Bandgap with Corrections

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Abstract

A band gap analysis is done with an eye towards correcting the voltage curve over temperature. A configuration is given, along with a correction method.

1 Introduction

Bandgap references have become common building blocks in integrated circuits. The first published article appeared in 1964 by D. F. Hilbiber [1]. He used two different pn junction diode types but the same physics applied. Robert Widlar published a silicon-only solution in 1971 using the bandgap principle in an integrated circuit [2]. The bandgap configuration provides a stable, repeatable reference voltage that has a fairly low temperature coefficient over a broad temperature range. This paper builds on a common configuration and analyzes a method to compensate for the temperature curve inherent in the basic bandgap circuit.

2 Bandgap Circuit

One of the most common configurations for a bandgap circuit, called a Brokaw Cell [3], is shown in Figure 1. Q1 has a base-emitter area A-times bigger than Q2. Q4 and Q5 act as a current mirror to keep the currents in Q1 and Q2 equal. The emitter current in a bipolar transistor is given by

$$I_E = AJ_s(e^{qVBE/KT} - 1) \cong AJ_s e^{qVBE/KT} \text{ for } I_E \text{ nonzero,} \qquad (1)$$

where I_E = emitter current (amps)
A = base-emitter area (m^2)
Js = Saturation current density ($amps/m^2$)
q = charge on an electron ($1.602x10^{19}$ coulombs)

VBE = base-emitter voltage (volts)
K = Boltzman's constant (1.38×10^{-23} Joules/°K)
T = Temperature (degrees Kelvin)

Q1 and Q2 have equal emitter currents due to having equal collector currents as forced by the current mirror consisting of Q4 and Q5 (neglecting minor corrections for base currents in Q3, Q4 and Q5, which will be compensated for later). If the emitter currents of Q1 and Q2 are equal we can find the relationship between their base-emitter voltages as follows:

$$I_{E2}/I_{E1} = (A_2J_s/A_1J_s)e^{(VBE2-VBE1)/Vt} \quad (2)$$

Where Vt = KT/q and is usually called the thermal voltage. Since Q1 and Q2 are made on the same integrated circuit and with similar geometries, their saturation current densities will be the same. Therefore,

$$e^{(VBE2-VBE1)/Vt} = (I_{E2}/I_{E1})(A_1/A_2) = A_1/A_2, \text{ if } I_{E1} = I_{E2}. \quad (3)$$

