A Self-Calibrated Bandgap Voltage Reference with 0.5 ppm/°C Temperature Coefficient

Le Jin, Hanqing Xing, Degang Chen, and Randall Geiger
Department of Electrical and Computer Engineering
Iowa State University
Ames, IA 50011, USA

***Abstract*—This work introduces a multi-segment bandgap reference circuit with self-calibration. Thermal characteristics of the bandgap circuit will be modeled using test results under normal temperatures. With the characterization information, appropriate circuit parameters will be calculated for different temperature intervals and used to adjust the inflection point of the bandgap curve as the temperature changes, in order for the reference circuit to achieve high thermal stability. Simulation results show that the proposed circuit can achieve a better than 0.5 ppm/°C temperature coefficient over a range of 140 °C. This circuit is compatible with most of the existing bandgap circuit structures and can be used in low-voltage designs.**

I. INTRODUCTION

Voltage, current, and time references are widely used in electronic systems that support both the consumer market and the defense industry. The thermal stability of these references plays a key role in the performance of many of these systems. Unfortunately the best references available from the industry no longer meet the performance requirements of emerging systems and as the industry moves to system-on-chip (SoC) scale circuits where very low voltage operation is essential, there are no solutions on the horizon for providing even modest performance.

The magnitude of the problem can be best appreciated by considering the voltage reference as an example. Many emerging systems depend upon 14 and 16-bit data converters and segments of the industry have started working on 18-bit converters. The levels of 14, 16 and 18-bit accuracy require a temperature coefficient (TC) of 0.6 ppm/°C, 0.15 ppm/°C and 0.04 ppm/°C over a range of 100 °C, if one least significant bit variation is allowed [1]. These levels of thermal stability are difficult to maintain. Some companies use technologies such as thin film resistors, EEPROM registers, and multiple-temperature in-package trims to obtain 15-bit performance for their high-end parts. Even for many lower-end parts throughout the industry, expensive laser trimming operations are required. For voltage references that operate at or below a supply voltage of 2.5 V, the best prototypes reported in the literature have a TC at the 5 to 10 ppm/°C level over a range of 100 °C or smaller [2, 3]. This level of temperature dependence can only provide 11-bit accuracy and an improvement of nearly two orders of magnitude over the best reported results is necessary to obtain thermal stability at the 16-bit level.

This work focuses on an entirely new design strategy of bandgap references that uses standard low voltage CMOS processes and digital calibration techniques to offer potential for obtaining true 16-bit performance in SoC scale circuits, without requiring special processing steps and without requiring any trimming at manufacture test. This approach is based upon the idea of a multi-segment voltage reference [4] and a novel digital self-calibration algorithm that uses temperature triggers to control stepping between the segments. Transistor level simulation shows that the proposed approach can achieve 0.5 ppm/°C thermal stability over a range of 140 °C.

II. BANDGAP VOLTAGE REFERENCE

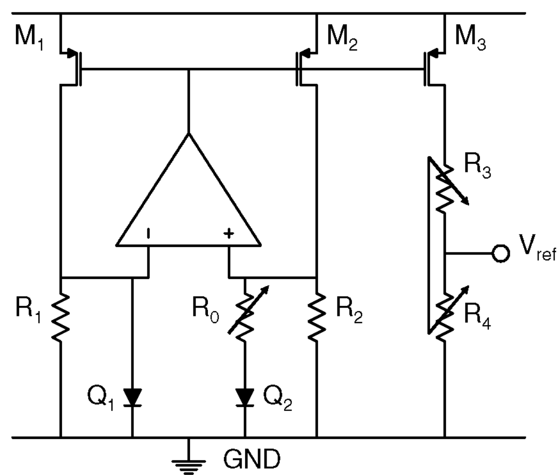

Figure 1. Schematic of the multi-segment bandgap reference.

