A high precision programmable bandgap voltage reference design for high resolution ADC*

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Abstract: A programmable high precision bandgap reference is presented, which can meet the accuracy requirements for all technology corners while a traditional bandgap reference cannot. This design uses SMIC 0.18 μm 1P4M CMOS technology. The theoretically achievable temperature coefficient is close to 0.69 ppm/°C over the whole temperature range.

Key words: bandgap reference; high precision design; second-order curvature compensation; low temperature coefficient

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1. Introduction

A high precision voltage reference circuit is often needed in a high resolution ADC, which is a critical part of analog circuit design. In particular, the accuracy of the voltage reference is a key factor in defining the precision of a high resolution ADC system. For a 14 bit resolution pipeline ADC design, a temperature coefficient of 0.6 ppm/°C over a range of 100 °C is required, if one least significant bit (LSB) variation is allowed[1]. So, the high precision bandgap reference has attracted a lot of attention because of its characteristics. A traditional bandgap reference is fabricated using bipolar technology, which is more precise than CMOS technology[2]. This is because a bipolar in standard CMOS technology is hard to manufacture with high precision. To overcome this problem, a programmable high precision bandgap reference is presented, which can overcome variation in temperature, supply voltage and technology corner. To reduce the effect of temperature variation, a two order compensation technique is applied in this system. To meet all the technology corners, a programmable resistor array is adopted. Another important thing for designing a bandgap reference is ensuring the stability of the design. To do this, a low noise, middle DC gain and large phase margin amplifier is designed. By adopting these techniques, this design achieves a 0.69 ppm/°C temperature coefficient (TC) when the temperature is ranging from –40 to 100 °C .

2. Traditional bandgap reference design

The traditional bandgap reference is a weighted sum of a negative TC voltage $V_{\rm BE}$ which is the forward-bias voltage across a p–n junction, a positive TC voltage $V_{\rm t}$ which is the thermal voltage $\frac{kT}{q}$, proportional to the absolute temperature (PTAT), shown in Fig. 1, where M is the adjusted weighted factor[2]. By adjusting M, the sum of the positive TC and the negative TC should be zero. A traditional bandgap reference is shown in Fig. 2[2]. There are three parts in the circuit: the start-up circuit, the PTAT generation circuit, and the reference voltage generation circuit. The reference voltage is

$$V_{\rm ref} = V_{\rm BE} + MV_{\rm t}. \tag{1}$$

Traditional bandgap references just use the first-order compensation method over the whole temperature range.

Because the first-order compensation method can just provide one positive temperature coefficient voltage, which

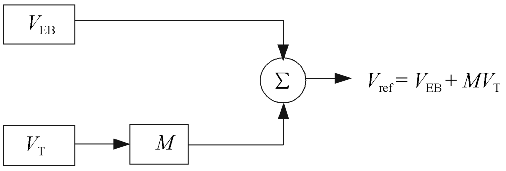

Fig. 1. Traditional bandgap reference overview.

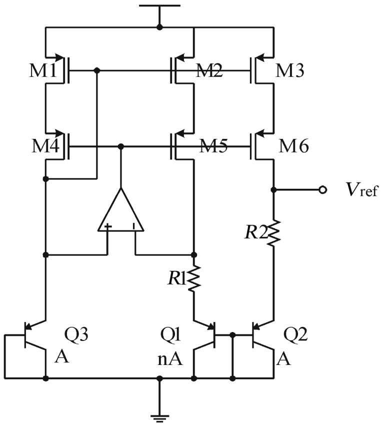

Fig. 2. First-order bandgap reference circuit.

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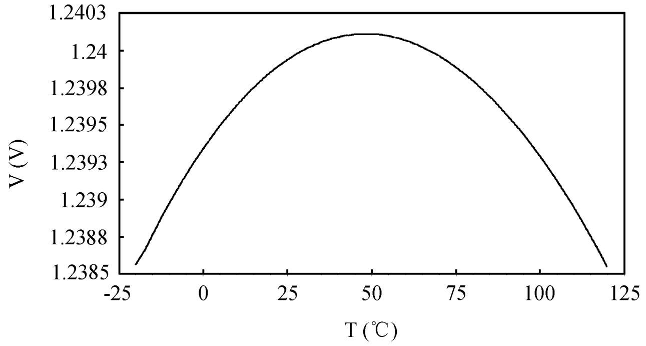

Fig. 3. Output curve of first-order compensated bandgap reference.

can not meet the compensation requirement over the whole temperature range, a first-order bandgap reference can be designed to ensure that a zero TC is obtained at the midpoint of the whole temperature range. A traditional bandgap reference temperature response curve is shown in Fig. 3. The traditional bandgap references can achieve several tens of ppm/°C. To overcome this problem, a second-order compensation method is developed.