Then,

$$VBE2 - VBE1 = (Vt)\ln(A_1/A_2). \quad (4)$$

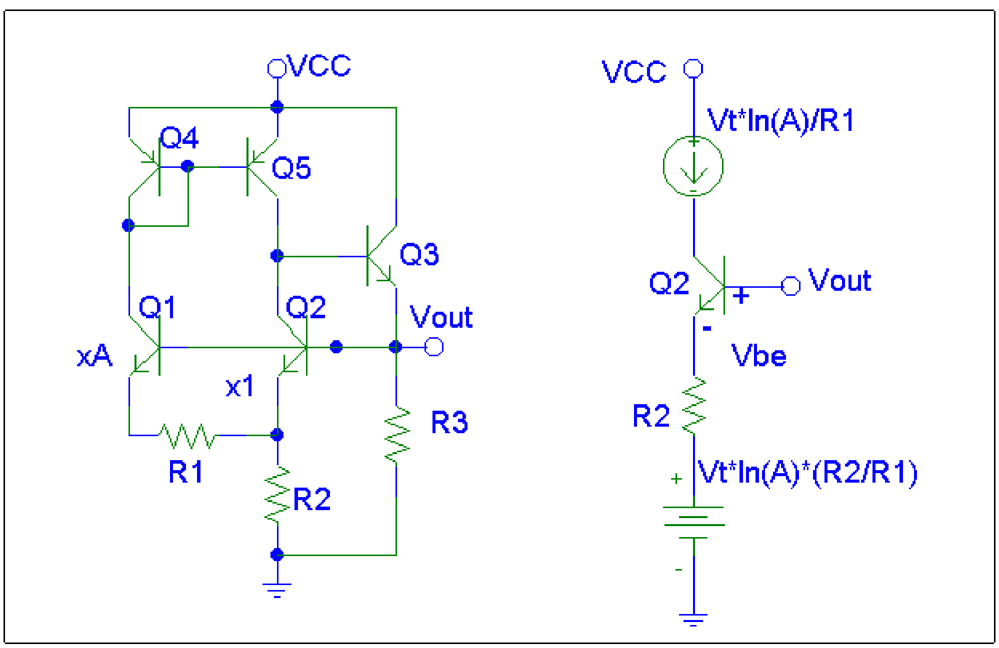


Figure 1. Bandgap Cell (Brokaw) and Simplified Equivalent

If $A_1 > A_2$, VBE2 - VBE1 = $(Vt)\ln(A_1/A_2) = \Delta Vbe$. This is the voltage across R1 in Figure 1. The current through R1 = $\Delta Vbe/R1$. This also has to be equal to I_{E1} (which is equal to I_{E2}). Therefore, the current through R2 is $I_{E1}+I_{E2} = 2I_{E1} = 2\Delta Vbe/R1$. The common base voltage, VBG, will have two solutions that allow IR2 = 2IR1. One is zero. The other depends on the transistor area ratio and temperature. The equivalent circuit on the right in Figure 1. simplifies the analysis. The mirrored emitter current of Q1 is shown as a current source in the collector of Q2. The emitter of Q2 has the thevenin equivalent of Q1's emitter current injected in R2. It becomes a voltage source in series with R2. The base of Q2 then is seen to be sum of Vbe(Q1), the voltage across R2 (which is Q1's collector current times R2) and the thevenin voltage Vt*ln(A)*(R2/R1). A is assumed to be 8 in the following analysis.

If we assume room temperature (T = 300°K) and an area ratio of 8 (Q1 has 8 times the base-emitter area of Q2), we can solve for I_{E1}.

$$I_{E1} = IR1 = \Delta Vbe/R1 = (.026)\ln(8)/R1 = 54.07mv/R1. \quad (5)$$

Choosing 20K for R1 (arbitrary, but this is determined by the current capability of the transistors, optimum beta and the desired power dissipation limitations), we have

$$IE1 = (54.07mv)/(20K) = 2.7ua \text{ at room temperature.}$$

Now we can find the output voltage, V_{BG}, at any temperature.

$$V_{BG} = 2(IE1)R2 + VBE2 = 2(R2)(Vt)\ln(8)/(R1) + VBE2. \quad (6)$$

We have represented the current by (Vt)ln(8)/(R1) to show its dependence on temperature (Vt = KT/q). The Vt relationship is fundamental and gives a linear temperature relation based only on physical constants.

3 Temperature effects

The temperature of a pn-junction (base-emitter) has been shown to vary by approximately –2mv/°C over a very broad temperature range. This value is found through testing and is generally larger for small bias currents and smaller for larger bias currents. If this linear variation is extrapolated back from the Vbe at a given temperature to zero degrees Kelvin it will intersect the ordinate axis close to the bandgap voltage, $V_{BG}(0)$, of the material (silicon, in this case). Figure 2. shows this extrapolation for three different bias currents [3]. Io is an arbitrary reference current.

The ΔVBE voltage is seen to vary directly with temperature. If we take the derivative of V_{BG} with respect to temperature and set it equal to zero we can solve for a value of R2 that should give a zero variance of V_{BG} with temperature.

$$\partial VBG/\partial T = 2(R2/R1)\ln(8)(k/q) - 2mv = 0. \quad (7)$$

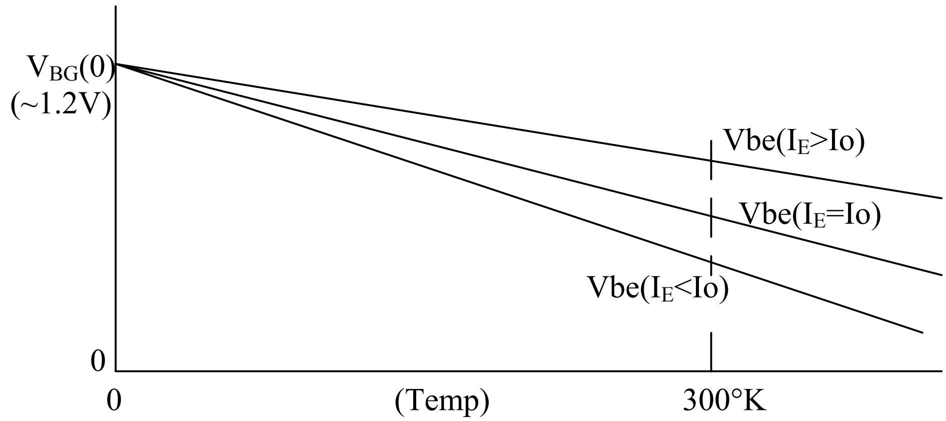


Figure 2. Vbe Variation with Temperature.

