and $V_t = 0.026$ V at room temperature for temperature independent reference on the previous slide. Find R_2/R_1 to give a zero temperature coefficient at room temperature. If $V_{OS} = 10$ mV, find the change in V_{REF}. Note that $I_1R_2 = V_{REF} - V_{EB2} - V_{OS}$.

Evaluating the temperature independent constant gives

$$\left(\frac{R_2}{R_1}\right)\ln\left(\frac{R_2\,A_{E1}}{R_3A_{E2}}\right) = \frac{V_{GO} - V_{CTAT} + (\gamma-\alpha)V_{t0}}{V_{PTAT}} = \frac{1.205 - 0.7 + (2.2)(0.026)}{0.026} = 21.62$$

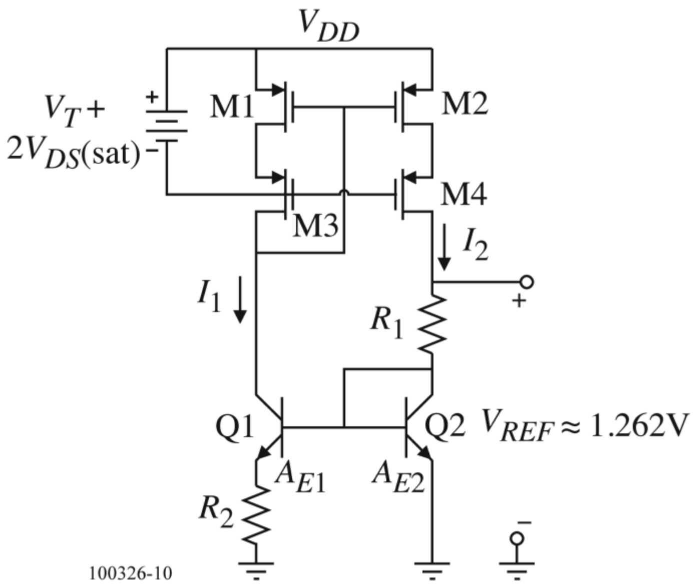
Therefore, $R_2/R_1 = 9.39$. In order to use the equation for V_{REF} with $V_{OS} \neq 0$, we must know the approximate value of V_{REF} and iterate if necessary because I_1 is a function of V_{REF}. Assuming V_{REF} to be 1.262, we obtain from

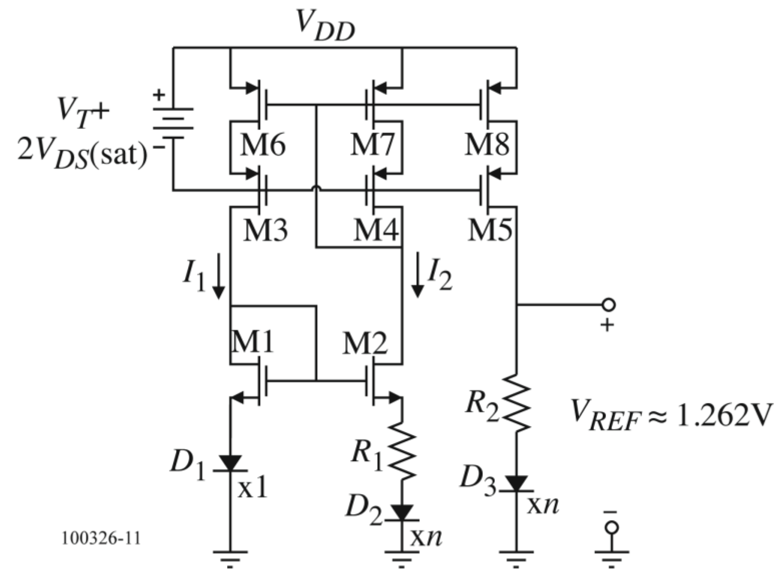
$$V_{REF} = V_{EB2} - \left(1 + \frac{R_2}{R_1}\right)V_{OS} + \frac{R_2}{R_1}\,V_t\,ln\left[\frac{R_2A_{E1}}{R_1A_{E2}}\left(1 - \frac{V_{OS}}{V_{REF} - V_{EB2} - V_{OS}}\right)\right]$$

a new value $V_{REF} = 1.153$ V. The second iteration makes little difference on the result because V_{REF} is in the argument of the logarithm

Series Temperature Independent Voltage References

The references shown do not use an op amp and avoid the issues of loop stability and PSRR.





$$I_1 = I_{\text{PTAT}}' = \frac{V_{BE2} - V_{BE1}}{R_2} = \frac{V_t}{R_2}\left[\ln\left(\frac{I_2}{I_{s2}}\right) - \ln\left(\frac{I_1}{I_{s1}}\right)\right]$$

$$= \frac{V_t}{R_2}\ln\left(\frac{I_{s1}}{I_{s2}}\right) = \frac{V_t}{R_2}\ln\left(\frac{A_{E1}}{A_{E2}}\right)$$

Since $I_1 = I_2$, $V_{REF} = V_{BE2} + I_1R_1 = V_{BE2} + \left(\frac{R_1}{R_2}\ln\left(\frac{A_{E1}}{A_{E2}}\right)\right)V_t$

