A new curvature-corrected CMOS bandgap voltage reference

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Abstract: The current paper presents an improved bandgap voltage reference (BGR) that utilizes curvature-corrected current generators which compensate for the voltage reference at lower and higher temperature range. The voltage reference is operated with a supply voltage of 2.5 V to achieve an output reference of 1.1835 V. The temperature coefficient achieved from the circuit is 1.342 ppm/°C, resulting from temperature changes between −50°C to 125°C, sixfold improvement from first-order BGR. The proposed circuit is simulated using Silterra 0.13 μm CMOS technology.

Keywords: CMOS bandgap reference, low variation

Classification: Integrated circuits

References

1 Introduction
The performance of most circuit blocks is connected to that of the voltage references used to bias and power them. A first-order bandgap reference adds the forward-bias voltage across the p-n diode, and that voltage is weighted by adjusting the ratio of two resistors [1]. The voltage across the p-n diode is
expressed as the sum of a constant term, a term proportional to temperature and a nonlinear term clearly explained in [2]. The variation of the nonlinear term with respect to temperature reported in [2] is 4.5 mV for the temperature between $-50^\circ C$ to $150^\circ C$. A few works reported on curvature-corrected BGR are presented in [3, 4]. Although these circuits have been proven to lower the voltage variation, the variation only ranges from $0^\circ C$ to $125^\circ C$. In the current work, the variation of the nonlinear term is decreased through the inclusion of curvature-corrected current generators that compensate for the voltage reference at lower and higher temperature.

2 Proposed design

The operation of the proposed design is shown in Fig. 1. The first-order BGR produces an output given as

$$V_{REF} = K_1 V_T ln(n) + V_{EB}, \quad (1)$$

where $K_1$ is the temperature independent coefficient, $V_T$ is the thermal voltage, and $n$ is the emitter area ratio of BJT.

![Curvature-corrected BGR](image)

To compensate the nonlinearity of the first-order BGR, the nonlinear curvature-corrected voltages, $V_{NL1}$ and $V_{NL2}$, are added. As a result, a curvature-corrected BGR is obtained, as graphically shown in Fig. 1. The proposed BGR consists of first-order BGR, current generators, $G_A$ and $G_B$, and a startup circuit, as illustrated in Fig. 2 (a).

The output of the first-order BGR is expressed as follows:

$$V_{ref} = \frac{R_2 + R_3}{R_1} V_T ln(n) + V_{EB3}, \quad (2)$$

where $n$ is the emitter area ratio of $Q_2$. The proposed current generator $G_A$ is illustrated in Fig. 2 (b). The current $I_{PTAT1}$ flowing through the resistor
Fig. 2. (a) Proposed BGR, (b) Current generator, $G_A$, and (c) Current generator, $G_B$.

$R_4$ produces a PTAT voltage given as

$$V_{GMP6} = R_4 I_{PTAT1}, \quad (3)$$

where

$$I_{PTAT1} = \frac{V_T \ln(n)}{R_1}. \quad (4)$$

Parameter $\alpha$ is the ratio of the size of $M_{P4}$ to $M_{P2}$. The size of $M_{P7}$ is larger than $M_{P6}$ to reduce the variation of the source voltage $M_{P6}$ and $M_{P7}$. At temperature below $T_{REF}$, when the voltage $V_{SGMP6}$ is much larger than its threshold voltage, $M_{P6}$ is operating in the saturation region. By further increasing the temperature, $M_{P6}$ will no longer be in the saturation region; it starts operating in the weak inversion region.
When $V_{SGMP6}$ is much lower than its threshold voltage, the transistor $MP6$ will be completely cut off and there will be no current flowing through $MP6$. The operation of the proposed circuit by [4] is illustrated in Fig. 2(c). It works similar to the circuit of Fig. 2(b), but it produces current $I_{NL2}$ at high tempearature only. The voltage at gate terminal of $MP9$ is given by

$$V_{GM9} = V_{DD} - R_5 I_{PTAT3},$$

where

$$I_{PTAT3} = \frac{\gamma V_T \ln(n)}{R_1}.$$  

(6)

Parameter $\gamma$ is the ratio of the size of $MP8$ to $MP2$. The gate-source voltage of transistor $MP9$ is insensitive to power supply variation expressed as follows

$$V_{SGMP9} = \frac{R_5 V_T \ln(n)}{R_1}.$$  

(7)

Currents $I_{NL1}$ and $I_{NL2}$ run through $R_3$. As a result, the corrected voltages $V_{NL1}$ and $V_{NL2}$ are generated. The addition of the corrected voltages with the output voltage produced by the first-order BGR expresses the following equation:

$$V_{REF} = \frac{R_2 + R_3}{R_1} V_T \ln(n) + V_{EB3} + (I_{NL1} + I_{NL2}) R_3.$$  

(8)

The corrected voltages are given by the third term of Eq. (8). It efficiently compensates the voltage variation, thereby keeping the output voltage of $V_{REF}$ from changing with the change in temperature.

### 3 Simulation results

The proposed BGR shown in Fig. 2(a) is carried out in a standard 0.13 $\mu$m CMOS process. Figure 3 shows the variation of voltage reference within the temperature range $-50^\circ C$ to $125^\circ C$. The voltage variation is only 0.278 mV for the proposed BGR, sixfold improvement from 1.714 mV for the first-order BGR. The curvature-corrected currents $I_{NL1}$ and $I_{NL2}$ are also shown in Fig. 3. When the temperature is less than $20^\circ C$, the nonlinear-corrected current $I_{NL1}$ is increasing while $I_{NL2}$ is completely cut off. By contrast, the current $I_{NL2}$ starts increasing, whereas the current generator $GA$ is in off state when the temperature is greater than $20^\circ C$. The maximum currents of $I_{NL1}$ and $I_{NL2}$ are 450 and 250 nA, respectively.

### 4 Conclusion

A BGR with very low voltage variation has been presented. The proposed design produces an output voltage reference of 1.1835 V over a temperature range of $-50^\circ C$ to $125^\circ C$. The temperature coefficient achieved from the circuit is 1.342 ppm/$^\circ C$, whereas the temperature coefficient of 8.276 ppm/$^\circ C$ is obtained for the first-order BGR.
Fig. 3. Voltage reference and nonlinear current.

Acknowledgments
The authors would like to express their sincerest appreciation to all the ICDC group members, Silterra Malaysia Sdn. Bhd., and the Collaborative Microelectronic Design Excellence Centre (CEDEC).