Solving for R2 gives

$$R2 = (R1)(2x10^{-3})/[2\ln(8)(k/q)] = (R1)(10^{-3})(1.602x10^{-19})/(2.079)(1.38x10^{-23})$$

$$= 5.584(R1) = 111.7K \text{ (assuming R1=20K).} \qquad (8)$$

The actual variance of Vbe is not exactly linear with temperature. A closer analysis of this variance is given by the following expression [6]:

$$Vbe(T)=V_G(T)-(T/T_r)V_G(T_r)+(T/T_r)Vbe(T_r)-(4-n)(kT/q)\ln(T/T_r)+(kT/q)\ln[I_C(T)/I_C(T_r)] \quad (9)$$

Equation (9) is given to show the complexity of the variation of Vbe with temperature. T_r is a reference temperature at which measured parameters are taken (Vbe and V_G, the bandgap voltage at temperature T). I_C is the collector current and n is given in the mobility equation (10)

$$\mu(T) = CT^{-n} \qquad (10)$$

The best way to determine the curvature is by measuring it over the temperature range desired. A compensator can then be designed to adapt to this curve. The curve in this paper has been generated from the Spice simulation model for a dielectrically isolated bipolar process.

4 Compensation

Figure 3. shows a simulation of the output voltage vs. temperature. The peak-to-peak voltage variance is about 800uv. R2 was chosen to center the voltage peak at 15°C. If we flatten the temperature curve at the lower end we can add a simple correction circuit that adds a linear correction term with a positive slope. This will bring up the downward sloping portion of the temperature curve at higher temperatures. Note: R2 has been

decreased a little to shift the peak of the output voltage vs. temperature to a lower temperature. See Figure 4. for the curve to be compensated. The correction circuit consists of the pnp and bias network on the output emitter follower.