$$= V_{\text{CTAT}} + \left(\frac{R_1}{R_2}\right)V_{\text{PTAT}}$$

$$V_{D1} = I_2R_1 + V_{D2}$$

$$I_3 = I_2 = I_{\text{PTAT}}' = \frac{V_t}{R_1}\,ln(n)$$

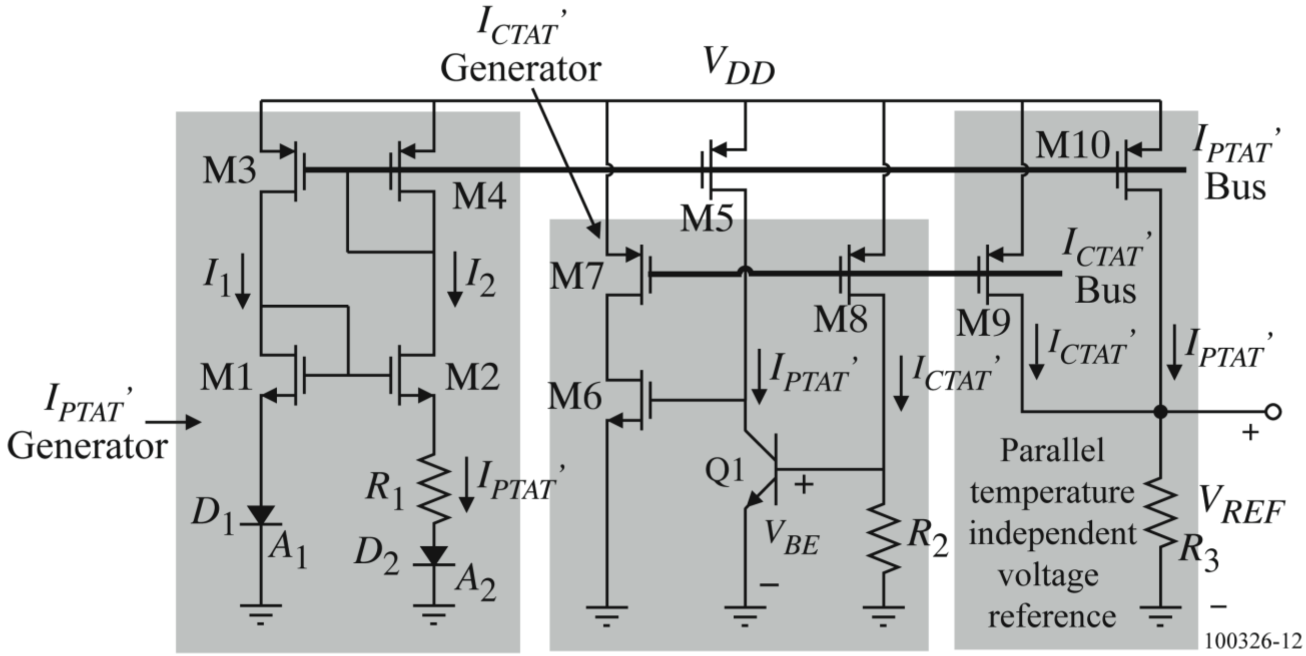
Let $R_1 = R$ and $R_2 = kR$,

$$V_{REF} = V_{D3} + I_3(kR) = V_{D3} + kV_t\ln(n)$$

$$= V_{\text{CTAT}} + kV_{\text{PTAT}}$$

Parallel Temperature Independent Voltage Reference

A parallel form of the temperature independent voltage reference is shown below:



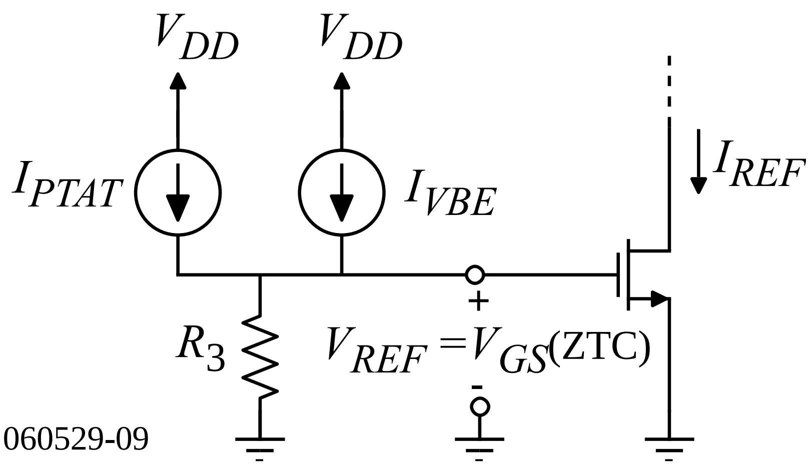
$$V_{REF} = \left(\frac{R_3}{R_1}\right)V_{PTAT} + \left(\frac{R_3}{R_2}\right)V_{CTAT}$$

Comments:

- The BJT of the I_{CTAT}' generator can be replaced with an MOSFET-diode equivalent
- Any value of V_{REF} can be achieved
- Part (b.) of Example 17-1 showed how to design the resistors of this implementation

How Can a Bandgap "Current" Reference be Obtained?

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



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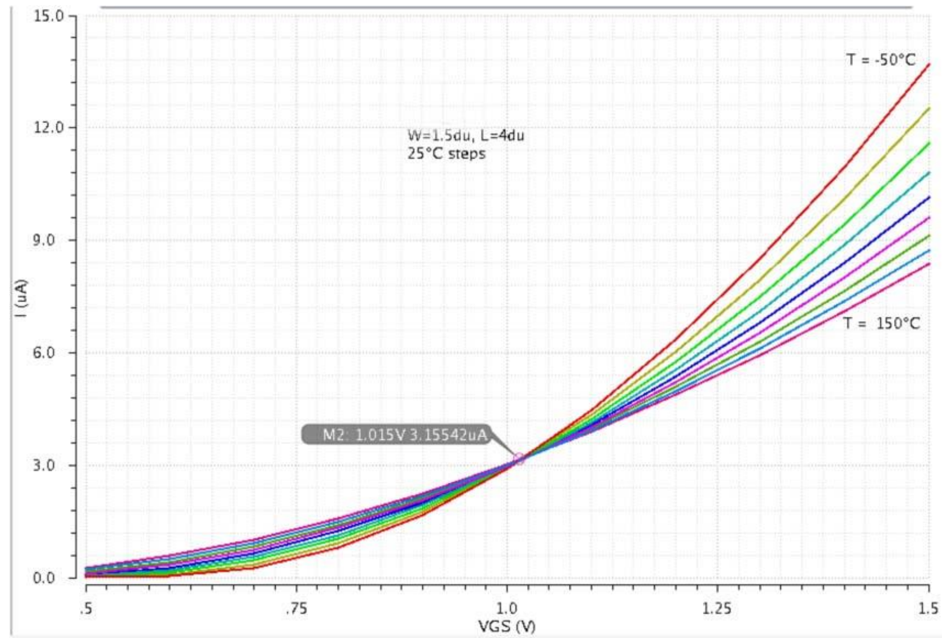
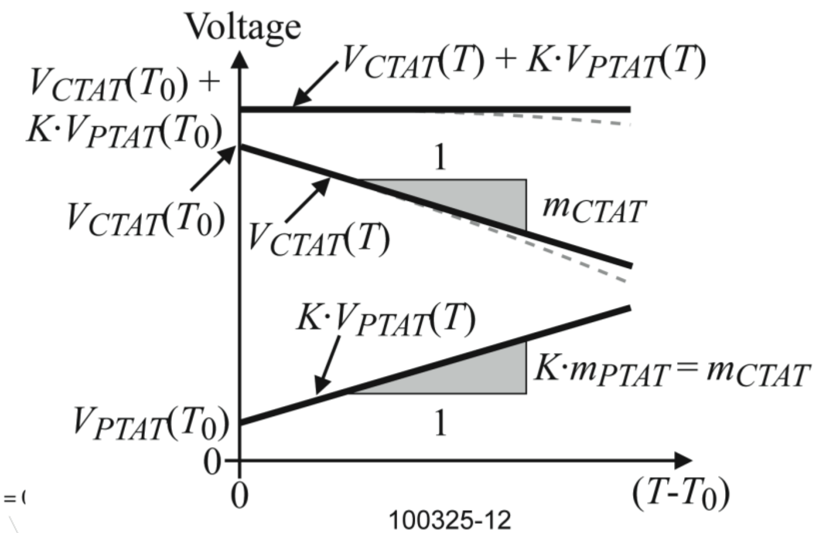


