Design methods of low-voltage curvature-corrected bipolar bandgap references based on the sum of base-emitter voltages.

R. Amador, A. Polanco, A. Nagy, M. Alvarez

Persona de contacto: Ricardo Amador Pérez

Email: ramador@electrica.ispjae.edu.cu

Abstract
A new design method is proposed to reduce even further, temperature dependence of low-voltage curvature-corrected bandgap references. This method uses the linear approximation of bandgap voltage $V_G(T)$. A comparative assessment with a design that uses a non linear expression of $V_G(T)$ is made in a low –voltage reference based on the sum of two base-emitter voltages. With the method proposed here a 0.09 ppm/°C theoretical stability has been achieved, which is almost three times better. The experimental results agree with the theoretical one and confirm the validity of the linear approximation of $V_G(T)$ and the advantages of the proposed design method.

Resumen
Se propone un nuevo método de diseño que reduce aún más la dependencia térmica en una fuente de referencia bandgap de bajo voltaje con corrección de curvatura. Este método utiliza la aproximación lineal del voltaje de la banda prohibida $V_G(T)$. Se realiza una evaluación comparativa con los resultados teóricos del método que utiliza una expresión no lineal del $V_G(T)$. Con el método propuesto aquí se obtiene una estabilidad teórica de 0.09 ppm/°C que es casi tres veces mejor. Los resultados experimentales coinciden con los teóricos confirmando la validez de la aproximación lineal de $V_G(T)$ y las ventajas del método de diseño propuesto.

Authors’ affiliations:
R. Amador, A. Polanco, A. Nagy, Centro de Investigaciones en Microelectrónica, Apartado 8016, Ciudad Habana 8, Cuba.

M. Alvarez, Dpto de Matemática, ISPJAE, Cuba.
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Introduction.
A new design method is proposed to reduce even further, temperature dependence of low-voltage curvature-corrected bandgap references.
The best design method of these references was published by Staveren [1] in 1995 with a theoretical temperature stability of 0.23 ppm/°C in the 0 – 100 °C interval.
With the method proposed here a 0.09 ppm/°C theoretical stability has been achieved, which is almost three times better. These theoretical results can be seen in Fig.1 The assessment of this design method showed an experimental stability better than 0.1 ppm/°C.

![Fig. 1 Temperature dependence of \( V_{\text{REF}}(T) \)](image)

The first bandgap reference with curvature correction.
Curvature correction in a low voltage bandgap reference was introduced by Widlar [2] in 1978 using the circuit shown in Fig.2
In this circuit Widlar, for the first time, biases one transistor with a PTAT current and the other with a constant current, thereby creating different curvatures in their $V_{BE}(T)$ characteristics. This allowed obtaining a reference voltage $V_{REF}(T)$ based on the difference of both $V_{BE}$'s with very small curvature as shown in Fig.3.

**Design methods.**
Recently Staveren used this transistor biasing scheme and developed a design method [1] for a voltage reference based on the sum of two base-emitter voltages as shown in the block diagram of Fig.4.
Where,

$$V_{REF}(T) = a_1V_{BE1}(T) + a_2V_{BE2}(T)$$  \hspace{1cm} (1)$$

In his method the non-linear expression of Varshni for silicon bandgap voltage $V_G(T)$ [3] is used in the equation of $V_{BE}(T)$.

$$V_{BE}(T) = V_G(T) - V_G(T_r)\frac{T}{T_r} + V_{BE}(T_r)\frac{T}{T_r} - \frac{kT}{q} (\eta - m)\ln\left(\frac{T}{T_r}\right)$$  \hspace{1cm} (2)$$

Taylor polynomials are used for all non-linear expressions to cancel 1st and 2nd order temperature dependencies. With the block diagram of Fig. 4 higher order dependencies cannot be cancelled. Therefore in this method $V_{REF}(T)$ shows a flat zone around $T_r$ as shown in Fig. 5 and a non-linear behavior away from $T_r$ is caused by higher order temperature dependencies.

Fig. 4 Block diagram of the low-voltage curvature-corrected bandgap reference

Fig. 5 $V_{REF}(T)$ of Staveren’s bandgap reference as a function of temperature
In the method proposed here, the same block diagram of Fig. 4 is used, but a linear approximation of the bandgap voltage $V_G(T)$ is used to consider the influence of high base-impurity concentration ($N > 10^{17}$ cm$^{-3}$) upon bandgap narrowing [5]. Several authors [4,5], based on the optical experiments of MacFarlane [6], use a linear approximation of the bandgap voltage $V_G(T)$. A convenient linear approximation of $V_G(T)$ [7] around $T = T_r$ is

$$\hat{V}_G(T) = V_{G0} + \alpha T$$

where $\alpha = dV_G/dT|_{T=T_r}$.