Figure 1 gives the schematic of a bandgap circuit used for operating with low supply voltages [3]. The voltage across R_2 is equal to the base-emitter voltage V_{BE} of Q_1 which has a negative temperature coefficient, while the voltage across R_0 is proportional to the absolute temperature (PTAT). Therefore the currents going through the two

This work is supported by the National Science Foundation.

resistors have opposite temperature coefficients that cancel each other at a specific temperature. Summation of the two currents generates a bandgap voltage V_{ref} across R_4 through the current mirror. The voltage level of V_{ref} can be adjusted by changing the relative ratio between R_3 and R_4 while the total resistance of them is kept the same. This circuit is adopted in the proposed design, because it allows the temperature and voltage of the inflection point of V_{ref} to be changed through tuning the resistances of R_0 and R_4. We will implement the tuning operation as a digitally controlled process.

If we write the current-voltage characteristic of a forward biased diode as [5]

$$I_C = \sigma A T^r \exp(\frac{V_{BE} - V_G}{kT/q}), \quad (1)$$

where T is the absolute temperature, A the junction area, and σ and r temperature-independent constants, we can get the bandgap voltage generated by the circuit as [6]

$$V_{ref} = \frac{R_4}{R_0}\frac{kT}{q}\ln\frac{A_2}{A_1} + \frac{R_4}{R_1}[\frac{kT}{q}\ln(\frac{k\ln(A_2/A_1)}{qR_0\sigma A_1 T^{r-1}}) + V_G], \quad (2)$$

where A_1 and A_2 are junction areas of diode Q_1 and Q_2, respectively. For simplicity, we will neglect the temperature dependence of V_G in the following derivation. Simulation results will show that this approximation does not affect the circuit performance. To show the bandgap characteristic of V_{ref}, we rewrite (2) as

$$V_{ref}(T) = C_0 + C_1 T + C_2 T\ln(T), \quad (3)$$

where

$$C_0 = \frac{R_4}{R_1}V_G, \quad (4)$$

$$C_1 = \frac{kR_4}{q}[\frac{1}{R_0}\ln\frac{A_2}{A_1} + \frac{1}{R_1}\ln(\frac{k\ln(A_2/A_1)}{qR_0\sigma A_1})], \quad (5)$$

and

$$C_2 = -(r-1)\frac{R_4}{R_1}\frac{k}{q}. \quad (6)$$

An inflection point of the bandgap voltage is a point at which the derivative of V_{ref} with respect to T equals to zero. Using (3), the inflection point temperature can be calculated as

$$T_{\text{inf}} = \exp(-C_1/C_2 - 1) \quad (7)$$

and the inflection point voltage is

$$V_{\text{inf}} = C_0 - C_2 T_{\text{inf}}. \quad (8)$$

Coefficients C_0, C_1 and C_2 are related to circuit elements, so their values are affected by process variations. The relationship between these coefficients and circuit elements is dependent on the circuit architecture and other unknown effects, such as the gain and offset of the op amp and current mirror characteristics, and may not be exactly the same as described by (4-6). These uncertainties make it impossible to predict the inflection point for a fabricated circuit. This is why trimming operation is often required in production.

III. CALIBRATION SCHEME

The bandgap voltage has a very small variation in the neighborhood of the inflection point, since the derivative is very close to zero. The variation will dramatically increase, however, when the temperature range increases, see Fig. 2(a). This work will introduce a multi-segment bandgap circuit to improve the thermal stability. The overall bandgap curve, the bold one in Fig. 2(b), contains several segments from different curves, thin ones in Fig. 2(b), and each segment is in the neighborhood of an inflection point. At a specific temperature, the segment with the closest inflection point will be used to provide the reference voltage, which gives a much smaller overall V_{ref} variation as compared to the single-inflection point case.

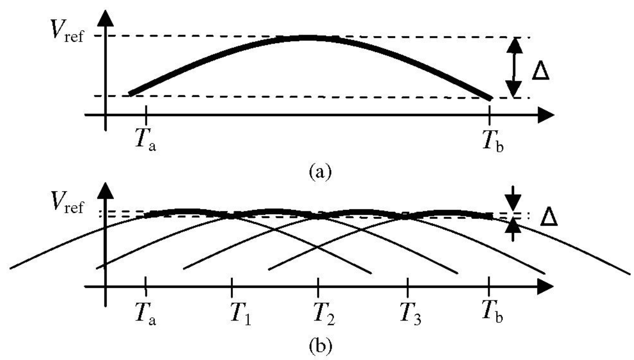

Figure 2. Conceptial depiction of (a) Single-inflection point bandgap curve and (b) Multi-segment bandgap curve.