Comments:

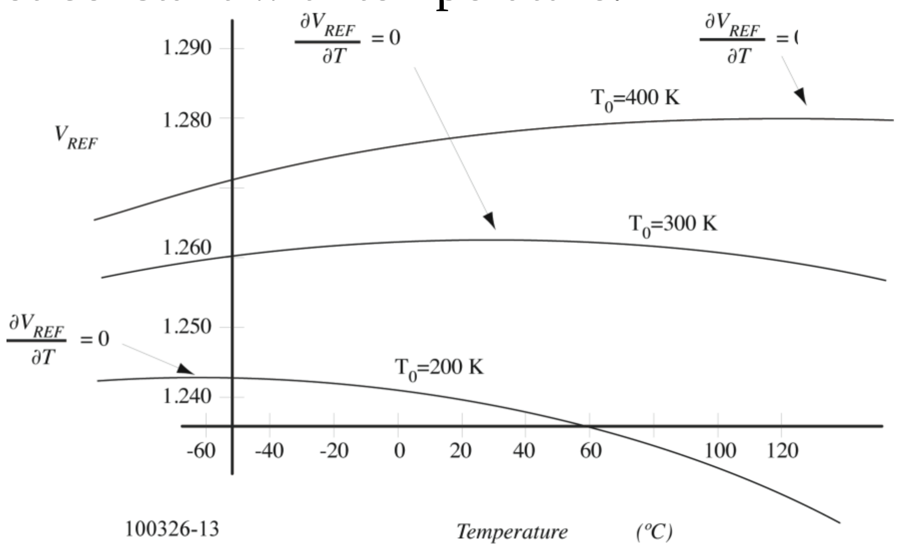
- Ability of the ZTC point not to drift with temperature restricts the temperature range
- The reference voltage must be equal to the ZTC voltage
- The voltage V_{REF} will suffer the bandgap curvature problem which can be translated into I_{REF}.

Bandgap Curvature Problem

Unfortunately, the $\frac{\gamma kT}{q}\ln\left(\frac{T_0}{T}\right)$ term of the *pn* junction contributed a nonlinearity to the CTAT realization. This is illustrated by the dashed lines in the plot shown.



The result is shown below where the reference voltage is not constant with temperature.



Comments:

- True temperature independence is only achieved over a small range of temperatures
- References that do not correct this problem have a temperature dependence of 10 ppm°/C to 50 ppm/°C over 0°C to 70°C.

Some Curvature Correction Techniques

- Squared PTAT Correction:

  Temperature coefficient ≈ 1-20 ppm/°C

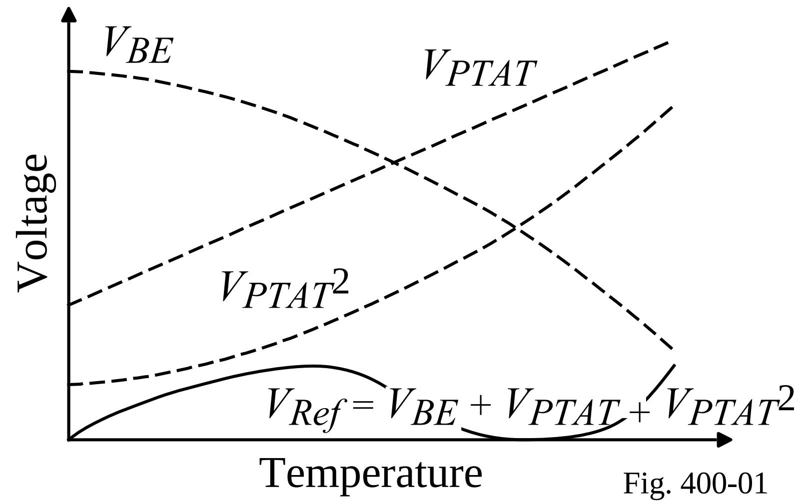


Fig. 400-01

- V_{BE} loop

  M. Gunaway, *et. al.*, "A Curvature-Corrected Low-Voltage Bandgap Reference," *IEEE Journal of Solid-State Circuits*, vol. 28, no. 6, pp. 667-670, June 1993.

- Nonlinear cancellation

  G.M. Meijer et. al., "A New Curvature-Corrected Bandgap Reference," IEEE Journal of Solid-State Circuits, vol. 17, no. 6, pp. 1139-1143, December 1982.

V_{BE} Loop Curvature Correction Technique

Circuit:

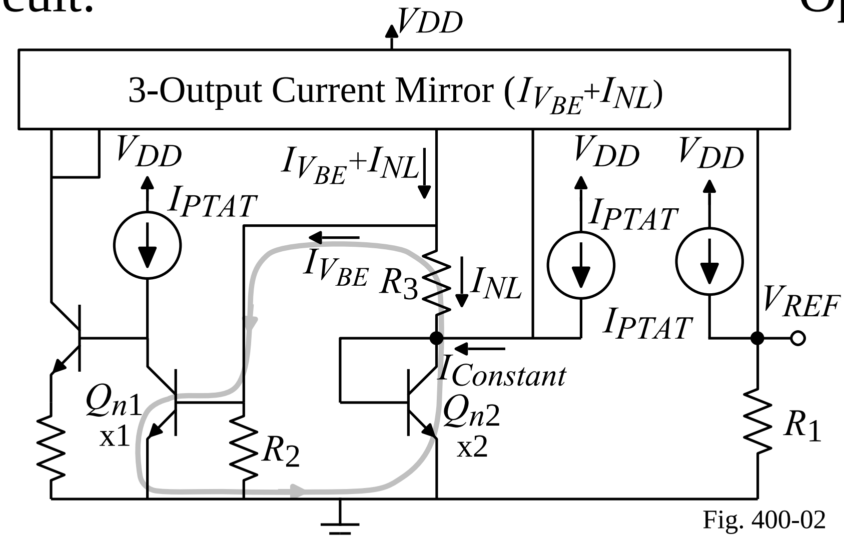


Fig. 400-02

Operation:

