An improvement of a piecewise curvature-corrected CMOS bandgap reference

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Abstract: In the current paper, an improvement of piecewise curvature-corrected CMOS bandgap reference (BGR) circuit is proposed. The circuit utilizes piecewise nonlinear curvature-corrected current (PNCCC) in a conventional BGR with a current control circuit, which compensates for the voltage reference at a higher temperature range. The current control circuit (CCC) is used to reduce the total current at low temperature when the PNCCC generator is inactive. The proposed circuit is realized in CMOS 0.13 μm and has been verified to be able to save power consumption by 18.6% compared with a circuit without the current control circuit.

Keywords: bandgap reference circuit, piecewise curvature-corrected

Classification: Integrated circuits

References

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1 Introduction

A reference circuit is an independent voltage or current source with a high degree of precision and stability. The output voltage or current should be independent of the power supply, temperature, and process variations [2]. Traditionally, the output voltage reference has always been approximately equal to the theoretical 1.22 eV bandgap of silicon at 0 K [1].

The bipolar junction transistor (BJT) can be utilized in the BGR design. The properties of base-emitter voltage V_{BE} are applied to generate the BGR signal. As the second-order non linearity of the function $V_{BE}(T)$ is generally the main limitation of the accuracy of the BGR [3], the bandgap reference circuit proposed in [4] has been reported to successfully compensated the nonlinear voltage. However, the proposed PNCCC generator in [4] consumes power, although the circuit remains inactive at low temperature. To avoid this problem, the control current circuit is proposed to suppress the current in the PNCCC generator without disturbing the output voltage variation.

2 Proposed circuit

The BGR circuit proposed by [4] utilizes a PNCCC generator to compensate for the nonlinear term of the first-order BGR in the higher temperature range only. The operation of the proposed circuit by [4] is illustrated in Fig. 1.

Fig. 1. Operation of the curvature-corrected BGR.

The temperature coefficient of the conventional BGR is slightly negative in the entire temperature range, resulting in small changes in the voltage reference for the temperature lower than T_1 . A piecewise nonlinear curvature-corrected voltage is added to the first-order BGR when the temperature is higher than T_1 , significantly compensating for the nonlinear voltage in the first-order BGR circuit. The proposed circuit by [4] is shown in Fig. 2 (a).

The PTAT current I_{PTAT} , through the resistor R_4 , produces a PTAT

Fig. 2. (a) Previous BGR circuit proposed by [4], and (b) The proposed BGR circuit.

voltage given as

$$V_{G_{M_{12}}} = R_4 I_{PTAT}, \quad (1)$$

where

$$I_{PTAT} = \frac{V_T \ln(n)}{R_1}. \quad (2)$$

Parameter n in Eq. (2) is the emitter-area ratio of Q_1 and Q_2 . At a temperature below T_1 , when the voltage $V_{SG_{M_{12}}}$ is much larger than its threshold voltage, M_{12} operates in the saturation region. By increasing the temperature, M_{12} will no longer be in the saturation region as it enters into the weak inversion region. When $V_{SG_{M_{12}}}$ is much lower than its threshold voltage, the transistor M_{12} will be completely cut off, and no current will flow through

M_{12} . The voltage reference V_{REF} of the curvature-corrected BGR can be derived from the circuit given as follows [4]:

$$V_{REF} = V_{EBQ3} + \frac{V_T \ln(n)(R_2 + R_3)}{R_1} + I_{NL} R_2, \quad (3)$$

where I_{NL} is a nonlinear current flowing through M_{12} . Although Fig. 2 (a) works well in terms of output voltage compensation, the piecewise corrected current generator is not completely turned off for the temperature below T_1 because of the PTAT current flowing through transistor M_9 .

We propose a BGR circuit along with a current control circuit in Fig. 2 (b). The transistor M_{13} is added to the previous circuit and is biased with the PTAT voltage V_B . V_B increases with temperature expressed as

$$V_B = \frac{V_T \ln(n) R_4}{R_1}. \quad (4)$$

In the proposed circuit, V_B is also used to bias the operational amplifier. The overall operation of the proposed BGR is similar to that of the circuit in Fig. 2 (a), except the current flowing through M_9 , which is controlled by M_{13} . When the temperature is lower than T_1 , the gate-source voltage of M_{13} is less than its threshold voltage, resulting in the drain voltage of M_9 to be approximately equal to V_{DD} . A current near zero through M_9 occurs as M_9 enters the deep triode region. As the temperature increases, M_{13} will be turned on when the gate-source voltage is larger than the threshold voltage. Conversely, the drain voltage of M_9 decreases with the increase in temperature, and the nonlinear current begin to flow through M_9 until it enters the saturation region. In this region, the PTAT current is generated, which is given as

$$I_{PTAT} = \frac{V_T \ln(n)}{R_1}. \quad (5)$$

3 Simulation

We performed intensive simulations using an analog design environment and the Spectre-s simulator from Cadence on the proposed BGR circuit. The technology used was the $0.13 \mu\text{m}$ CMOS with a 2.5 V supply voltage.

The nonlinear curvature-corrected current I_{NL} and the current through M_9 are plotted in Fig. 3 (a). The minimum current through M_9 for the proposed circuit is only 12.9 nA at -50°C , which differs by as much as $2.72 \mu\text{A}$ from the BGR without the current control circuit. When the temperature reaches 40°C , M_9 enters the saturation region and produces a linear current, as presented in the same figure. The current I_{NL} is generated through M_{12} . The maximum current of 538 nA is obtained at 125°C .

Fig. 3 (b) shows the total current consumption and voltage reference within the temperature range of -50 to 125°C . The minimum current of $29.3 \mu\text{A}$ is achieved at -50°C in the proposed BGR, whereas the previous BGR consumes $36.4 \mu\text{A}$ in the same temperature. An improvement of 18.6% in terms of power consumption is achieved in the proposed BGR. The maximum and minimum output voltage references V_{REF} are 1.17984 and

Fig. 3. (a) Current through M_9 and nonlinear curvature-corrected current, and (b) Voltage reference and total current.

1.17921 V, respectively. Based on these values, the temperature coefficient is only 3.1 ppm/ $^{\circ}\text{C}$.

4 Conclusion

An improvement of the piecewise curvature-corrected BGR circuit is presented. The minimum current flowing through M_9 in the proposed circuit is only 12.9 nA at -50°C , whereas a current of $2.73 \mu\text{A}$ is obtained from the

previous circuit in the same temperature. The newly proposed circuit has been verified to be able to save power consumption up to 18.6% compared with the circuit without a current control circuit. The temperature coefficient of the voltage reference is 3.1 ppm/°C in the proposed BGR.

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