To use the multi-segment bandgap reference, we will first determine the number of segments and divide the specified temperature range $[T_a, T_b]$ into corresponding intervals, e.g. $[T_a, T_1]$ and $[T_1, T_2]$, based on the stability requirement. Then we would like to place the inflection point for each segment so that T_{inf} will be close to the middle of the corresponding temperature interval and V_{inf} close to the up-bound of the voltage window for the best performance. The proposed approach tunes R_0 and R_4 to select the inflection point.

A. T_{inf} placement

The relationship between the inflection point and the resistance values are unknown and can not be predicted, so we will take measurements to identify the relationship and use it to choose appropriate values for R_0 and R_4.

C_0, C_1 and C_2 in (3) are unknown, but they will change in fixed functional forms when R_0 is changing and other parameters are fixed, and subsequently change the reference voltage. Equations (4-6) are informational but too idealistic. In light of them, we model the three coefficients as linear combinations of $1/R_0$, $\ln(R_0)$, and a constant term as

$$C_0 = b_{00} + b_{01}/R_0 + b_{02}\ln(R_0), \quad (9)$$

$$C_1 = b_{10} + b_{11}/R_0 + b_{12}\ln(R_0), \quad (10)$$

and

$$C_2 = b_{20} + b_{21}/R_0 + b_{22}\ln(R_0), \quad (11)$$

where b_{ij}'s are unknown coefficients. When b_{ij}'s are identified, we can figure out how to pick R_0 so that a desired T_{inf} can be achieved as in (7).

To get b_{ij}'s values, we apply a set of R_0 values $\{R_{0,k}, k=1, 2, \ldots, K\}$ to the circuit under a temperature T_1, and measure the reference voltage $\{V_{\mathrm{ref},k}(T_1), k=1, 2, \ldots, K\}$. Then we change the temperature and measure the reference voltage with the same set of R_0 values under another two temperatures T_2 and T_3. We get $\{V_{\mathrm{ref},k}(T_2), k=1, 2, \ldots, K\}$ and $\{V_{\mathrm{ref},k}(T_3), k=1, 2, \ldots, K\}$, respectively. Now we have three reference voltages, $V_{\mathrm{ref},k}(T_1)$, $V_{\mathrm{ref},k}(T_2)$ and $V_{\mathrm{ref},k}(T_3)$, for one resistance value $R_{0,k}$. We can solve for three variables $C_0(R_{0,k})$, $C_1(R_{0,k})$ and $C_2(R_{0,k})$ using (3) under three temperatures. There are totally K copies of (9) relating $C_0(R_{0,k})$ to $R_{0,k}$, so the least squares (LS) method can be used to solve for b_{00}, b_{01} and b_{02} as long as K is no less than three. Similarly, b_{1i} and b_{2i}, i=0, 1, 2, can be solved from (10) and (11) as well.

When segmentation of the bandgap curve are determined, we can calculate R_0 values for each segment that will give desired T_{inf} values, the middle of each interval, using (7) and (9-11). Although the relationship between R_0 and T_{inf} is nonlinear, numerical methods such as binary search and linear interpolation are accurate enough to get the result. R_0 values for individual segments will be saved on-chip and used when the temperature is in an associated interval.

B. V_{ref} level adjustment

The thermal stability requirement of the bandgap reference together with the desired output voltage level specifies a window of voltage variation. With the multi-segment design, the voltage in every segment should stay inside this window, and voltage levels in different segments should be very close to each other. Instead of matching the maximum voltages of different segments that happen at different temperatures, we will match the voltages of two segments at the temperature where the transition from one segment to the other happens, e.g. T_1 in Fig. 2(b). The voltage at the transition temperature is the minimum voltage in a segment if T_{inf} for the segment is at the middle of the interval. If we place this voltage above the lower bound of the variation window, the maximum voltage in the segment should be guaranteed lower than the upper bound of the window by appropriately choosing a small width for the interval.

