4. References

Voltage or Current References

Circuit that yields a precise DC voltage or current independent of external influences is called a voltage reference or a current reference.

The primary external influences are:

- Power supply variations
- Temperature variations

Sensitivity and Fractional Temp. Coefficient

Used to characterize the dependence of a reference on power supply and temperature.

A. The Sensitivity of V_{ref} to changes in power supply V_{DD} is given by,

$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} \qquad (1)$$

Or,

$$\frac{\partial V_{ref}}{V_{ref}} = S_{V_{DD}}^{V_{ref}} \cdot \frac{\partial V_{DD}}{V_{DD}} \qquad (2)$$

Sensitivity

Sensitivity may vary from 0.0 to 1.0.

Sensitivities less than 0.01 are practical values for a monolithic voltage reference.

The above formulation is valid for current references by simply replacing V_{ref} by I_{ref}.

Fractional Temp. Coefficient

B. The Sensitivity of V_{ref} to changes in temperature T is given by, S_T^{Vref}.

$$S_T^{V_{ref}} = \frac{T}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial T}$$

Got just by replacing V_{DD} by T in eqn (1)

Or,

$$\frac{\partial V_{ref}}{V_{ref}} = S_T^{V_{ref}} \cdot \frac{\partial T}{T}$$

Fractional Temp. Coefficient

<u>Fractional Temp. Coefficient</u>, $TC_F(V_{ref})$:

This is another popular concept used to measure the degree of temperature dependence of reference.

$$TC_F(V_{ref}) = 1/V_{ref}\,(\partial V_{ref}/\partial T) = 1/T\,(S_T^{Vref})$$

Units of TC_F - parts per million/°C or ppm/°C.

Example:

Sensitivity, $S_T^{V_{ref}} = 0.01$ at room temperature,

$$\Rightarrow TC_F(V_{ref}) = 1/T\,(S_T^{V_{ref}})$$
$$= (1/300) \times 0.01 \times 1{,}000{,}000$$
$$= \underline{33.3\ \text{ppm}/^\circ\text{C}}$$

References with TC_F of less than 50ppm/°C are considered to be stable w.r.t. temperature.

Simple Voltage References

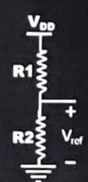
In CMOS IC design, we can derive reference voltages from the power supplies using resistors and MOSFETs.

1. Resistor – Only Voltage Reference
2. Resistor – MOSFET Voltage Reference
3. MOSFET – Only Voltage Reference

1. Resistor – Only Voltage Reference

This voltage divider, formed with 2 resistors, provide a DC voltage between V_{DD} and ground depending on values of R_1 and R_2.

Here, $V_{ref} = \frac{R_2}{(R_1+R_2)} V_{DD}$



Advantages:

- Simple
- Temperature Insensitive
- Process Insensitive – changes in the sheet resistance have no effect on the voltage division.

Disadvantages:

- To reduce the power dissipation, the resistors must be made large. But large resistors require a large die area.
- The sensitivity of V_{ref} w.r.t. V_{DD} is found to be,

$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} = 1$$

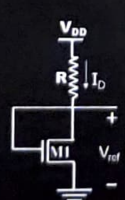
2. Resistor – MOSFET Voltage Reference

Since gate and drain terminals are shorted, M_1 always remains in saturation.

Here, $V_{DS} = V_{GS} = V_{ref}$

$I_D = (V_{DD}-V_{ref})/R = \frac{1}{2}\beta_1(V_{GS}-V_{tn})^2$

Or, $V_{ref} = V_{tn} + \sqrt{\frac{2I_D}{\beta_1}} = V_{tn} + \sqrt{\frac{2(V_{DD}-V_{ref})}{R\beta_1}}$



$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial V_{DD}} = \underline{\underline{\frac{1}{V_{tn} \cdot \sqrt{\frac{2R\beta_1}{V_{DD}}} + 2}}}$$

$$TC_F(V_{ref}) = \frac{1}{V_{ref}} \cdot \frac{\partial V_{ref}}{\partial T}$$

$$TC_F(V_{ref}) = \frac{1}{V_{ref}}\left[\underbrace{\frac{\partial V_{tn}}{\partial T}}_{V_{tn}.TCV_{tn}} - \frac{1}{2}\sqrt{\frac{2V_{DD}}{R\beta_1}}\left(\frac{1}{R}\frac{\partial R}{\partial T} - \frac{1.5}{T}\right)\right]$$

