Method for BGR’s second-order temperature compensation using resistor combinations with specified temperature coefficients

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Abstract: In this paper, an original method is proposed to implement temperature compensation for a bandgap reference (BGR) circuit without any auxiliary circuits. By employing resistor combinations (formed by different type of resistors) with specified temperature coefficients (TC), the temperature coefficient of a previous reported bandgap reference is improved from 22.11 ppm/°C to 3.499 ppm/°C (−25°C–85°C). In order to accomplish the improvement, a useful model is also proposed to help understand the relationship among the TCs of resistors’ combinations and BGR.

Keywords: bandgap reference, high-order compensation, temperature coefficient, resistors

Classification: Electron devices, circuits and modules

References

1 Introduction

Bandgap references are very important components in integrated systems, which can provide stable voltage/current references insensitive to process, power supply voltage and temperature variations. First-order compensation is considered to be a basic approach to implement high-precision BGRs, which, however, can only help to achieve a temperature coefficient between 20 to 100 ppm/°C [1]. To solve this problem, many high order curvature correction techniques have been developed [2, 3, 4, 5, 6, 7], in which, auxiliary circuits with considerable area must be employed. For optimizing the temperature coefficients of BGRs without auxiliary circuits, different types of resistors are employed which lacks of a full elaboration on the selections of resistors types [8]. In this paper, the combination of different type of resistors rather than single kind of resistor are employed in a sub-1V BGR, in which, the resistor combinations’ TC can be specified to implement higher-order temperature compensation and then achieve a very low BGR’s TC. Besides, the mathematical model of the TCs’ relationship among BGR and the resistor combinations is also proposed in this work.

2 Topology of proposed sub-1V bandgap reference

The proposed sub-1V bandgap reference is shown in Fig. 1, which is derived from a previous work [9]. In which, all the transistors are working in sub-threshold region to realize low power consumption and be suitable for low power supplies. The reference voltage $V_{\text{ref}}$ can be calculated as Eq. (1):

$$V_{\text{ref}} = \alpha \cdot \frac{R_2}{R_1} \cdot V_T + V_{GS2}$$  \hspace{1cm} (1)

in which $\alpha$ is a positive coefficient related with the physical parameters of the components; $V_{GS2}$ is the gate-source voltage of $M_2$; $V_T$ is the thermal voltage. Since $M_2$ works in sub-threshold region, which makes $M_2$ behaving like a bipolar transistor, $V_{GS2}$ has a negative TC (around $-1.5 \text{ mV/}^\circ\text{C}$ at $25^\circ\text{C}$) varying with temperature. While regarding the resistors as a same type of device, we take a derivative of $V_{\text{ref}}$ with respect to absolute temperature $T$. We can find Eq. (2):

$$\frac{dV_{\text{ref}}}{dT} = \frac{\alpha \cdot k}{q} \cdot \frac{R_2}{R_1} + \frac{dV_{GS2}}{dT} $$  \hspace{1cm} (2)

where, $k$ is the boltzmann constant and $q$ is the elementary charge. In order to generate a reference voltage with a near zero TC, all that we can do is to adjust the
ratio $R_2/R_1$ in the situation that $R_1$ and $R_2$ have the same TC. However, since $dV_{GS2}/dT$ is not a constant value but varies with temperature, this kind of first-order compensation can be used to achieve a temperature coefficient of no less than 22.11 ppm/°C after carefully review [5].

In our work, $R_1$ and $R_2$ are firstly set to 36.5 k and 547.5 k through conventional first-order compensation. Especially, $R_1$ and $R_2$ are implemented using resistors-combinations as shown in Fig. 1. Therefore it’s able to adjust $R_1$ and $R_2$’s TC to realize a second-order compensation which is describe in next section.