Looking at the output node of the circuit, we find that the reference voltage can be effectively changed by tuning R_4 without affecting T_{inf} as the total resistance of R_3 and R_4 is not changed. When the temperature is entering a new interval, a new value of R_0, pre-calculated for the next segment, will be used for a correct T_{inf}. A new value of R_4 should be searched as well so that the voltage of the next segment is the same as that of the current segment at the transition temperature. This R_4 will be saved for later use whenever the temperature comes back into the associated interval. A comparator can be used to test whether the voltages from two segments are equal. Binary search over R_4 can be used to find the correct value while the first attempt can be calculated by using (8).

Combining the R_0 selection and R_4 searching algorithm, the bandgap voltage of the multi-segment reference circuit can be guaranteed to stay in a small window and have high thermal stability. The block diagram of the bandgap circuit with self-calibration is shown in Fig. 3, where a temperature sensor, a look-up (LU) table of resistances, a comparator and a simple controller are included on-chip also. The LU table can be implemented with non-volatile memories. A delta-sigma ADC can serve as the comparator since the voltages to be compared never arrive simultaneously.

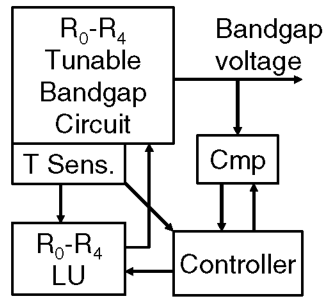

Figure 3. Block diagram of the bandgap circuit with self-calibration.

Since the algorithm takes measurements and calibrates the chip after manufacture and packaging, the effects of process variation and other factors on the bandgap curves can also be compensated by correctly choosing the R_0 and R_4 values, as long as the output voltage has the general bandgap property as described in (3). Therefore trimming is not necessary.

IV. SIMULATION RESULTS

Circuit level simulation was done in Cadence to validate performance of the multi-segment reference design and effectiveness of the calibration method. The supply voltage is 2.5 V for a TSMC 0.35 μm process. Transistors are cascoded for the current mirrors. The W/L ratio for all transistors is 30 μm/0.4 μm. The junction area of Q_1 is 10 μm^2. Q_2's area is eight times of Q_1's. R_1 and R_2 are set to be 6 KΩ. The total resistance of R_3 and R_4 is 6 KΩ as well. At the current stage, only the bandgap circuit was built with transistors. R_0-R_4 tuning and storage are not included on-chip and done with human interaction. An op amp was modeled in Veriloga with a gain of 70 dB.

Because the measurements for b_{ij} identification were done around the room temperature, the T_{inf} modeling accuracy at high or low temperatures would degrade. Therefore, we made the interval of the bandgap curve narrower for segments on both sides. As the intervals on sides are narrower than the one in the middle, the voltage variation of them is smaller. Values of R_4 are so chosen that at the transition temperature, the voltage of the segment closer to the terminal temperature is a bit higher than the voltage of the segment close to the middle. This will place the voltage level of the side segments at the middle of the voltage variation window to provide more tolerance on modeling and estimation errors.

TABLE I. INFLECTION POINT PLACEMENT

T_{inf_des} (°C)	-15	0	22.5	50	77.5	100	115
R_0 (Ω)	1247	1240	1229	1217	1206	1197	1192
T_{inf_act} (°C)	-12.3	0.8	23.3	50.1	76.8	100.2	113.8

The targeted temperature range was from -20 to 120 °C. It was partitioned into seven intervals as [–20 –10], [–10 10], [10 35], [35 65], [65 90], [90 110], and [110 120] °C. The desired T_{inf} for these segments are listed on the first row of Table I. For T_{inf} placement, V_{ref} was measured for R_0 ranging from 1150 to 1250 Ω with 1 Ω increment under T=20, 22, and 24 °C. The measured voltage has accuracy of 1 μV. The estimated T_{inf}-R_0 relationship was compared to the actual relationship from transistor level simulation in Fig. 4. The estimation error is plotted in Fig. 5. The values of R_0 for generating desired inflection point temperatures are derived from the calculated curve in Fig. 4 using linear interpolation and given on the second raw of Table I, with actual T_{inf}'s generated with them on the third row.