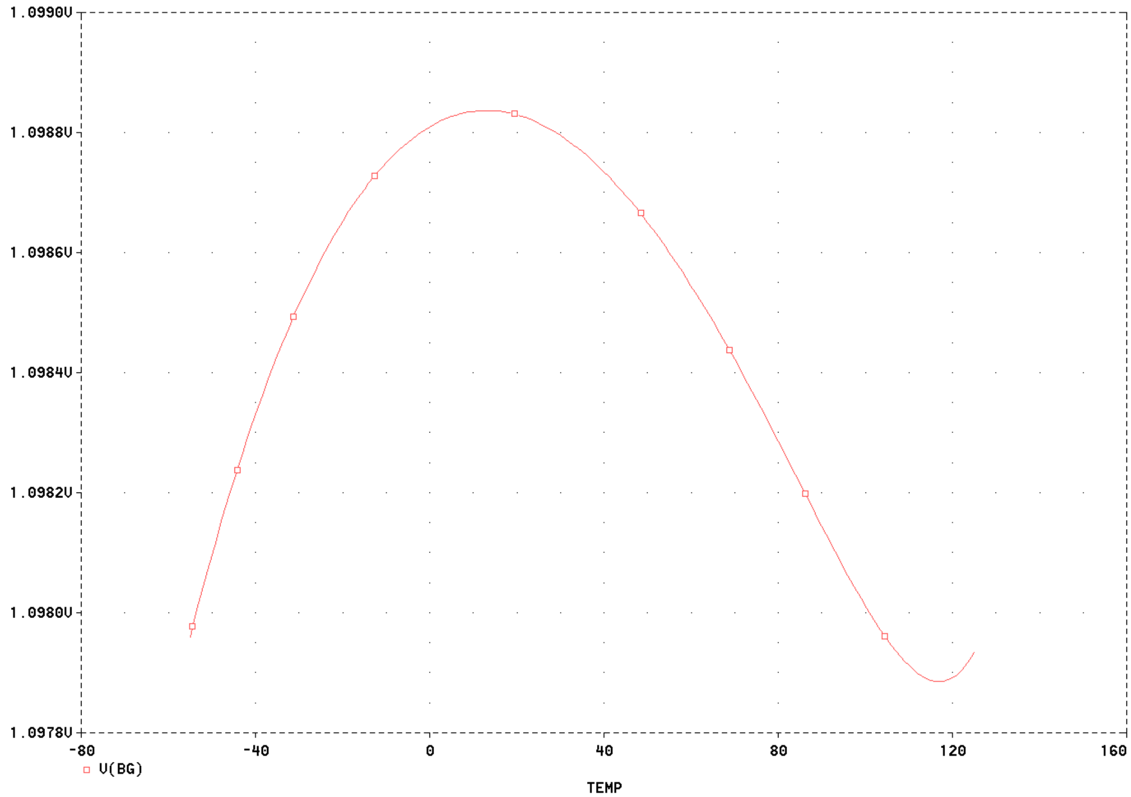


Figure 3. Output Voltage vs. Temperature

A current injected into a resistor can be changed to a Thevenin configuration to show the voltage influence on the bandgap. Figure 5. Shows this relationship. The bandgap output voltage is unchanged, with the exception of having a voltage (Vth) added directly to it. Controlling Vth (Thevenin voltage) will allow us to modify the bandgap output voltage over temperature. R2 is broken into two series resistors that add to the appropriate value (calculated above). The Norton equivalent shown can be converted to the Thevenin circuit shown, with the only change to the bandgap being the added Thevenin voltage. It is up to us to generate a voltage to counteract the temperature variation in the output voltage by adding an error term to subtract out the error in the bandgap's output DC voltage.

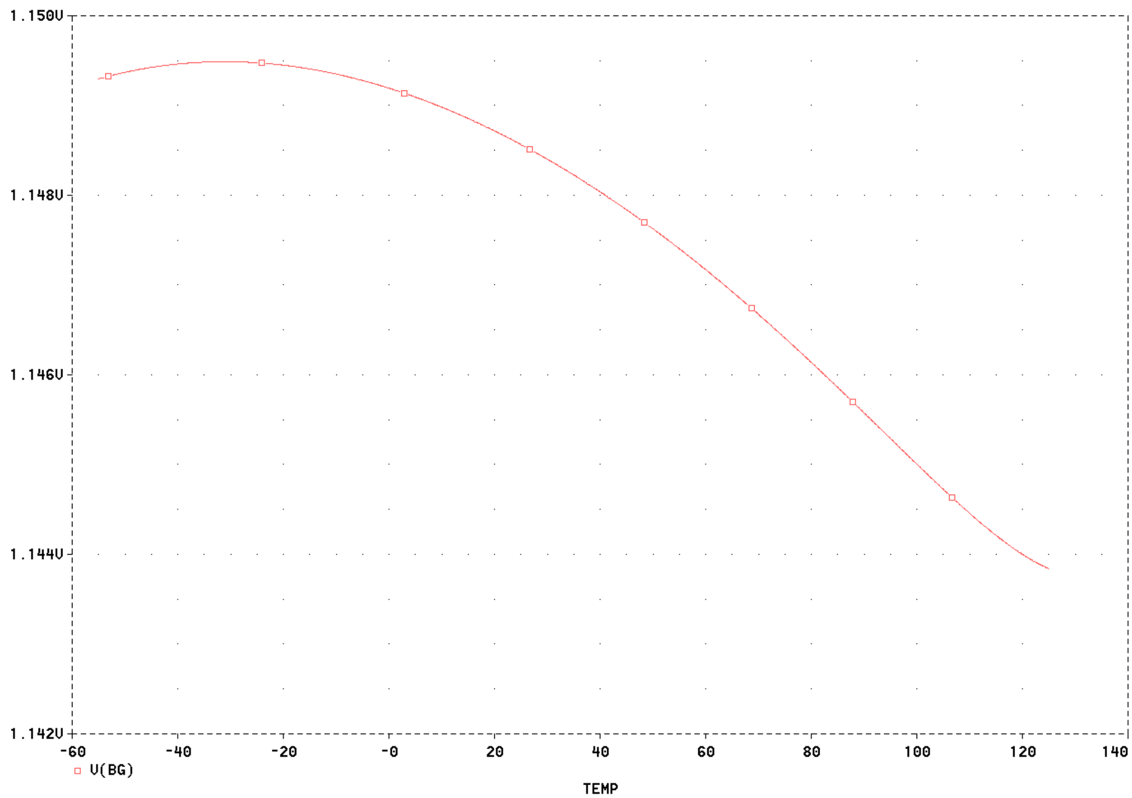
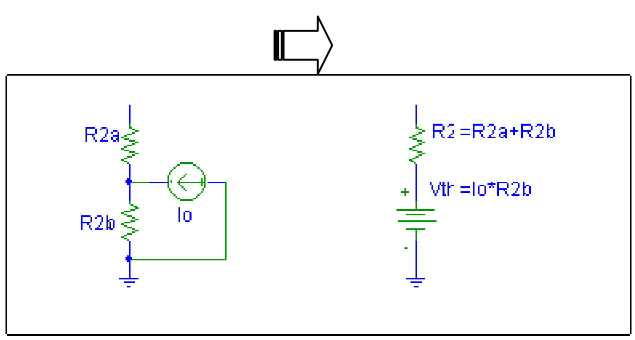