3. Second-order compensation method

There are many ways of generating a second-order compensation voltage. One method is to generate a PTAT^{2}current and then to relate all temperature dependent variables to a reference voltage, which is temperature independent. Another method is to use devices with positive temperature coefficients to generate a second-order compensation voltage, such as Ref. [3] and Ref. [4].According to reports, both methods can be used to design a high precision bandgap reference. In this paper, the latter was adopted because it is simple to design and to fit to the programmable correction method presented later in this paper.

In modern standard CMOS technology, more than one type of resistor is provided. Different types of resistors have different temperature coefficients. In conventional bandgap reference circuits, there is only one type of resistor used, which means that there is no temperature coefficient in the term for the resistor ratio R_2/R_1, shown in Fig. 2. The advantage of this method is that the matching between resistors is easy to achieve, but it does not make use of the difference between different resistors. When splitting R_2 into two resistors R_c and R_d with different types, R_c is of the same type as R_1; R_d is not, and R_d/R_1 has a temperature coefficient. Then the design can have another term with a second-order positive temperature coefficient other than PTAT, which means that two positive temperature dependent terms can compensate the negative temperature dependent term V_{BE}. The operational principle of the second-order compensated bandgap reference has been described in Ref. [3]. The resistors adopted in Ref. [3] are p-diffusion resistors to provide a second-order compensation. However, the resistivity of the p-diffusion resistor is much smaller than that of the poly resistor in SMIC 0.18 μm CMOS technology. Thus, matching between two types of resistors is hard to achieve, and the technology tolerance for the p-diffusion resistor is large.

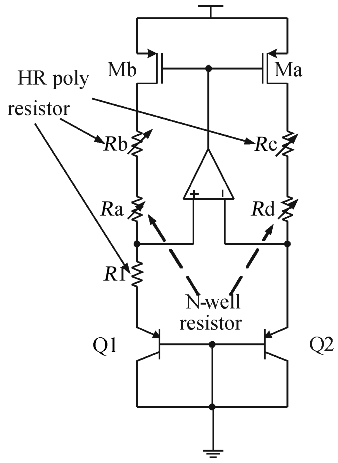

Fig. 4. Second-order bandgap circuit.

So, in this paper, n-well resistors are used instead of p-diffusion resistors, as they have a similar resistivity to a high-resistive poly resistors. According to this concept, a second-order compensation high precision bandgap reference core is presented, shown in Fig. 4. R_1, R_b, and R_c are high-resistive poly resistors (HR-poly R), while R_a and R_d are n-well resistors (n-well R). The reference voltage, V_{ref}, is given by

$$V_{ref} = V_{EB2} + V_{Rc} + V_{Rd}, \tag{2}$$

where

$$V_{Rc} = \frac{R_c}{R_1} \ln(N) V_T, \tag{3}$$

$$V_{Rd} = \frac{R_d}{R_1} \ln(N) V_T. \tag{4}$$

So,

$$V_{ref} = V_{EB2} + \left[\frac{R_c}{R_1} \ln(N) + \frac{R_d}{R_1} \ln(N)\right] V_T. \tag{5}$$

The resistor ratio R_c/R_1 is temperature-independent as R_c and R_1 are implemented by the same material, while the ratio of R_d/R_1 is temperature-dependent as two different types of materials are used[3, 4]. So, the temperature coefficient of the different types of resistors compensates the second-order term of V_{EB}.

4. Programmable resistor string design for calibration

In theory, a second-order compensated bandgap reference can achieve a more precise reference voltage than a traditional first-order compensated bandgap reference. However, the actual result will not be as good as the theoretical analysis suggests, because a lot of mismatches and noise exist in the real system, and the technology changes from wafer to wafer. For the second-order compensated bandgap reference presented above, there are two types of resistors which have different sheet resistance values and fabrication accuracy. Thus, any mismatch between resistors and technology variations will affect the second-order compensation effect. To overcome this problem, trimming must be carried out in the traditional design[5, 6]. In this paper, a programmable resistor string is proposed, which can be adjusted by a control signal

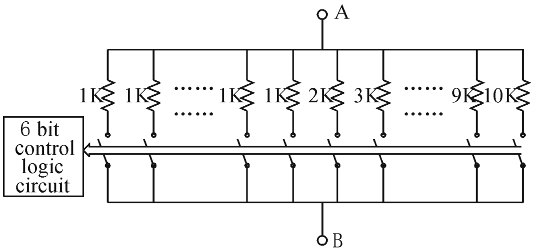

Fig. 5. Programmable resistor circuit.