$$I_{NL} = \frac{V_{BE1}-V_{BE2}}{R_3} = \frac{V_t}{R_3} \ln\left(\frac{I_{c1}A_2}{A_1 I_{c2}}\right)$$

$$= \frac{V_t}{R_3} \ln\left(\frac{2I_{PTAT}}{I_{NL}+I_{Constant}}\right)$$

where

$$I_{constant} = I_{NL} + I_{PTAT} + I_{VBE}$$

$$\approx I_{NL} + \frac{V_t}{R_x} + \frac{V_{BE}}{R_2}$$

($I_{constant}$ a quasi-temperature independent current subject to the TC_F of the resistors)

where

$V_t = kT/q$

I_{c1} and I_{c2} are the collector currents of Q_{n1} and Q_{n2}, respectively

R_x = a resistor used to define I_{PTAT}

$$\therefore \quad V_{REF} = \left[\frac{V_{BE}}{R_2} + \frac{V_t}{R_3} \ln\left(\frac{2I_{PTAT}}{I_{NL} + I_{constant}}\right) + I_{PTAT}\right] R_1$$

Temperature coefficient ≈ 3 ppm/°C with a total quiescent current of 95µA.

Series Temperature Independent Voltage Reference with Curvature Correction

Objective: Eliminate nonlinear term from V_{CTAT}.

Result: 0.5 ppm/°C from -25°C to 85°C.

Operation:

$$V_{REF} = V_{PTAT} + 3V_{CTAT} - 2V_{Constant}$$

Note that, $I_{PTAT} \Rightarrow I_c \propto T^1 \quad \Rightarrow \alpha = 1$

and $I_{Constant} \Rightarrow I_c \propto T^0 \quad \Rightarrow \alpha = 0,$

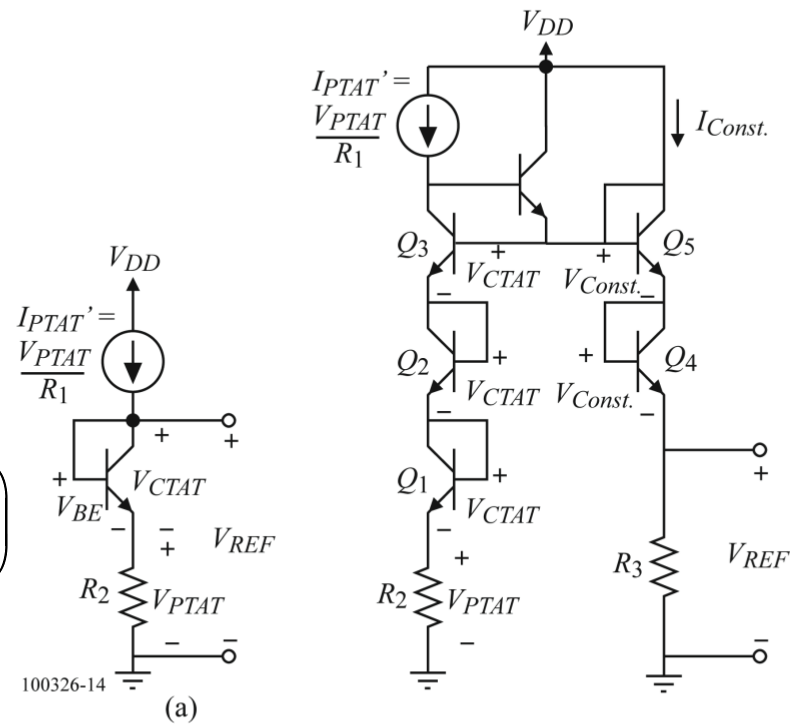
Previously we found,

$$V_{CTAT}(T) \approx V_{GO} - \frac{T}{T_0}\left[V_{GO} - V_{CTAT}(T_0)\right] - (\gamma - \alpha)V_t \ln\left(\frac{T}{T_0}\right)$$

so that

$$V_{CTAT}(I_{PTAT}) = V_{GO} - \frac{T}{T_0}\left[V_{GO} - V_{BE}(T_0)\right] - (\gamma - 1)V_t \ln\left(\frac{T}{T_0}\right)$$

and $V_{CTAT}(I_{Constant}) = V_{GO} - \dfrac{T}{T_0}\left[V_{GO} - V_{CTAT}(T_0)\right] - \gamma V_t \ln\left(\dfrac{T}{T_0}\right)$



Combining the above relationships gives,

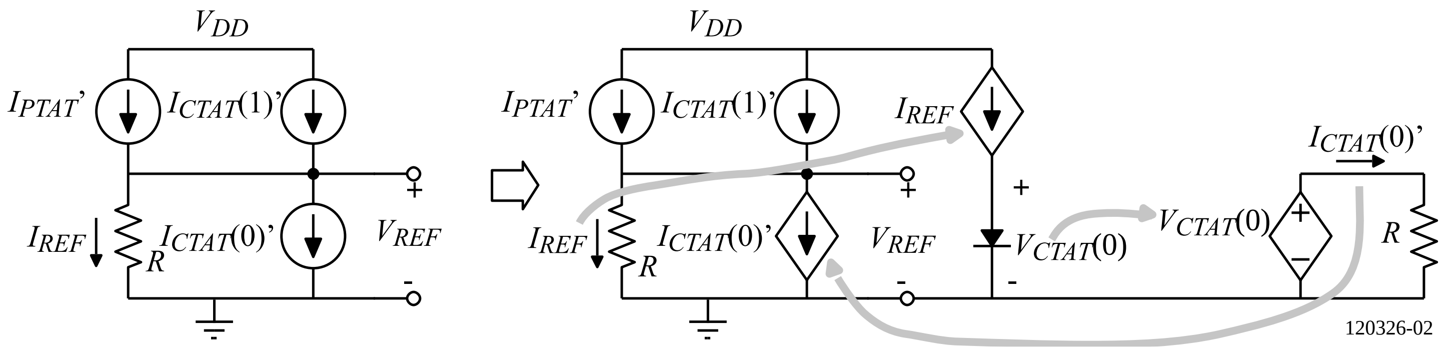
$$V_{REF}(T) = V_{PTAT} + V_{GO} - (T/T_0)[V_{GO} - V_{CTAT}(T_0)] - [\gamma - 3]\, V_t \ln((T/T_0))$$