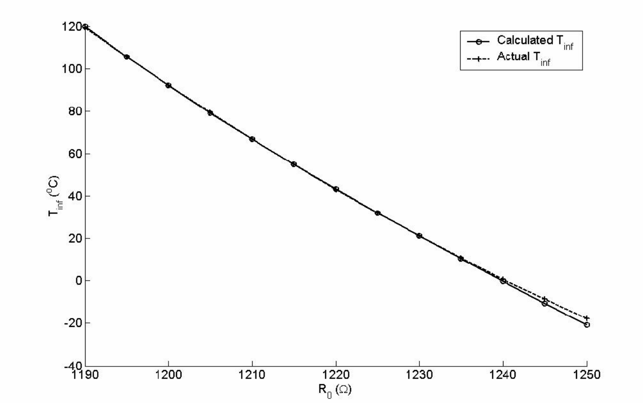

Figure 4. Estimated and Actual T_{inf}-R_0 relationship.

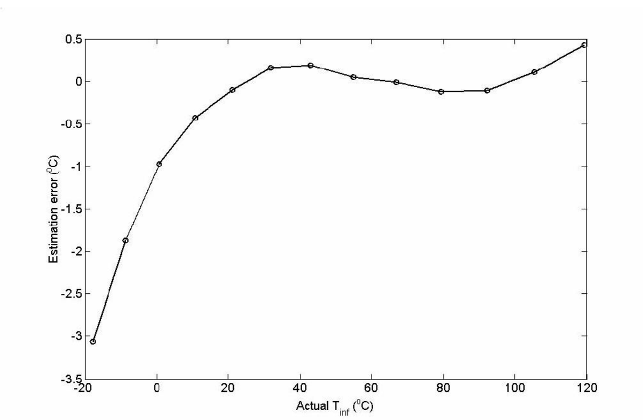

Figure 5. Estimation error in T_{inf}-R_0 relationship.

Using the R_0 values for each segment, we get a multi-segment bandgap curve as shown in Fig. 6. The bandgap voltage is around 1.2 V. Variation of the voltage stays in a 60-μV window over the temperature range of 140 °C, which gives a TC of 0.36 ppm/°C. This thermal stability is sufficient for being used in applications requiring 14-bit accuracy. The T_{inf} estimation error is larger at low temperatures but it does not introduce excessive errors.

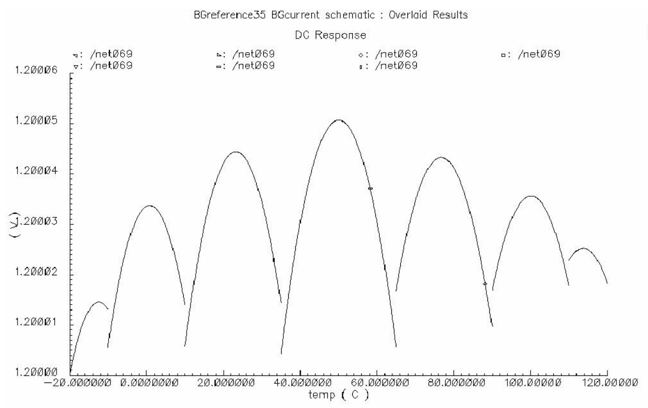

Figure 6. Self-calibrated multi-segment bandgap voltage curve.

V. CONCLUSION

A multi-segment bandgap voltage reference with self-calibration is introduced in this paper. The calibration algorithm measures the thermal characteristics of the bandgap circuit and uses appropriate circuit parameters to set inflection points of each segment based on the identified model of the bandgap circuit over a wide temperature range. When T_{inf} is placed at the middle of each segment and V_{ref} is put in the allowed voltage window, the bandgap circuit can achieve high thermal stability. Simulation results show that the proposed circuit has 0.36 ppm/°C temperature coefficient over a range of 140 °C. This circuit is compatible with most of the existing bandgap circuits and can be extended for low voltage designs.

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