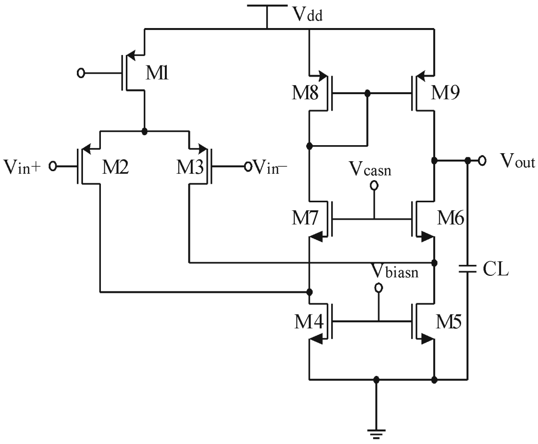

Fig. 6. Low noise amplifier circuit.

to provide a proper resistor value to meet the design requirement.

The programmable resistance module would use R_a, R_b, R_c, and R_d. R_1 is used to set the current I_0. When using two types of resistors with similar resistivity and technology tolerance, matching between resistors is easy to achieve. The easy way to realize the programmable resistor is to connect the unit resistors in series. But it is hard to design a programmable resistor as no ideal switch exists in the integrated circuit design. So the resistor and the MOS switch must be connected in parallel by using this method. But the off resistor of the MOS is not infinite, and the unit resistor is small to ensure the programming accuracy. The result is that the MOS switch will affect the value of the programmable resistor in both “ON” and “OFF” states. To solve this, the MOS switch must be in series with the resistor, which means that the unit resistors must be connected in parallel. The programmable resistor is shown in Fig. 5. The range of the programmable resistor is from 0.1 to 10 kΩ, which is not average. The programmable resistor is controlled by a 6-bit control signal, which means that it has 64 steps over the whole range.

5. Noise analysis and suppressive methods

Noise is an important factor which affects the performance of bandgap references. Some noise comes from the interference between devices and wires, which can be reduced by careful layout design. Other noise can only be reduced, but cannot be removed[7]. Because it is caused by the characteristics of the circuit; it can be divided into three types: thermal noise, $1/f$ noise, and flicker noise[8, 9]. These errors can be kept to a minimum by a structured design.

The main noise sources in the bandgap references are bipolar transistors and resistors. Noise in the top MOS transistors can be neglected by reducing the r_{ds} of the transistors. The noise contributions of the resistors dominate because they are greater than the r_{ce} value of the BJTs. So, the whole noise of the bandgap reference core is:

$$\begin{aligned} V_{ref}^2 &= 4kT(R_c+R_d) + \left[(R_c+R_d)\left(\sqrt{\frac{4kT}{R_a+R_b+R_1}}\right)\right]^2 \\ &= 4kT(R_c+R_d)\left(1+\frac{R_c+R_d}{R_a+R_b+R_1}\right). \qquad (6) \end{aligned}$$

For the resistors, this is controlled by the current I_0, so

$$\begin{aligned} V_{ref}^2 &= 4kT\frac{V_{ref}-V_{EB}}{I_0} \\ &\quad + 4kT\left(\frac{V_{ref}-V_{EB}}{I_0}\right)^2\frac{I_c}{V_{ref}-V_{EB}+\Delta V_{EB}} \\ &= 4kT\frac{V_{ref}-V_{EB}}{I_0}\left(1+\frac{V_{ref}-V_{EB}}{V_{ref}-V_{EB}+\Delta V_{EB}}\right). \qquad (7) \end{aligned}$$

Because $I_c = \Delta V_{EB}/R_a$, the larger ΔV_{EB} is, the lower the noise is. To make ΔV_{EB} large, the ratio of BJT′s must be large, and R_1 should be large.

The noise of the amplifier is also an important noise source, so this noise must be suppressed. Another important requirement for an amplifier is that the DC gain should be large, making the precision and the phase margin large and thus ensuring design stability[8]. So the design uses a modified folded cascode structure, shown in Fig. 6. The top PMOS cascode transistors are canceled; so a trade-off result between the DC gain and the phase margin is achieved. Another advantage of this is that the top part of the output voltage swing is large, which fits the bandgap reference application.