### 3 Proposed method for second-order compensation

In our design, we use different types of resistors to fabricate $R_1$ and $R_2$, respectively, thus the resistors could have different TCs. In this scenario, the derivative of $V_{ref}$ in Eq. (1) can be taken again as Eq. (3), in which, more factors are induced to contribute to the balance of $V_{ref}$’s temperature curve.

$$\frac{dV_{ref}}{dT} = \alpha \cdot \frac{kT}{q} \cdot \left(\frac{1}{R_1} \frac{dR_2}{dT} - \frac{R_2}{R_1^2} \frac{dR_1}{dT}\right) + \left(\alpha \cdot \frac{k}{q} \cdot \frac{R_2}{R_1} + \frac{dV_{GS2}}{dT}\right)$$  \hspace{1cm} (3)

Eq. (3) suggests that if $V_{ref}$’s TC is not as good as expected after $R_2/R_1$ being set to an appropriate value according to the demand of first-order compensation (PART 2 in Eq. (3)), we can still adjust $R_1$ and $R_2$’s TCs implementing second-order compensation (PART 1 in Eq. (3)) to achieve a better TC for $V_{ref}$. Thus, if an zero TC is expected for Eq. (3), it can be turned into Eq. (4).

$$A \cdot \frac{dR_2}{dT} + B \cdot \frac{dR_1}{dT} + C = 0$$  \hspace{1cm} (4)

where $A = 1/R_1$, $B = -R_2/R_1^2$ and $C = R_2/(TR_1) + (q/akT) \cdot (dV_{GS2}/dT)$. After $R_1$ and $R_2$’s values are decided to meet the demand of first-order compensation, $A$ and $B$ can be treated as constants. $C$ is supposed to be related to absolute temper-
nature. Assuming that $C$ varies little in the concerned temperature range (thus $C$ can be considered to be a constant, which will be further proved to be acceptable), it can be derived that if the $R_1$ and $R_2$’s TCs satisfy the linear relationship described in Eq. (4), a zero TC can be achieved for $V_{ref}$.

The reference circuits are designed using TSMC0.18 µm standard CMOS process. There are several types of resistors can be fabricated using this process and part of them and their corresponding TCs are described in Table I. (rphpoly: poly resistor without silicide. rpplus..2T: P+ diffusion resistor without silicide. mplus..2T: N+ diffusion resistor without silicide. rnhpoly: N+ poly resistor without silicide. $W$ is the width of the resistive layer as well as the contacts. The resistance of core resistive layer, contact layer and their TCs are represented by $R_{co}$, $R_{ct}$, $TC_{co}$ and $TC_{ct}$, respectively. $TC_{min}$ and $TC_{max}$ is the minimum and maximum TCs that can be achieved employing single type of transistor using method in [10] taking the contacts’ TC into account.) However, the temperature range between $TC_{min}$ and $TC_{max}$ is too small to make $R_1$ and $R_2$’s TCs satisfying Eq. (4). Therefore we propose using resistor combinations rather than single kind of resistor to implement BGR circuits which is shown in Fig. 1. If two kinds of the resistors listed in Table I are used to form a resistors’ combination, we can make the combinations’ TCs range from $−1515.61$ µΩ/°C to $1478$ µΩ/°C.

In order to verify the TCs relationship in Eq. (4), mass simulations are implemented among different $R_1$ and $R_2$’s TCs. At the temperature of $27°C$, $R_1$ and $R_2$’s TCs are selected every $75$ µΩ/°C, respectively, from the whole combinations’ TC range. The corresponding $V_{ref}$’s TCs are simulated and illustrated in Fig. 2. It can be seen clearly that, the lowest $V_{ref}$’s TCs lies in a line determined by the linear relationship of $R_1$ and $R_2$’s TCs. Same simulations are also implemented at the temperature of $−25°C$, $0°C$, $56°C$ and $85°C$, which are illustrated in Fig. 3. It can be noted that the same linear relationships are found between $R_1$ and $R_2$’s TCs as well, in achieving lowest $V_{ref}$’s TCs. Fig. 4 shows that the lines derived from Fig. 2 and Fig. 3 almost stack together, which proves that, in the concerned temperature range, the lowest BGR’s TC depends on the similar linear relationships between the TCs of $R_1$ and $R_2$. For convenience, the linear equation being fitted at $27°C$ are chosen to decide the relationship between $R_1$ and $R_2$’s TCs. According to the analysis above, $R_1$ and $R_2$ are decided as $36.5$ k and $547.5$ k with desired TCs of $−757.9$ µΩ/°C and $−1263$ µΩ/°C, respectively. In such a scenario the best BGR’s TC can be achieved. They are implemented using the combination of rphpoly and