If $\gamma \approx 3$, then $V_{REF}(T) \approx V_{PTAT} + V_{GO}(1 - (T/T_0)) + V_{CTAT}(T_0)(T/T_0)$

A Parallel Version of the Nonlinear Curvature Correction Technique

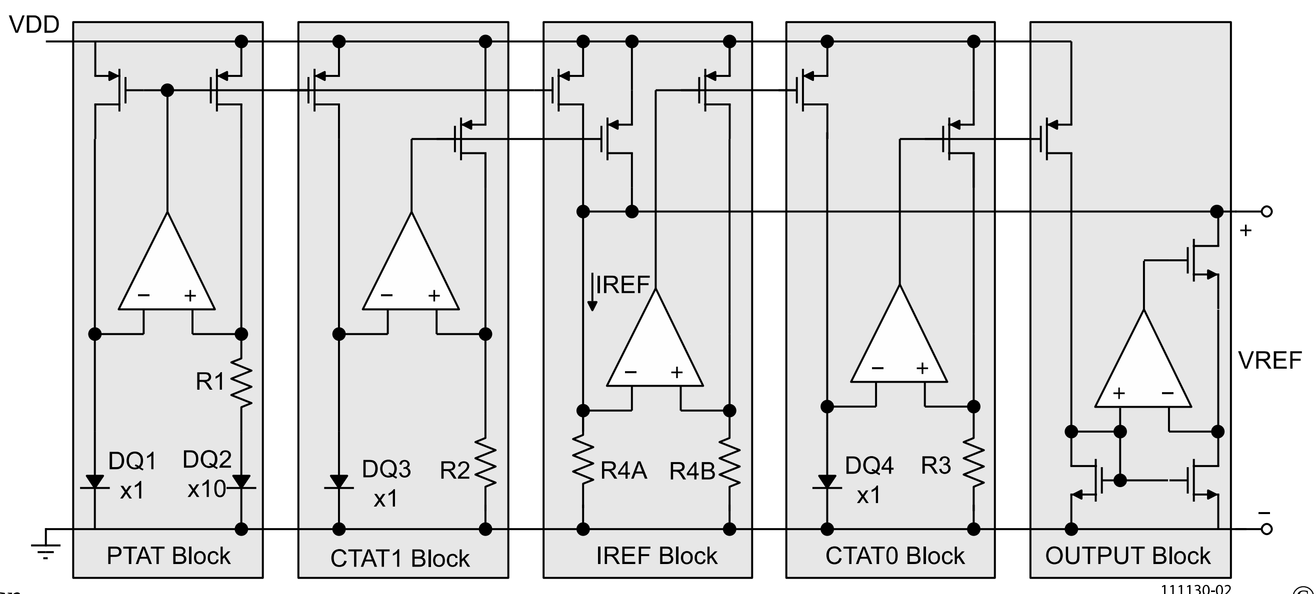
Disadvantages of the series temperature independent voltage reference includes stacking of transistors and integer resolution in the cancellation of the nonlinear term.

Concept:



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

Block Diagram:



Design Relationships for the Parallel Nonlinear Curvature Correction Reference

From the previous block diagram, if $R_{4A} = R_{4B} = R_4$, then

$$V_{REF} = \frac{R_4}{R_1} V_{PTAT} + \frac{R_4}{R_2} V_{CTAT1} - \frac{R_4}{R_3} V_{CTAT0}$$

Previously we saw that,

$$V_{CTAT1} = V_{CTAT}(I_{PTAT}) = V_{GO} - \frac{T}{T_0}\left[V_{GO} - V_{BE}(T_0)\right] - (\gamma - 1)V_t \, ln\left(\frac{T}{T_0}\right)$$

and

$$V_{CTAT0} = V_{CTAT}(I_{Constant}) = V_{GO} - \frac{T}{T_0}\left[V_{GO} - V_{CTAT}(T_0)\right] - \gamma V_t \, ln\left(\frac{T}{T_0}\right)$$

To cancel the nonlinear temperature term requires that,

$$\frac{R_4}{R_2}(\gamma - 1)V_t \, ln\left(\frac{T}{T_0}\right) = \frac{R_4}{R_3}\gamma V_t \, ln\left(\frac{T}{T_0}\right) \qquad \text{or} \qquad \boxed{\frac{R_3}{R_2} = \frac{\gamma}{\gamma - 1}}$$

Define $V_{CTAT} = V_{GO} - \frac{T}{T_0}\left[V_{GO} - V_{BE}(T_0)\right] = V_{BE}(T_0)$ if $T = T_0$.

Therefore,

$$V_{REF} = \frac{R_4}{R_1} V_{PTAT} + \frac{1}{\gamma}\frac{R_4}{R_2} V_{CTAT}$$

Design Relationships – Continued

Differentiating V_{REF} with respect to temperature at $T = T_0$ and setting equal to 0 gives,

$$\boxed{\frac{R_2}{R_1} = -T\,\frac{\dfrac{dV_{CTAT}}{dT}}{\gamma V_{PTAT}}}$$

The design procedure for the parallel, curvature corrected reference is:

1.) Pick R_1. Can be used to set the magnitude of current flow based on *IPTAT*.

2.) Choose R_2 to satisfy $\dfrac{R_2}{R_1} = -T\,\dfrac{dV_{CTAT}/dT}{\gamma V_{PTAT}}$

3.) Pick R_3 to satisfy $\dfrac{R_3}{R_2} = \dfrac{\gamma}{\gamma - 1}$

4.) Finally, select $R_{4A} = R_{4B} = R_4$ to achieve the desired magnitude of V_{REF}

$$V_{REF} = \frac{R_4}{R_1} V_{PTAT} + \frac{1}{\gamma}\frac{R_4}{R_2} V_{CTAT} = \frac{R_4}{R_2}\left[\frac{R_2}{R_1} V_{PTAT} + \frac{V_{CTAT}}{\gamma}\right]$$

$$= \frac{R_4}{R_2}\left[\frac{-T}{\gamma}\frac{d}{dT}\left(V_{GO} - \frac{T}{T_0} V_{GO} + \frac{T}{T_0} V_{CTAT}\right) + \frac{V_{CTAT}}{\gamma}\right] = \frac{R_4}{R_2}\frac{V_{GO}}{\gamma}$$

Example 17-3 – Design of a Zero Temperature Coefficient Voltage Reference

Assume that $V_{CTAT} = 0.7$ V, $R_1 = 10\text{k}\Omega$, $\gamma = 3.2$, $A_2 = 10A_1$, $V_t = 0.026$ V and $dV_{CTAT}/dT = -3\text{mV/°C}$ at room temperature for the parallel temperature independent voltage reference. Find R_2, R_3 and R_4 to give a zero temperature coefficient at room temperature and a reference voltage of 0.72V.