The noise of the amplifier comes from the noise of MOSFETs. The dominant noise of a saturated MOSFET is flicker noise and thermal noise[9]. The total noise of the amplifier, shown in Fig. 5, is:

$$\begin{aligned} V_{no}^2 &= 2(g_{m2}R_o)^2V_{n2}^2 + 2(g_{m5}R_o)^2V_{n5}^2 + 2V_{n5}^2 \\ &\quad + 2[g_{m9}(r_{ds9}\|R_o)]^2V_{n9}^2 \\ &\approx 2(g_{m2}R_o)^2V_{n2}^2 + 2(g_{m5}R_o)^2V_{n5}^2. \qquad (8) \end{aligned}$$

According to Eq. (8), to reduce noise, g_m, W and L of M2, M3, M4 and M5 should be large. M2 and M3 are PMOS transistors, since the noise of PMOS transistors is lower than that of NMOS transistors. The simulated integral noise from 1 Hz to 20 MHz is only 0.3 mV.

6. Simulation and test results

The whole design circuit is shown in Fig. 7, and includes two start-up circuits, a bandgap reference core circuit and an amplifier. The design is simulated under all technology corners, and the temperature sweep range is from –40 to 100 °C.

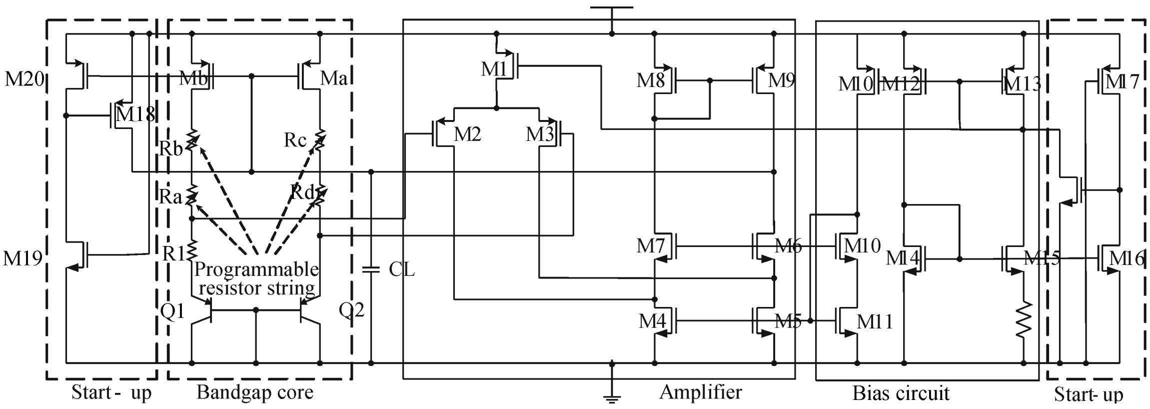

Fig. 7. Presented bandgap voltage reference circuit.

