ES 330: Electronics II

Laboratory Experiment No. 8

Title: Study of a Voltage Reference Circuit

Objective: The main objectives of this lab session will be

1) Study the temperature effect on voltage reference circuit
2) Study the behavior of a bandgap voltage reference circuit

N. B. This lab experiment will be a part of your **project 4**. SO YOU MUST SAVE YOUR DESIGN.

Introduction:

Precision **voltage references** need to not only be independent of power supply voltage, but also be independent of temperature. It is possible to generate reference currents and voltages that are substantially independent of power supply voltage. However they all still vary with temperature. RobertWidlar solved this problem with his invention of the elegant bandgap reference circuit, and today, the bandgap reference is the most common technique used to generate a precision voltage. It has supplanted Zener reference diodes in the majority of applications.

Based on his detailed understanding of bipolar transistor characteristics, Widlar realized that the negative temperature coefficient associated with the base-emitter junction could be canceled out by the positive temperature dependence of a scaled PTAT voltage as shown in Fig. 1.

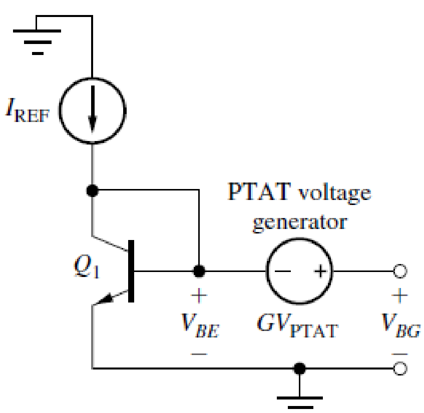

Fig. 1 : Concept of the bandgap reference

The output voltage of the circuit in Fig. 1 can be written as

$$V_{BG} = V_{BE} + GV_{\text{PTAT}} \tag{1}$$

We desire this output voltage to have a zero temperature coefficient:

$$\frac{\partial V_{BG}}{\partial T} = \frac{\partial V_{BE}}{\partial T} + G\frac{\partial V_{\text{PTAT}}}{\partial T} = 0 \tag{2}$$

Using the dependence of *VBE* and *V*PTAT on temperature into Eq. (2) gives

$$\frac{\partial V_{BG}}{\partial T} = \frac{V_{BE} - V_{GO} - 3V_T}{T} + G\frac{V_{\text{PTAT}}}{T} = 0 \tag{3}$$

$$GV_{\text{PTAT}} = V_{GO} + 3V_T - V_{BE} \tag{4}$$

where V_{GO} is the silicon bandgap voltage at 0 K (1.12 V). Substituting this result into Eq. (4) reduces the output voltage to

$$V_{BG} = V_{GO} + 3V_T \tag{5}$$

The output voltage at which zero temperature coefficient is achieved is slightly above the bandgap voltage of silicon. Hence, this circuit is referred to as a “bandgap reference.” At room temperature, the output voltage is approximately 1.20 V.

A circuit realization of the bandgap reference is shown in Fig. 2. This circuit is attributed to another talented designer, Paul Brokaw of Analog Devices, and is easier to understand

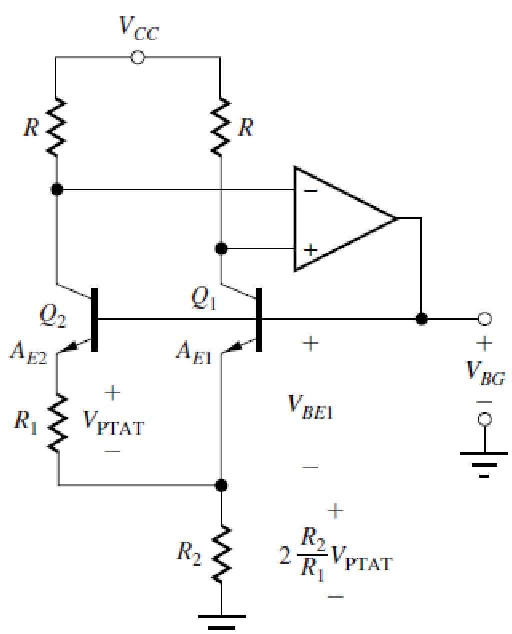

Fig. 2: Brokaw version of bandgap reference

than the original circuit of Widlar. In this circuit, the output voltage is equal to the sum of the base-emitter voltage of *Q*1 plus the voltage across resistor *R*2, which is a scaled replica of the PTAT voltage being developed across resistor *R*1. The scaling factor is controlled by the op amp and resistors *R*.