<table>
<thead>
<tr>
<th>Parameters</th>
<th>rphpoly</th>
<th>rppplus..2T</th>
<th>mplus..2T</th>
<th>rnhpoly</th>
</tr>
</thead>
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<tr>
<td>$W$ (µm)</td>
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<td>2</td>
<td>2</td>
<td>2</td>
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<td>$R_{co}$ (Ω/µm)</td>
<td>163.35</td>
<td>67.645</td>
<td>29.365</td>
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<td>$TC_{co}$ (µΩ/°C)</td>
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<td>$1383$</td>
<td>$1478$</td>
<td>$−1506$</td>
</tr>
<tr>
<td>$R_{ct}$ (Ω/µm)</td>
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<td>$13.661$</td>
<td>$43.001$</td>
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<tr>
<td>$TC_{ct}$ (µΩ/°C)</td>
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<td>$−1550$</td>
<td>$769$</td>
<td>$−1584$</td>
</tr>
<tr>
<td>$TC_{min}$ (µΩ/°C)</td>
<td>$−575.5$</td>
<td>$920.584$</td>
<td>$1344.2$</td>
<td>$−1515.61$</td>
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<tr>
<td>$TC_{max}$ (µΩ/°C)</td>
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<td>$1383$</td>
<td>$1478$</td>
<td>$−1506$</td>
</tr>
</tbody>
</table>
rhopoly resistors, as illustrated in Fig. 5 and Table II (all the contacts are as long as 2 µm).

4 Experimental results

In order to validate the effectiveness of the proposed method, the bandgap reference is fabricated and evaluated using TSMC 0.18 µm CMOS process. Experiments are implemented and the results are illustrated in Fig. 6. The $V_{reg}$’s TC and linear sensitivity finally turn out to be 3.499 ppm/°C (−25°C–85°C) and 556.68 µV/V (0.7 V–1.7 V at 25°C) after trimming.
5 Conclusion

A method for implementing second-order bandgap reference temperature compensation using resistor combinations with specified TCs is presented in this paper. According to mathematical analysis and the whole-temperature-range simulation results, achieving best TC for \( V_{\text{ref}} \) depends on the linear relationship between \( R_1 \) and \( R_2 \)’s TCs. An approach for resistors’ type selection and TC adjustment techniques is also introduced to help us to carry out this method. Proposed BGR as well as resistors’ combinations with specified TCs are designed and fabricated using TSMC 0.18 um CMOS process. Besides, a model is derived from mass of simulations to help us understand the relationship among the TCs of resistors’ combinations and BGR. The experimental results show that the \( V_{\text{ref}} \)’s temperature curve is tested as 3.499 ppm/°C.

### Table II. The parameters of resistor combinations, \( R_1 \) and \( R_2 \).

<table>
<thead>
<tr>
<th>Name</th>
<th>Length of rphpoly</th>
<th>Series number of rphpoly</th>
<th>Length of rnhpoly</th>
<th>Series number of rnhpoly</th>
<th>Parallel number</th>
</tr>
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<tbody>
<tr>
<td>R1</td>
<td>6.185 µm</td>
<td>20</td>
<td>3.89 µm</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>R2</td>
<td>2.086 µm</td>
<td>1010</td>
<td>7.48 µm</td>
<td>1000</td>
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</table>

![Fig. 5. Resistor Combinations, \( R_1 \) and \( R_2 \), employed in the BGR shown in Fig. 1.](image)

![Fig. 6. Experimental results of \( V_{\text{ref}} \) using proposed method.](image)
Acknowledgments

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