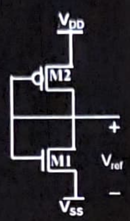
3. MOSFET – Only Voltage Reference

This generates a reference voltage equal to the voltage on the gates of the MOSFETs w.r.t. ground.

$$\tfrac{1}{2}\beta_1(V_{ref}-V_{SS}-V_{tn})^2 = \tfrac{1}{2}\beta_2(V_{DD}-V_{ref}-V_{tp})^2$$

Or the reference voltage is given by,

$$V_{ref} = \frac{V_{DD}-V_{tp}+\sqrt{\frac{\beta_1}{\beta_2}}\,(V_{SS}+V_{tn})}{\sqrt{\frac{\beta_1}{\beta_2}}+1}$$



$$\frac{\beta_1}{\beta_2} = \left[\frac{(V_{DD}-V_{ref}-V_{tp})}{(V_{ref}-V_{SS}-V_{tn})}\right]^2$$

Sensitivity of V_{ref} w.r.t. V_{DD} is given by,

$$S_{V_{DD}}^{V_{ref}} = \frac{V_{DD}}{V_{ref}}\cdot\frac{\partial V_{ref}}{\partial V_{DD}} = \frac{V_{DD}}{V_{DD}-V_{tp}+\sqrt{\frac{\beta_1}{\beta_2}}\,(V_{SS}+V_{tn})}$$

Assuming the temperature dependence of the ratio of the transconductance parameters, β_1/β_2, is negligible, the $TC_F(V_{ref})$ is given by,

$$TC_F(V_{ref}) = \frac{1}{V_{ref}}\cdot\frac{\partial V_{ref}}{\partial T}$$

$$TC_F(V_{ref}) = \frac{1}{V_{ref}}\,\frac{1}{\sqrt{\frac{\beta_1}{\beta_2}}+1}\left[\frac{\partial(-V_{tp})}{\partial T}+\sqrt{\frac{\beta_1}{\beta_2}}\,\frac{\partial V_{tn}}{\partial T}\right]$$

To achieve $TC_F(V_{ref}) = 0$ requires,

$$TC_F(V_{ref}) = \frac{1}{V_{ref}}\,\frac{1}{\sqrt{\frac{\beta_1}{\beta_2}}+1}\left[\frac{\partial(-V_{tp})}{\partial T}+\sqrt{\frac{\beta_1}{\beta_2}}\,\frac{\partial V_{tn}}{\partial T}\right] = 0$$

i.e., $\frac{\partial(-V_{tp})}{\partial T} = -\sqrt{\frac{\beta_1}{\beta_2}}\,\frac{\partial V_{tn}}{\partial T} \Rightarrow 2.7\text{mV}/°\text{C} = \sqrt{\frac{\beta_1}{\beta_2}}\,(2.4\text{mV}/°\text{C})$

i.e., $\beta_1/\beta_2 = 1.125$

Zero temperature coefficient, to a first order can be met by satisfying this equation. However, this ratio is most often set by the desired V_{ref}. So for a particular single value of V_{ref}, the reference becomes temperature insensitive.

Design Example:

Design a 3V MOSFET-Only voltage reference. Determine the temperature coeff. of the reference. Data given: V_{DD}=+5V, V_{SS}=0V, V_{tn}=0.8V, V_{tp}=0.9V, $L_1=L_2$=5μm, K_n=50μA/V², K_p=17μA/V².

$$\frac{\beta_1}{\beta_2} = \left[\frac{(5-3-0.9)}{(3-0-0.8)}\right]^2 = 0.25$$

Setting $L_1=L_2=W_1$ = 5μm,

$$\frac{\beta_1}{\beta_2} = \frac{K_nW_1L_2}{K_pW_2L_1} = \frac{50\mu A/V^2\ 5\mu m\ 5\mu m}{17\mu A/V^2\ W_2\ 5\mu m} = 0.25$$

Solving gives, W_2 = 60μm.