Figure 4. Voltage vs. Temperature Curve Peak Shifted by lowering R2 Value.

The circuit given in Figure 6. will create a linear (with temperature) current that is injected into the R2 bias resistor. The current can be selected to start at an appropriate value of temperature and increase from that temperature on. From -55°C to +25°C the added current is zero. From +25°C on, the current will be (VBG – Vbe(Q6) – Vbe(Q7))/Rfb. The sizing of the pnp was chosen to make the sum of the Vbe's equal to the bandgap voltage at +25°C in the actual circuit of Figure 7. Further increases in temperature would increase the voltage across Rfb at a rate roughly equal to 4mv/°C. The product of this current and R2b adds a compensating voltage to the bandgap output voltage, giving the curve shown in Figure 5. It can be seen that the peak-to-peak variation of the bandgap output voltage has been decreased to about 200uV peak-to-peak.



(Norton structure) (Thevenin equivalent)

Figure 5. Equivalent Voltage Addition through Current Injection

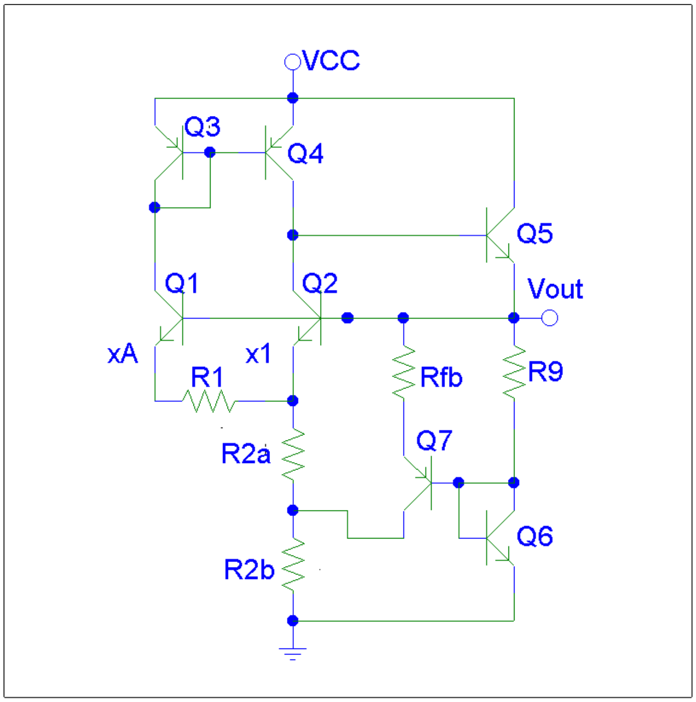


Figure 6. Compensation Circuit

5 Improved Bandgap Circuit

Some additional changes can be made to the circuit shown in Figure 6. to improve the bandgap operation. The loads at the collectors of Q1 and Q2 are better equalized by mirroring their loading and by creating similar collector voltages to minimize differences in currents due to the Early Effect (output impedances). Figure 7. shows a circuit with these changes. Figure 8. shows the compensation feedback current, as well as the output voltage. Note that, as mentioned before, there are two solutions for stable Brokaw cell operation. To insure that the zero-current solution will not occur, a start-up circuit is added. This consists of Q20, Q13, R6 and R2. A trickle current is forced into the current mirrors that drive the cell. Q13 is then turned off as soon as the cell comes up to its non-zero solution. Q16 lessens the base-current differences in the current sources that drive the bandgap circuit (Q17 and Q14). Q18 is used to compensate (equalize) the loads on the cell and Q12 is added to provide clearance bias and keep the voltages on the collectors of Q7 and Q19 equal, thereby minimizing Early-voltage induced current changes in those devices. The output is also generated from this voltage, isolating it further from loading the basic cell [7].