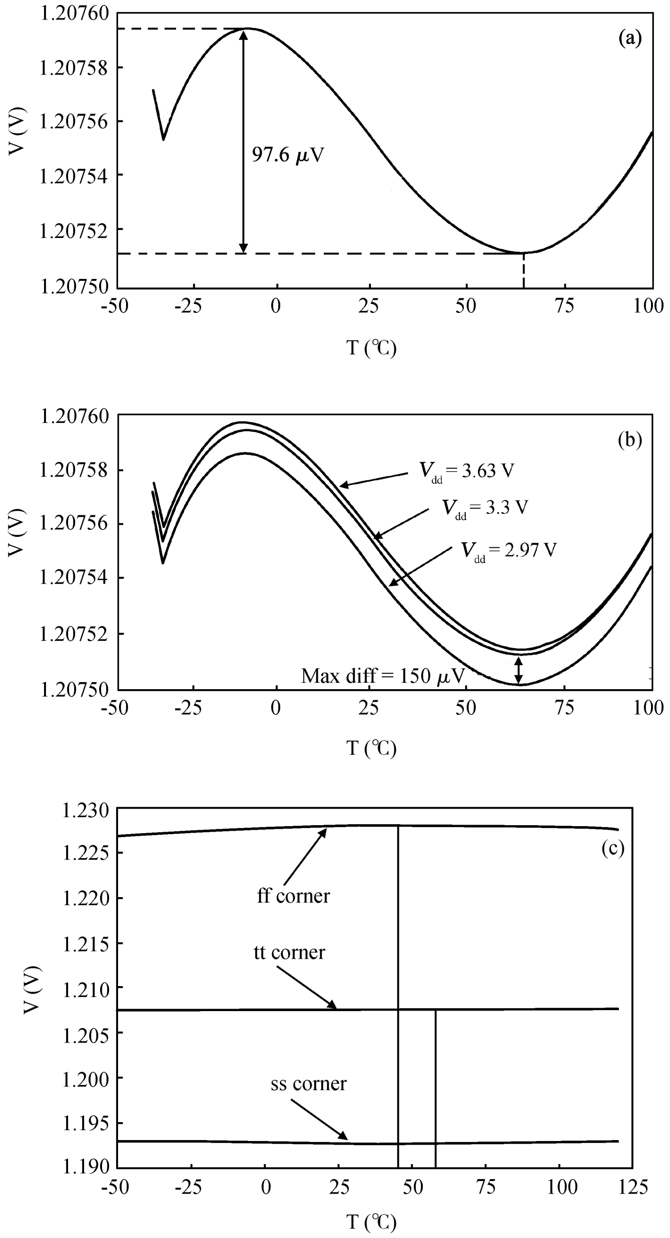

Fig. 8. (a) Output curve of the bandgap reference; (b) Output of the bandgap reference when power supply varies ±10%; (c) Output result in different corners.

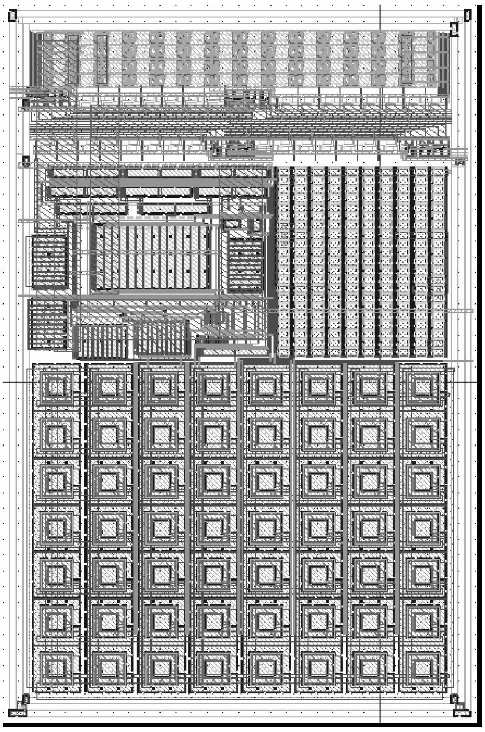

Fig. 9. Layout of the presented bandgap.

The simulation results are shown in Fig. 8(a), which shows that the reference voltage is compensated twice, and the maximum difference over the whole temperature range is only 97.2 μV, which means that the temperature coefficient is 0.69 ppm/°C. Figure 8(b) shows the maximum variation is only 150 μV when the power supply changes by ±10%. As shown in Fig. 8(c), the second-order compensation is achieved under three technology corners by adjusting the programmable resistor string. The power consumption of this work is about 99 μW. The design was made by using SMIC 0.18 μm 1P4M CMOS technology, and the layout is shown in Fig. 9. Rigorous matching between BJT′s and resistors was carried out, and dummy devices were applied in the layout design. The layout area is 0.0335 mm^2, which takes an extra area of 0.0075 mm^2 compared to the traditional ones with programmable adjustment. The extra area is about 1/4 of the traditional bandgap layout.

The bandgap has been done for part of a CMOS image sensor. Because the design is a part in the whole system, the

Table 1. Prime design parameters for the bandgap.

Parameter	Value
Die area	0.0335 mm^2
Power consumption	97.8 μW
Maximum difference of bandgap voltage	97.6 μV
Temperature range	–40 to 100 °C
Temperature coefficient	0.69 ppm/°C
Technology	SMIC 0.18 μm 1P4M CMOS

design has only been tested at room temperature. The control signals of the bandgap are controlled by one register in the I^{2}C circuit, which means that the bandgap can be easily programmed and controlled. The output voltage of the bandgap is 1.207 V, which is tested at room temperature and the control signal has a default value of 011111. The output voltage can be adjusted from 1.104 to 1.421 V by adjusting the control code from 000000 to 111111. The parameters are summarized in detail in Table 1.

7. Conclusion

This paper presents a programmable high precision bandgap reference circuit, which is suited to all technology corners. By using two types of resistors, a second-order compensated bandgap reference which has high precision has been achieved. The programmable resistor method is simple, easy to fabricate, and controllable. The simulation results show the maximum temperature coefficient is only 0.69 ppm/°C over the commercial temperature range. A system, which uses the bandgap, has been tested and verified. Indirect results prove that the bandgap works well.

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