The ideal op amp forces the voltage across the two matched collector resistors to be the same, thereby setting *IC*2 = *IC*1 and *IE*2 = *IE*1. Thus the PTAT voltage is equal to *VT* ln*(AE*2*/AE*1*)*, and the emitter current of *Q*2 equals *V*PTAT*/R*1. The current in *R*2 is twice that in *R*1, since *IE*2 = *IE*1.

Combining these results yields an expression for the output voltage *VBG*:

$$V_{BG} = V_{BE1} + 2\frac{R_2}{R_1} V_T \ln \frac{A_{E2}}{A_{E1}} \tag{6}$$

For this circuit, the gain *G* = 2*R*2*/R*1, and based on Eq. (3) and (4), the resistor ratio is given by

$$\frac{R_2}{R_1} = -\frac{1}{2}\frac{\frac{\partial V_{BE1}}{\partial T}}{\frac{\partial V_{\text{PTAT}}}{\partial T}} = \frac{V_{GO} + 3V_T - V_{BE1}}{2V_{\text{PTAT}}} \tag{7}$$

Often we want an output voltage that is not equal to 1.2 V, and other voltages are easy to achieve by adding a two-resistor voltage divider to the Brokaw circuit as in Fig. 3. In this case the op amp output voltage becomes

$$V_O = \left(1 + \frac{R_4}{R_3}\right) V_{BG} \tag{8}$$

which can be scaled up to any desired value (e.g., 2.5 or 5 V).

A word of caution is needed here. In most bandgap reference designs, zero-output voltage is a valid operating point, and some additional circuitry must be added to ensure that the circuit “starts up” and reaches the desired operating point. In many simple circuit cases, SPICE will have considerable difficulty converging to the desired operating point.

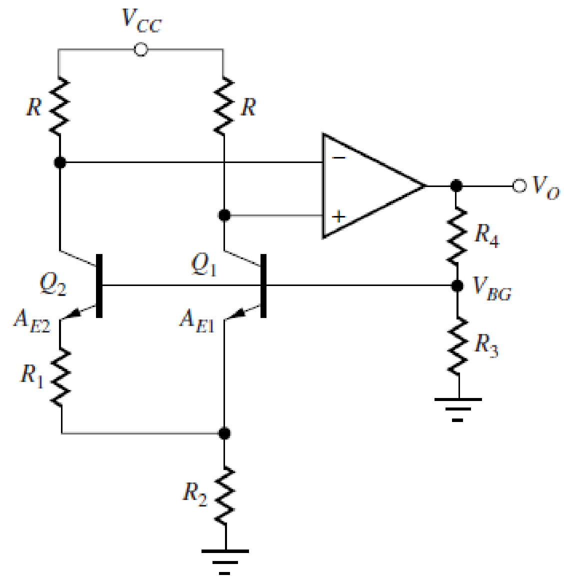

Fig. 3: Bandgap reference with Vo>VBG

Design:

Now design a bandgap reference circuit with R = 30 kΩ, $R1$ = 1 kΩ, and $R2$ = 4.16 kΩ. Assume IS = 0.1 fA and $AE2$ = 10$AE1$, VCC = 10 V

Sample Calculation

$$V_T = \frac{kT}{q} = \frac{1.380 \times 10^{-23}(300)}{1.602 \times 10^{-19}} = 25.84 \text{ mV}$$

$$V_{\text{PTAT}} = V_T \ln\left(\frac{A_{E2}}{A_{E1}}\right) = V_T \ln(10) = 59.50 \text{ mV}$$

$$I_C = I_E = \frac{V_{\text{PTAT}}}{R_1} = 59.50\ \mu\text{A}$$

$$V_{BE1} = V_T \ln\left(\frac{I_{C1}}{I_{S1}}\right) = (25.84 \text{ mV}) \ln\left(\frac{59.50\ \mu\text{A}}{0.1 \text{ fA}}\right) = 0.7006 \text{ V}$$

$$V_{BG} = V_{BE1} + 2\frac{R_2}{R_1}V_{\text{PTAT}} = 0.7006 + 2\frac{4.16\text{ k}\Omega}{1\text{ k}\Omega}(59.50 \text{ mV}) = 1.196 \text{ V}$$

Reference:

Jaeger and Blalock, *Microelectronics Circuit Design*, 3rd Edition, MacGraw Hill