The temp. coeff. is given by,

$$TC_F(V_{ref}) = \frac{1}{V_{ref}}\,\frac{1}{\sqrt{\frac{\beta_1}{\beta_2}}+1}\left[\frac{\partial(-V_{tp})}{\partial T}+\sqrt{\frac{\beta_1}{\beta_1}}\,\frac{\partial V_{tn}}{\partial T}\right]$$

But, $\frac{\partial V_{tn}}{\partial T} = V_{tn}\cdot TCV_{tn} = (0.8V)(-0.003/°C) = -2.4\text{mV}/°\text{C}$

$-\frac{\partial V_{tp}}{\partial T} = -V_{tp}\cdot TCV_{tp} = -(0.9V)(-0.003/°C) = 2.7\text{mV}/°\text{C}$

$$TC_F(V_{ref}) = \frac{1}{3}\,\frac{1}{\sqrt{\frac{50\times5}{17\times60}}+1}\left[0.0027+\sqrt{\frac{50\times5}{17\times60}}\,(-0.0024)\right]$$

$$= 337\text{ppm}/°\text{C}$$

Current Source Self-Biasing Circuits

The drawback of the 3 references discussed so far are that, they are very sensitive to power supply and temperature.

Here, we discuss 3 methods of biasing which reduce the effects of power supply variations and possibly temp.

1. Threshold Voltage Referenced Self-Biasing
2. Diode Referenced Self-Biasing
3. Thermal Voltage Referenced Self-Biasing

1. Threshold Voltage Referenced Self-Biasing

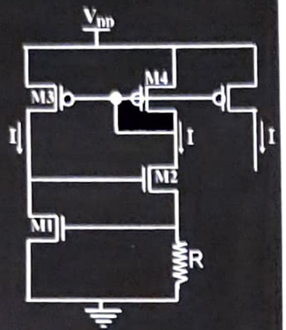
MOSFETs M3 & M4 force the same current to flow through M1 & M2.

$$IR = V_{GS1} = V_{TN} + \sqrt{\frac{2I}{\beta_1}}$$

If β_1 is very large, then, I is given by,

$$\boxed{I \approx V_{TN}/R}$$

i.e., current is independent of the power supply voltage (neglecting channel length modulation and body effect).



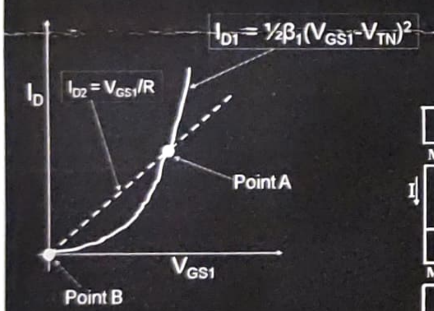
$$I = ½\beta_1(V_{GS1}-V_{TN})^2$$

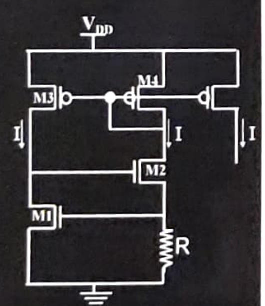
$$\text{Or, } V_{GS1} = V_{TN} + \sqrt{\frac{2I}{\beta_1}}$$

Note:

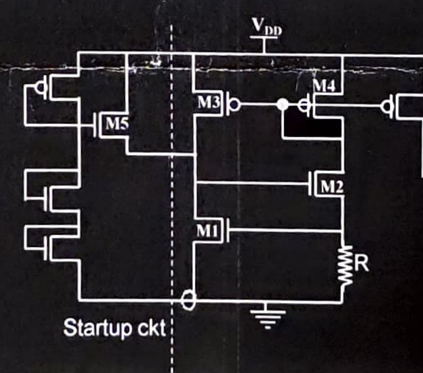
- Here we assumed the output resistance of the MOSFET were infinite. But by cascoding M3 and M4 helps to make the bias circuit behave more ideal.
- The accuracy of I is limited by the threshold voltage accuracy, which may vary by 20%, and the n+ resistivity, which may vary by 20% as well.
- $TC_F(I)$ depends on $TC_F(V_{TN})$ and $TC_F(R)$.
  But $TC_F(V_{TN})$ = -3000 ppm/°C and $TC_F(R)$ = +2000ppm/°C.
  So, the reference current, I has a large negative temperature coefficient.