Solution

Following the previous design procedure, we get,

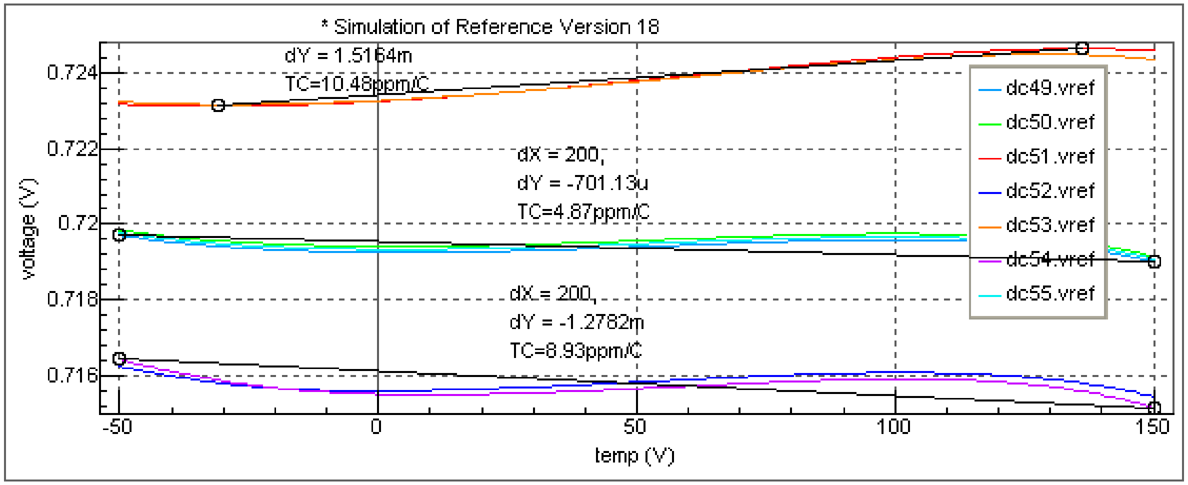
1.) $R_2 = (-300)\dfrac{(-0.003)}{3.2(0.0259)ln10}\ 10\text{k}\Omega = 47.16\ \text{k}\Omega$

2.) $R_3 = R_2\dfrac{\gamma}{\gamma\text{-}1} = \dfrac{47.16\text{k}\Omega(3.2)}{2.2} = 68.60\ \text{k}\Omega$

3.) $V_{REF} = 0.72\text{V} = \dfrac{R_4}{R_2}\dfrac{V_{GO}}{\gamma} \quad \Rightarrow \quad R_4 = \dfrac{V_{REF}}{V_{GO}}\gamma R_2 = \dfrac{0.72}{1.205}\ 3.2(47.16\ \text{k}\Omega)) = 90.17\ \text{k}\Omega$

Results and Practical Considerations

Worst case tempco:

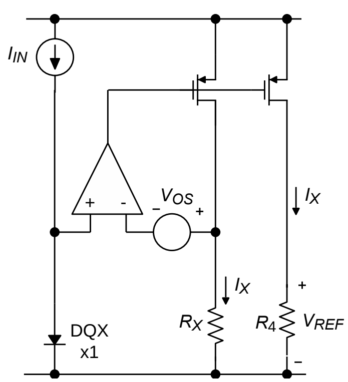


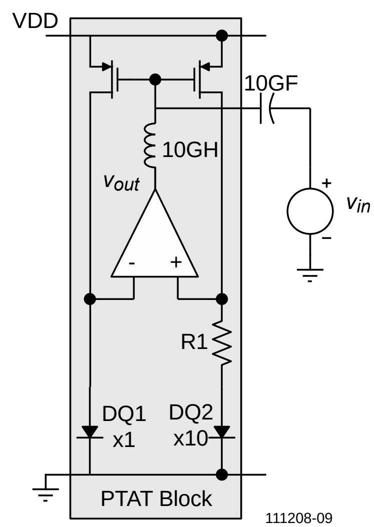
Practical considerations:

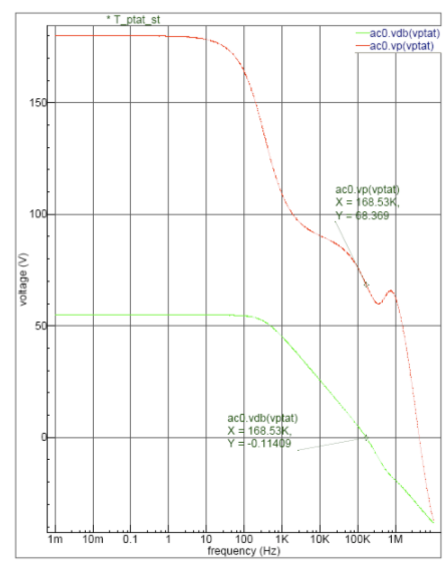
- Stability of feedback loops
- Influence of the op amp V_{OS}

$$V_{REF}(\text{error}) \approx V_{OS}\left(\frac{R_4}{R_1} + \frac{R_4}{R_2} + \frac{R_4}{R_3}\right)$$

- Tuning







Other Characteristics of Bandgap Voltage References

Noise

Voltage references for high-resolution ADCs are particularly sensitive to noise.

Noise sources: Op amp, resistors, switches, etc.

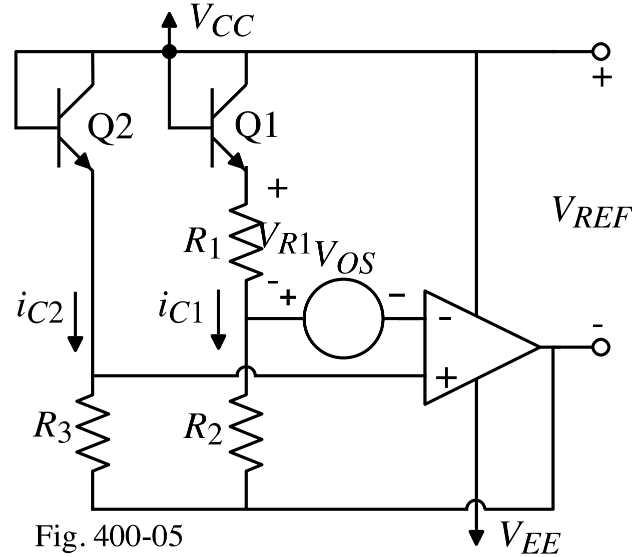


Fig. 400-05

PSRR

Maximize the PSRR of the op amp.