The approximate expression $\hat{V}_{BE}(T)$ uses $\hat{V}_G(T)$ and, neglecting both Early effects, can be given [4] as the sum of a constant term, a linear term and a non-linear term in $T$:

$$\hat{V}_{BE}(T) = \left\{\hat{V}_{G0} + (\hat{\eta} - m) \frac{kT_r}{q} \right\} - \hat{\lambda}T + (\hat{\eta} - m) \frac{k}{q}(T-T_r - T \ln \frac{T}{T_r}) \tag{4}$$

where $\hat{\lambda} = [V_{G0} + (\eta - m)kT_r/q - V_{BE}(T_r)]/T_r$

with fitting values $\hat{\eta}$ and $\hat{V}_{G0}$. These fitting values allow close matching of $\hat{V}_{BE}(T)$ to the accurate expression (2), and can be obtained by setting $\hat{V}_{BE}(T)$ equal to $V_{BE}(T)$ at temperatures $T_{min}$, $T_r$ and $T_{max}$, that is, an interpolation procedure. As these fitting values are obtained from measurement of $V_{BE}(T)$ at temperatures $T_{min}$, $T_r$ and $T_{max}$ they contain the effects of the impurity concentration in the base of the bipolar transistors [8].

**Theoretical design using the approximation $\hat{V}_{BE}(T)$:**

The design of a bandgap reference whose block diagram is shown in Fig. 4 will be performed using the approximation $\hat{V}_{BE}(T)$ (see equation 4).

The expression of the approximate output voltage will be given then by

$$\hat{V}_{REF}(T) = a_1 \hat{V}_{BE1}(T) + a_2 \hat{V}_{BE2}(T) \tag{5}$$

The fitting values $\hat{\eta}$ and $\hat{V}_{G0}$ in the equation 4 for both base-emitter voltages can be found by interpolation of $\hat{V}_{BE2}(T)$ to $V_{BE2}(T)$ in equation 2, at $T_{min}= 273.15$ K, $T_r=323.15$ K and $T_{max}=373.15$ K, as has been described above.

Let the design requirements be, $V_{REF}(T_r) = 200$ mV, $V_{BE2}(T_r)=600$ mV. Other values to be considered are $m_1=1$ for PTAT current, $m_2 = 0$ for constant current, $\eta = 2.5$ a convenient typical value, obtaining:

$$\hat{\eta} = 4.6993044 \quad \hat{V}_{G0} = 1.1342006$$

From equations (4) and (5) it can be shown that second and higher order temperature dependence can be cancelled if

$$a_1/a_2 = \hat{\eta}/(\hat{\eta} - 1) \tag{6}$$

while first order temperature dependence can be cancelled if
\[ a_1 \hat{a}_1 = -a_2 \hat{a}_2 \]  \hspace{1cm} (7)

Solving the system of equations (5), (6) and (7) we obtain the values,

\[ a_1 = 0.8286549 \quad a_2 = -0.6523192 \quad V_{BE1}(T_r) = 0.7136765 \]

Using these values in equations (1) and (2), the output voltage \( V_{REF}(T) \) is plotted with the continuos line in Fig.1 showing a 0.09 ppm/K mean temperature dependence. This theoretical result is almost three times smaller than the theoretical one obtained using Taylor polynomials.

**Experimental assessment of the proposed method**

For the assessment of the proposed method the measurement of \( V_{BE}(T) \) at different temperatures of commercial bipolar transistors MAT-01 was realized. The temperature was measured with an accuracy better than 0.05 K and the voltages with 0.1 \( \mu \)V.

The fitting values \( \hat{\eta} \) and \( \hat{V}_{G0} \) for both base-emitter voltages were found from measured values \( V_{BE2}(T) \) at \( T_{min}=294.280 \) K, \( T_r=323.001 \) K and \( T_{max}=373.170 \) K. The obtained fitting values are:

\[ \hat{\eta} = 3.63582741 \quad \hat{V}_{G0} = 1.16218005 \text{ V} \]

Solving the system of equations using these values, results:

\[ a_1 = 0.62569090 \quad a_2 = -0.45360053 \quad V_{BE1}(T_r) = 0.58761450 \text{ V} \]

Using these values and the measured values of \( V_{BE1}(T) \), \( V_{BE2}(T) \) in the equation (1), the output voltage \( V_{REF}(T) \) is obtained and plotted in Fig. 6.

![Fig. 6 Measured \( V_{REF}(T) \) of bandgap reference as a function of temperature designed with the proposed method.](image)

The mean temperature dependence of the \( V_{REF}(T) \) obtained experimentally, shown in Fig. 6, is 0.092 ppm/°C in the 20 – 100 °C interval. This behavior agrees with the theoretical one, and confirm the validity of the proposed design method.
The variation of the voltage reference $V_{\text{REF}}(T)$ with the temperature is due to the linear approximation of the bandgap voltage $V_G(T)$.

**Discussion:** The mean temperature dependence with the proposed approximate method is almost three times smaller in the 0-100 °C interval than one obtained with Taylor polynomials. This can be explained in part because first and all higher order temperature dependencies are cancelled while the other method only cancels first and second order temperature dependencies.

Although the proposed method requires measuring $V_{\text{BE}}(T)$ at three temperatures, it does not require to know the expression of $V_G(T)$, and allow to take into account the base impurity concentration.

In conclusion an improved and simple design method using the linear approximation of $V_G(T)$ has been presented. With the method proposed here a 0.092 ppm/°C experimental stability has been achieved.

**References**