Startup Circuit



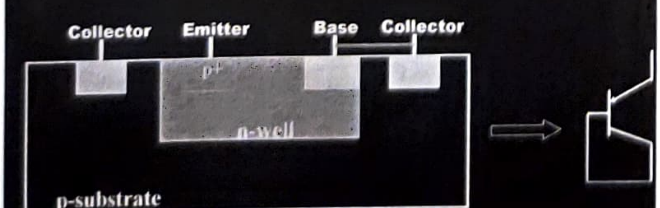


Startup Circuit



2. Diode Referenced Self-Biasing

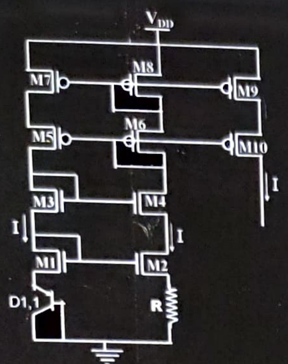
The parasitic PNP transistor, available in the n-well process, in conjunction with the CMOS transistors, is used to generate the reference current or voltage.



A Base-Collector connected transistor is equivalent to a Diode.

The no. '1' indicates the minimum sized emitter.
The current through a forward-biased Diode is given by,

$I_d = I_s e^{V_d/\eta V_T}$, Where V_T is the thermal voltage = kT/q
I_s is the saturation current



Diode Referenced Self-Biasing Circuit

Here the cascode mirrors made with M1 through M8 force the same current, I, to flow through D1 and R

$$\boxed{I = V_d/R = I_s . e^{V_d/\eta V_T}}$$

Or, $V_d = \eta V_T \ln(I/I_s)$

Solving for the resistor gives,

$$R = \frac{\eta V_T}{I} \ln(I/I_s)$$

The main benefit of this circuit over the threshold referenced self-biasing circuit is the better matching, from wafer to wafer and on the same die, of the diode voltage over the threshold voltage.

Sensitivity and $TC_F(I_{ref})$:

$$I_{ref} = V_d/R$$

This shows that the reference is insensitive to power supply variations.

$$TC_F(I_{ref}) = \frac{1}{I_{ref}}\frac{\partial I_{ref}}{\partial T} = \frac{1}{I_{ref}}\frac{\partial}{\partial T}\left(\frac{V_d}{R}\right)$$

$$= \frac{1}{I_{ref}}\left[\frac{R\frac{\partial V_d}{\partial T} - V_d\frac{\partial R}{\partial T}}{R^2}\right]$$

$$TC_F(I_{ref}) = \frac{1}{V_d}\frac{\partial V_d}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T} = TC_F(V_d) - TC_F(R)$$

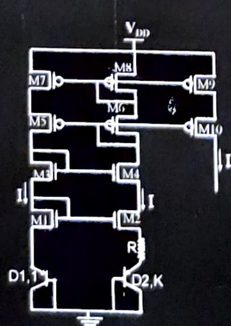
$$TC_F(I_{ref}) = TC_F(V_d) - TC_F(R)$$

Drawback: Temperature dependence.

The temp. coeff. of the diode ≈ - 3,300ppm/°C and R has +2000ppm/°C. This causes the biasing circuit to have a large negative temperature coefficient.

Therefore, this reference is also called as CTAT (Complimentary To Absolute Temperature).

3. Thermal Voltage Referenced Self-Biasing



M1 through M8 forces the same current through D1 and D2.

$$V_{d1} = IR + V_{d2} \longrightarrow (1)$$

$$I_{d1} = I_s . e^{V_{d1}/\eta V_T} \longrightarrow V_{d1} = \eta V_T \ln\frac{I}{I_s}$$

$$I_{d2} = K I_s . e^{V_{d2}/\eta V_T} \longrightarrow V_{d2} = \eta V_T \ln\frac{I}{K I_s}$$

From eqn. (1), solving for the resistor, R, gives,

$$R = (V_{d1} - V_{d2})/I = \frac{\eta V_T}{I}\ln(K)$$

Or, $\boxed{I = \frac{\eta V_T}{R}\ln(K)} = \frac{\eta k}{qR}\ln(K).T$ | $V_T = kT/q$

Or, $I = \frac{\eta V_T \ln(K)}{R} = \frac{\eta k \ln(K).T}{qR}$

Here, the current is proportional to the absolute temperature (PTAT).

$$TC_F(I_{ref}) = \frac{1}{I_{ref}}\frac{\partial I_{ref}}{\partial T} = \frac{1}{I_{ref}}\frac{\partial}{\partial T}\left(\frac{\eta V_T \ln(K)}{R}\right)$$

$$TC_F(I_{ref}) = \frac{1}{V_T}\frac{\partial V_T}{\partial T} - \frac{1}{R}\frac{\partial R}{\partial T} = TC_F(V_T) - TC_F(R)$$

$$TC_F(I_{ref}) = TC_F(V_T) - TC_F(R)$$

Advantages:

Since both V_T and R exhibit positive temperature coeff., it gives better temperature characteristics than the diode or threshold voltage references.