Offset Voltages

Becomes a problem when op amps are used.

$$V_{BE2} = V_{BE1} + V_{R1} + V_{OS}$$

$$\Delta V_{BE} = V_{BE2} - V_{BE1} = V_{R1} + V_{OS} = V_t \ln\left(\frac{i_{C2}A_{E1}}{i_{C1}A_{E2}}\right)$$

Since $\quad i_{C2}R_3 = i_{C1}R_2 - V_{OS}$

then $\quad \dfrac{i_{C2}}{i_{C1}} = \dfrac{R_2}{R_3} - \dfrac{V_{OS}}{i_{C1}R_3} = \dfrac{R_2}{R_3}\left(1 + \dfrac{V_{OS}}{i_{C1}R_2}\right)$

Therefore, $\quad V_{R1} = -V_{OS} + V_t \ln\left[\dfrac{R_2A_{E1}}{R_3A_{E2}}\left(1 + \dfrac{V_{OS}}{i_{C1}R_2}\right)\right]$

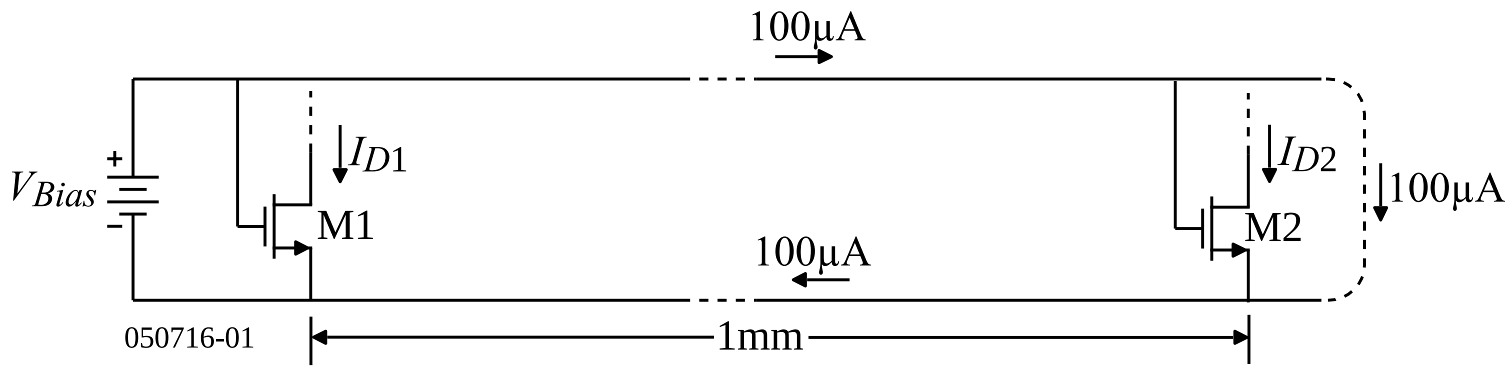
$$V_{REF} = V_{BE2} - V_{OS} + i_{C1}R_2 = V_{BE2} - V_{OS} + \left(\frac{V_{R1}}{R_1}\right)R_2 = V_{BE2} - V_{OS} + \left(\frac{R_2}{R_1}\right)$$

$$\therefore \quad \boxed{V_{REF} = V_{BE2} - V_{OS}\left(1+\frac{R_2}{R_1}\right) + \frac{R_2}{R_1}V_t \ln\left[\frac{R_2A_{E1}}{R_3A_{E2}}\left(1 - \frac{V_{OS}}{i_{C1}R_2}\right)\right]}$$

DESIGN OF BIAS VOLTAGES FOR A CHIP

Distributing Bias Voltages over a Distance

The major problem is the *IR* drops in busses. For example,



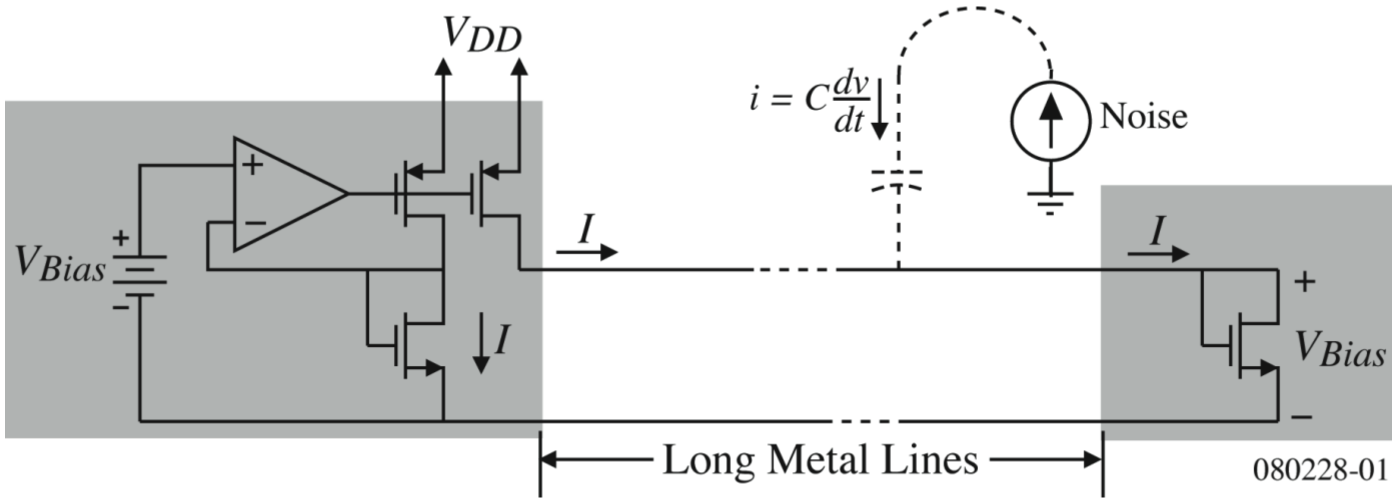
If the bus metal is 50mΩ/sq. and is 5µm wide, the resistance of the bus in one direction is (50mΩ/sq.)x(1000µm/5µm) = 10Ω. The difference in drain currents for an overdrive of 0.1V is,

$$V_{GS1} = 1\text{mV} + V_{GS2} + 1\text{mV} = V_{GS2} + 2\text{mV}$$

$$\frac{I_{D1}}{I_{D2}} = \frac{(V_{GS1}-V_{TN})^2}{(V_{GS2}-V_{TN})^2} = \frac{(V_{GS2}-V_{TN}+2\text{mV})^2}{(V_{GS2}-V_{TN})^2} = \left(\frac{0.1+0.002}{0.1}\right)^2 = 1.04$$