The curves of Figure 8. can be further improved by adding a succession of linear corrections to the circuit. This would consist of tapping resistor R3 and adding more pnp devices (with appropriately-valued emitter resistors). As the temperature went more positive, more of these pnp devices would turn on. This would allow a finer tuning of output voltage by adding a piece-wise linear correction to the basic temperature curve over more sections of the temperature range. The feedback currents would then consist of a sequence of linear-ramping curves that would turn on (and add to the prior corrections) at selected temperatures.

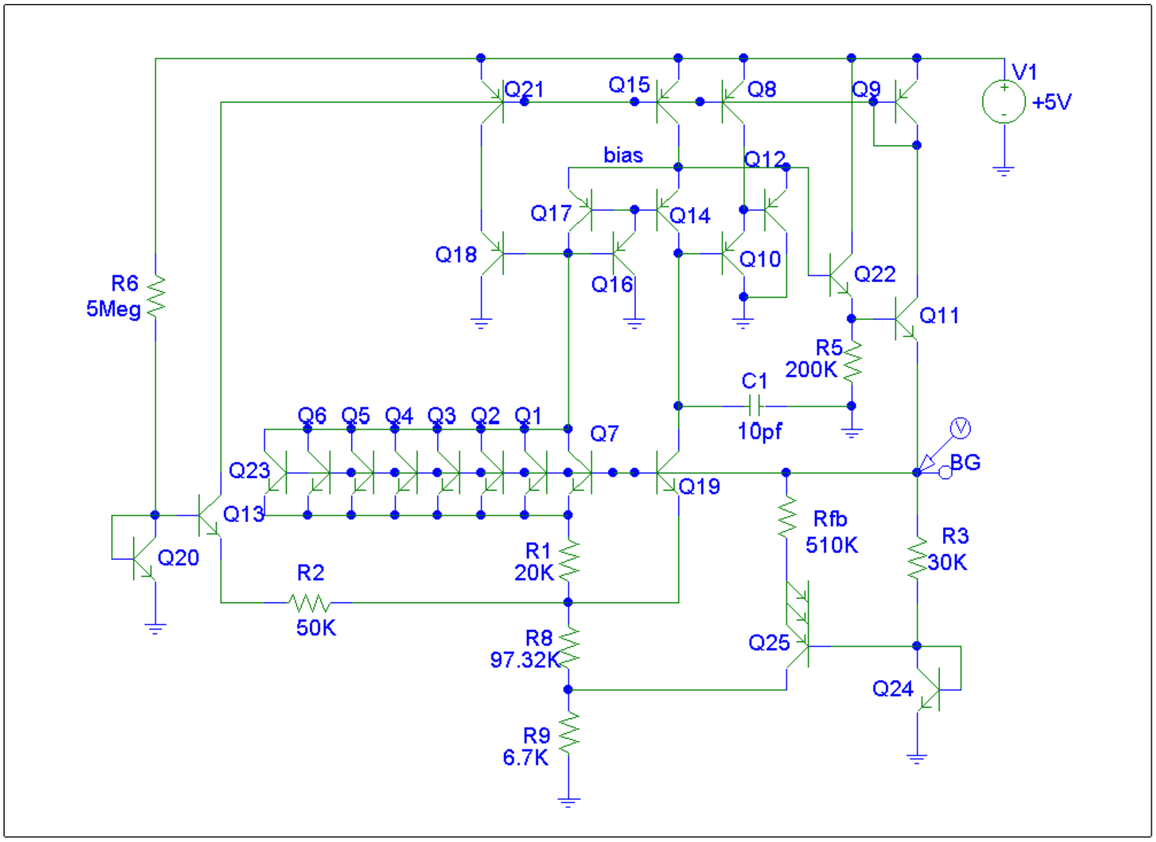


Figure 7. Final Circuit with Collector Currents and Output Voltage.

6 Stability

The basic bandgap cell requires a feedback configuration to properly operate. The question of stability then becomes meaningful. Capacitor C1 introduces a dominant pole in the feedback loop to insure proper phase margin. Connecting C1 between the base and collector of Q19 does not work well because these two signals are in phase. The effective capacitance (Miller capacitance) is then decreased by a considerable amount. The effective capacitance would be

$$C_{Miller} = C1*(1-A) = C1*(1-.99) = .01*C1 \qquad (11)$$

The gain of the emitter follower consisting of Q10, Q12, Q22 and Q11 is approximated at .99. For this reason C1 is tied between the collector (a high-impedance node) of Q19 and ground.