$TC_F(V_T) \approx +3{,}300$ ppm/°C, and $TC_F(R) = +2000$ ppm/°C

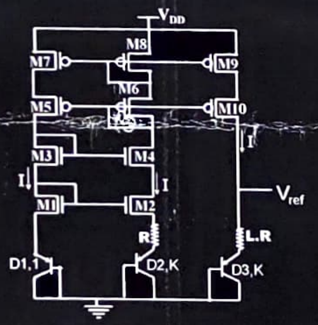
Hence, $TC_F(I_{ref}) \approx 1{,}300$ ppm/°C

Drawbacks:

Mismatches in the gate-source voltages of M1 and M2 can result in large variations in I_{ref}.

Bandgap Voltage References

Bandgap voltage references combine the ***positive TC*** of the thermal voltage with the ***negative TC*** of the diode forward voltage in a circuit to achieve a voltage reference with a ***zero TC***.



Bandgap Voltage Reference

Diode D3 is the same size as D2, while the resistor in series with D3 is L times larger than the resistor in series with D2.

The current I in the figure is given by,

$$I = \frac{\eta V_T \ln(K)}{R}$$

The reference output voltage w.r.t. ground is given by,

$$V_{ref} = I.\ L.R + V_{d3}$$

Or, $V_{ref} = (L.\eta \ln K)\,V_T + V_{d3} = (L.\eta \ln K)\,V_T + \eta V_T \ln\frac{I}{K I_s}$

The TC of the bandgap reference is zero when,

$$\frac{\partial V_{ref}}{\partial T} = L.\eta \ln K\,\frac{\partial V_T}{\partial T} + \frac{\partial V_{d3}}{\partial T} = 0$$

$$\frac{\partial V_{ref}}{\partial T} = L.\eta \ln K\,\underbrace{\frac{\partial V_T}{\partial T}}_{0.085\,mV/°C} + \underbrace{\frac{\partial V_{d3}}{\partial T}}_{-2\,mV/°C} = 0$$

This is true when,

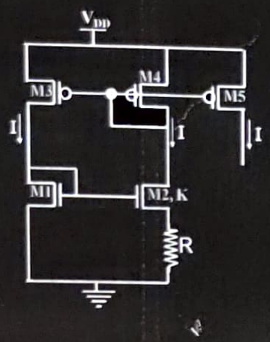
$L.\eta \ln K = 2/0.085 = 23.5$

For η=1 and K=8 the factor L = 11.3 ≈ 12 for a zero TC.

The value of V_{ref} [for η=1, K=8, L=12, V_T=26mV, I=10μA, I_s=10^{-15}A, T=300°K] will be,

$$V_{ref} = (L.\eta \ln K)\,V_T + \eta V_T \ln\frac{I}{K I_s} = 1.25V$$

Beta Multiplier Referenced Self-Biasing



Width of M2 is made 'K' times larger than width of M1, so that,

$\beta_2 = K.\beta_1$ assuming $L_1 = L_2$ and $W_2 = K.W_1$

and therefore,

$$V_{GS1} = V_{GS2} + IR \qquad (1)$$

But,

$$V_{GS1} = V_{TN} + \sqrt{\frac{2I}{\beta_1}}$$

Neglecting body effect,

$$V_{GS2} = V_{TN} + \sqrt{\frac{2I}{K.\beta_1}}$$

$I = ½\beta(V_{GS}-V_{TN})^2$

Or, $V_{GS} = V_{TN} + \sqrt{\frac{2I}{\beta}}$

Solving for I,

$$\boxed{I = \frac{2}{R^2\beta_1}\left(1 - \sqrt{\frac{1}{K}}\right)^2} \longrightarrow (2)$$

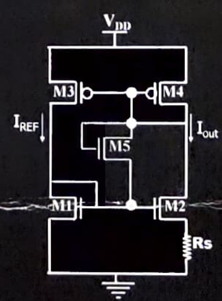
This is the basic design equation for this reference. K is always greater than 1.