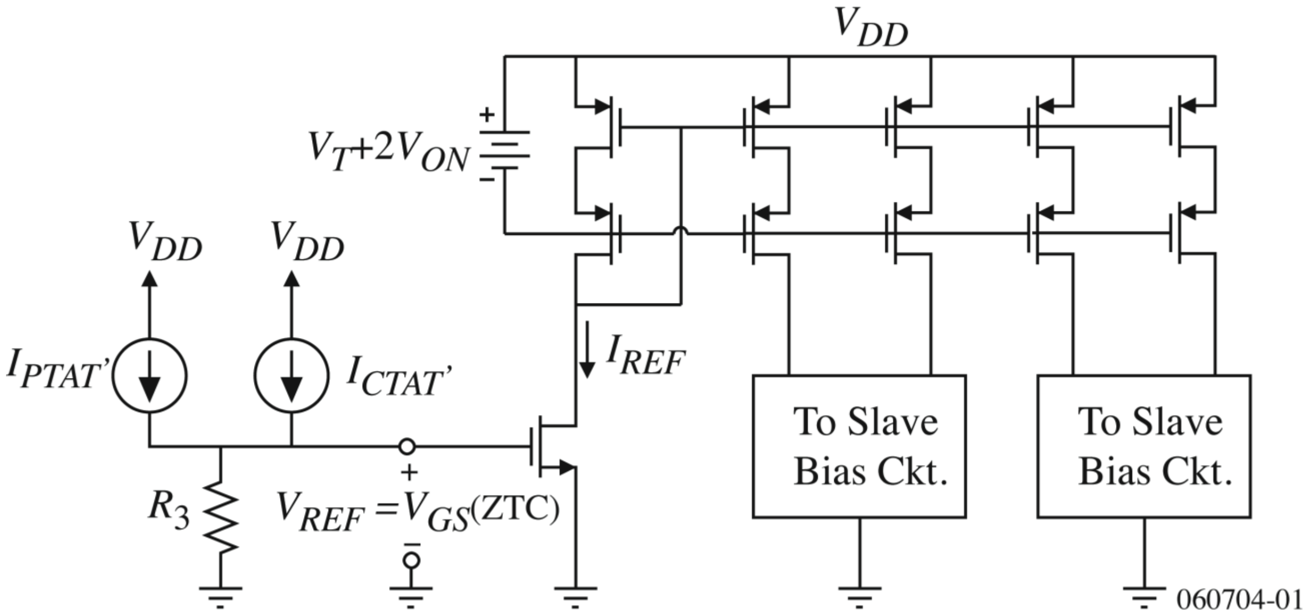
Use Current to Avoid *IR* Drops in Long Metal Lines

Example:



Practical Aspects of Temperature-Independent and Supply-Independent Biasing

A temperature-independent and supply-independent current source and its distribution:



The currents are used to distribute the bias voltages to remote sections of the chip.

Practical Aspects of Bias Distribution Circuits - Continued

Distribution of the current avoids change in bias voltage due to *IR* drop in bias lines.

Slave bias circuit:

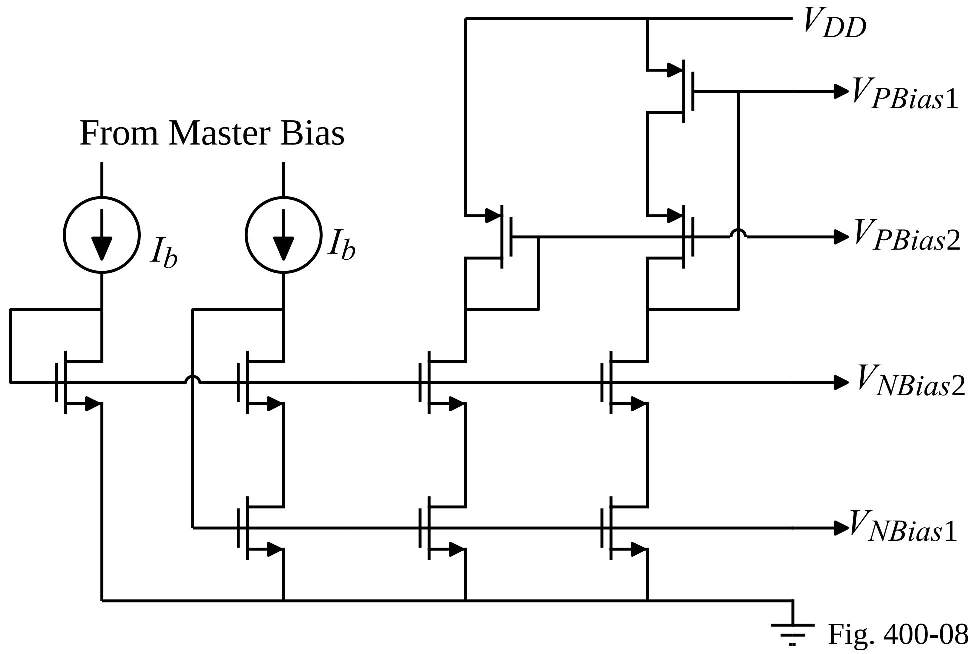


Fig. 400-08

From here on out in these notes,

$$V_{PBias1} = V_{PB1} = V_{DD}-|V_{TP}|-V_{SD}(\text{sat}) \qquad V_{PBias2} = V_{PB2} = V_{DD}-|V_{TP}|-2V_{SD}(\text{sat})$$

and

$$V_{NBias1} = V_{NB1} = V_{TN} + V_{DS}(\text{sat}) \qquad V_{NBias2} = V_{NB2} = V_{TN} + 2V_{DS}(\text{sat})$$

SUMMARY OF TEMPERATURE STABLE REFERENCES

- The classical form of the temperature stable reference has a value of voltage close to the bandgap voltage and is called the "bandgap voltage reference".
- Bandgap voltage references can achieve temperature dependence less than 50 ppm/°C
- Correction of second-order effects in the bandgap voltage reference can achieve very stable (1 ppm/°C) voltage references.
- Watch out for second-order effects such as noise when using the bandgap voltage reference in sensitive applications.
- Distribution of bias voltages over a long distance should be done by current rather than voltage.