Once the temperature compensation starts to occur (above approximately 25°C) there is an additional positive feedback loop that consists of Q25 and Rfb. The feedback factor (shunt) is R2b/Rfb. This amounts to 6.7K/510K = .0131. The gain enhancement would be 1/(1-.0131) = 1.013. This gain increase does not pose a stability problem but if further corrections were needed (added linear-sloped compensation sections) the net positive feedback would have to be checked for stability margins.

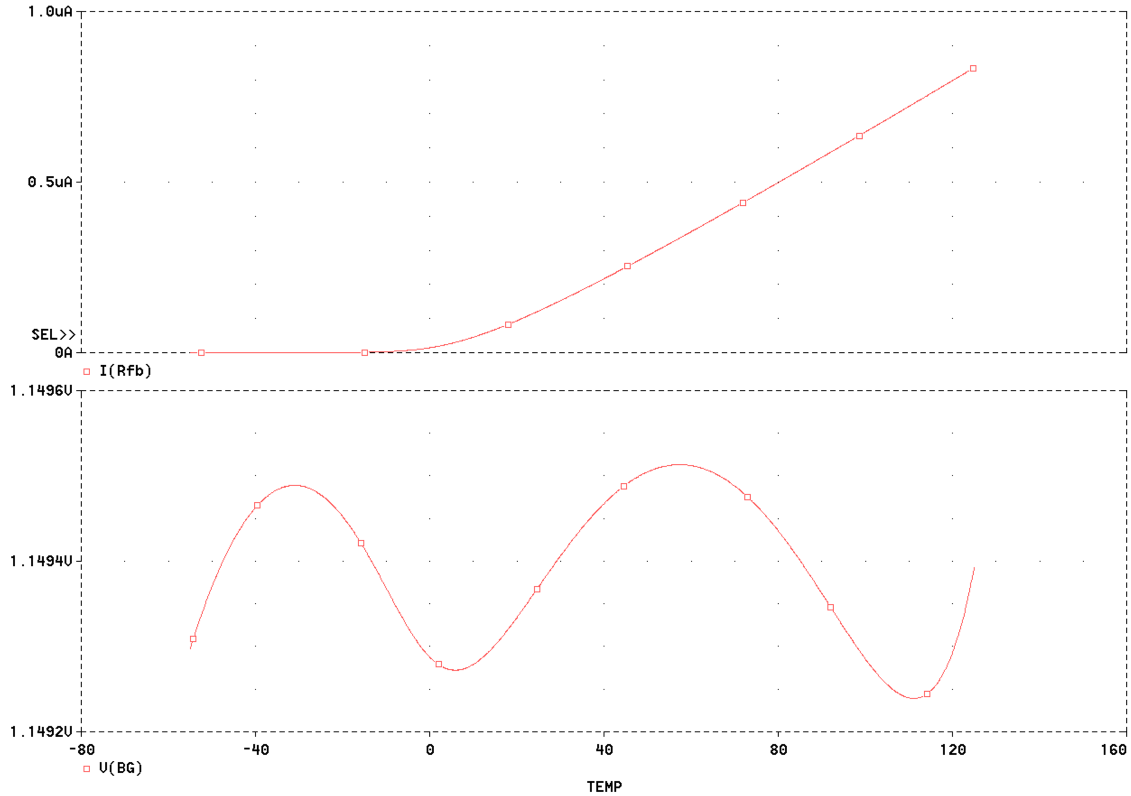


Figure 8. Final Circuit Feedback Current and Output Compensated Voltage

7 Conclusions

A Brokaw bandgap circuit is used as a basis for creating a compensation method to lessen the second-order temperature effects on a bandgap circuit. The compensation circuit is very simple to implement and can be modified to inject a second, or higher, order current curve to give an even better compensation for the bandgap's output voltage. Further improvements on the circuit that are fairly common have also been used in the final configuration. The same technique could be used to inject a current that had an inverse temperature relationship to the standard bandgap's curve. This would give a flatter output voltage. The generation of such a compensated curve has not been given in this paper. CMOS bandgaps may also be compensated with this method [8]-[12]. A very good reference for understanding the bipolar models used in simulators such as Spice is available from Tektronix [13].

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