Temperature coeff. of the current reference is,

$$TC_F(I_{ref}) = \frac{1}{I}\frac{\partial I}{\partial T} = -2\frac{1}{R}\frac{\partial R}{\partial T} - \frac{1}{\beta_1}\frac{\partial \beta_1}{\partial T}$$

$$= -4000ppm/°C + \frac{1.5}{T}$$

Biasing β multiplier reference



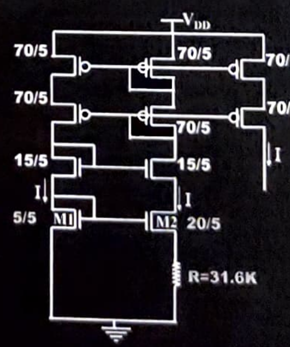
Example:

Using the β multiplier current reference, design a 10µA current source. Estimate the TC of the reference at 300°K and assume V_{DD}=5V, V_{SS}=0V.

If we set L1 = L2 = W1 = 5µm and K=4 then using eqn. (1) and solving for R,

$$R^2 = \frac{2}{10\mu A \; 50\mu A/V^2}\,\frac{1}{4} \Longrightarrow R = 31.6K\Omega$$

$$TC_F(I_{ref}) = -4000ppm/°C + \frac{1.5}{300} \times 1{,}000{,}000 = 1000ppm/°C$$



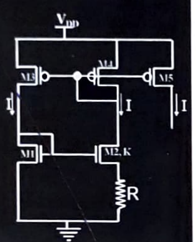
A Voltage Reference

If the reference is designed correctly, we can make the TC of V_{GS1} equal to zero. We define our reference voltage as,

$$V_{ref} = V_{GS1}$$

Substituting eqn. (2) in (1),

$$V_{ref} = V_{GS1} = \frac{2}{R\beta_1}\left(1 - \frac{1}{\sqrt{K}}\right) + V_{THN}$$



The change in V_{ref} with temperature is

$$\frac{dV_{ref}}{dT} = \frac{dV_{THN}}{dT} - \frac{2}{R\beta_1}\left(1 - \frac{1}{\sqrt{K}}\right)\left[\frac{1}{R}\frac{\partial R}{\partial T} + \frac{1}{\beta_1}\frac{\partial \beta_1}{\partial T}\right]$$

or

$$\frac{dV_{ref}}{dT} = -2.4\ \text{mV/°C} + \frac{2}{R\beta_1}\left[1 - \frac{1}{\sqrt{K}}\right]\left[-2{,}000\ \text{ppm/°C} + \frac{1.5}{T}\right]$$

At 300 °K Eq. (21.46) is equal to zero when

$$\frac{2}{R\beta_1}\left[1 - \frac{1}{\sqrt{K}}\right] = \frac{2{,}400}{3{,}000} = 0.8$$

Furthermore, if $K = 4$ we require that

$$R = \frac{1}{0.8 \cdot \beta_1}$$

and

$$V_{ref} = 0.8 + V_{THN} = 1.63\ \text{V}$$

- There will be an error in the reference voltage associated with the change in the threshold voltage due to process variations and body effect as well as changes in R, β, and T.
- Using p-channel MOSFETs in their own well eliminates errors due to the body effect.
- The threshold voltage can vary by as much as 20 percent (this is part of the reason why the body effect is neglected so often in our hand calculations).
- Thus, precision voltages are more difficult to achieve than the bandgap reference of the last section. Often, voltage references are adjusted on die by laser trimming via metal options a resistor value.

The following example illustrates the design and temperature performance of a zero *TC* voltage reference using the β multiplier self-biased reference.

Design a zero TC voltage β multiplier reference at 300°K with $V_{SS}=0$ V and $V_{DD} = 5$ V. Simulate the design for changing V_{DD} and temperature.

- We will use the general cascode schematic shown earlier with V_{DD} swept in the simulations and $V_{SS} = 0$.

The resistor for this design is,

$$R = \frac{1}{0.8\,\beta_1} = \frac{1}{0.8 \times 50} = 25\ \text{K}\Omega$$