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Optimization and improvement of voltage mode band-gap reference circuit and current mode band-gap reference circuit based on comparative analysis method

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Abstract. Voltage mode band-gap reference source and current mode band-gap reference source is the basic unit of integrated circuit, which plays an important role in some circuit systems such as low-voltage linear regulator, power control chip and analog-to-digital/analog-to-digital converter. Band-gap reference circuit is divided into voltage mode band-gap reference circuit and current mode band-gap reference circuit, and their basic principles and optimization methods are different. The voltage mode bandgap reference voltage is generated by superimposing voltages with positive and negative temperature coefficients, thereby producing a low-temperature related factor. In contrast, the current mode bandgap reference generates a reference voltage by superimposing currents with positive and negative temperature coefficients, requiring appropriate resistance matching and compensation. This paper analyzes the basic principles of the above two band-gap reference circuits, analyzes the temperature characteristics and mismatch sources of them, compares the research results including the implementation mode, temperature characteristics, application range and optimization scheme of the two, and looks forward to the future development prospect of both types of circuits.

Keywords: Voltage reference, Current mode, Circuit stability

1. Introduction

A bandgap reference source is a crucial component utilized in electronic devices [1] to provide a stable and precise voltage or current reference. The accuracy and stability of the reference source are particularly important in various electronic applications, including analog circuits, sensors, communication systems, and computer systems [2]. Hence, the design of reference source circuits with high accuracy and stability represents a significant area of interest in electronic engineering [3,4]. When developing reference source circuits, selecting the suitable implementation and technology is of utmost importance. Two commonly employed types of reference source circuits are voltage mode bandgap reference circuits and current mode bandgap reference circuits, both of which generate a reference voltage or current through distinct principles and implementations [5]. Voltage mode bandgap reference circuits employ the temperature characteristics of semiconductor devices to generate a reference voltage by superimposing voltages with positive and negative temperature coefficients. This principle relies on a bandgap reference voltage utilizing the temperature characteristics of Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) and a current proportional calibration technique enabling the result of a reference voltage with an elevated supply rejection ratio and a low temperature coefficient. Such reference source circuits are suitable for applications demanding high voltage accuracy, such as analog signal processing, precision measurement, and data conversion. Conversely, referencing the current-mode bandgap circuits generate a voltage as a benchmark superimposing a current with either positive or negative temperature coefficients. These circuits utilize a combination of bipolar devices (e.g., bipolar transistors) and resistors to obtain a reference current output with a 0% coefficient of thermal expansion and subsequently convert the reference current to a reference voltage using a resistor and current proportional calibration technique. This type of reference source circuit is appropriate for applications necessitating high current accuracy, such as sensor current sources and reference current sources for analog-to-digital converters (ADCs).

However, both types of reference source circuits still face challenges in practical applications. Conventional temperature compensation techniques for voltage mode bandgap reference source circuits have reached their limits and cannot achieve lower temperature coefficients. The present mode’s temperature coefficient bandgap reference source circuits is strongly influenced by resistance, necessitating further design optimization and compensation. To enhance the performance and accuracy of these circuits, continuous research and improvement of related techniques are needed. One potential research direction is the exploration of new temperature compensation techniques to achieve lower temperature coefficients and higher accuracy. This can involve investigating novel temperature compensation circuits that utilize temperature sensors and digital compensation techniques for more precise temperature compensation. Additionally, the development of new types of bandgap reference voltage devices based on new materials or processes can be explored to enhance the performance and stability of reference source circuits. Moreover, considerations must be given to mismatch, systematic misalignment, and packaging of the reference source circuits to ensure stability and reliability. For instance, optimizing the resistor network design can improve system matching and misalignment rejection. Proper packaging design and efficient heat dissipation measures are also crucial to minimize the impact of temperature variations and gradients on how well the reference source performed.

The main theme of this study is the voltage-mode bandgap reference circuit and the current-mode bandgap reference circuit. The research methodology primarily involves introducing the basic principles, performance, and respective issues of these two types of bandgap reference circuits. By comparing the basic principles, performance, and issues of these two circuits, this paper aims to identify their respective application scenarios and propose solutions to some problems.

The thesis is divided into several parts. The first section is introduction, gives the history and uses of bandgap reference circuits. The second section introduces the voltage-mode bandgap reference circuit, analyzing its basic principles, low thermal conductivity, high supply rejection ratio,and accuracy. The circuit contains bandage reference based on current is main topic for third section, presenting its basic principles, analysis of the Banba bandgap reference circuit, and its temperature characteristics. The fourth section compares the two types of bandgap reference circuits based on their basic principles, implementation methods, temperature characteristics, application scopes, and reasons for issues. The fifth section concludes the study by summarizing the characteristics and differences of the two circuits, as well as providing prospects for their future development.

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2. Voltage mode band gap reference circuit

2.1. Basic principle of voltage mode bandgap reference source circuit

As the reference source of many analog circuits and mixed signal circuits in IC, its performance determines whether the chip can work reliably. The working accuracy of voltage reference source is related to two key parameters. The lower the temperature coefficient, the higher the accuracy of the all-MOS voltage reference source in the wide temperature operating range. The other is the high power supply rejection ratio, so that the reference output voltage is not affected by the external power supply In order to make the circuit system adapt to different harsh working environment, it is necessary to design a wide temperature-voltage reference source. It's also critical to keep improving the accuracy.

In 2007, Giuseppe De Vita [6] et al. improved the circuit accordingly, compensating the temperature coefficient of the carrier in the whole temperature range, solving the problem that the circuit can only compensate the coefficient at a specific temperature. In 2010, Haesick Sul [7] implemented low voltage and low power CMOS voltage reference source by using substrate voltage that is proportional to temperature. In 2015, Ahmad Hassan [8] implemented a wide temperature full MOS voltage reference using the temperature compensation principle of linear difference of MOSFET gate source voltage operating in the subthreshold region. In 2016, C.Jhon A.Gomez [9] proposed that the temperature characteristic relationship between threshold voltage and thermal voltage could be used for temperature compensation. In recent years, the research on the MOS voltage reference source is not limited to the realization of a new theoretical method, but to improve and optimize the various performance of the circuit [10,11]. A variety of key parameters characterizing the voltage mode bandgap reference source circuit are mentioned below. By optimizing the relevant circuit parameters, the performance of the circuit can be improved to obtain a more stable output voltage.

2.2. Low temperature coefficient

The temperature coefficient generally refers to the rate at which the output voltage changes with temperature, expressed in mV/C° or ppm/C°. In general, depending on the temperature characteristics, the units mV/C and ppm/C° are suitable for use in different reference voltage sources. When ppm/C° is used as a unit, the temperature coefficient can be obtained from the following parameters:

$$TC = \frac{\Delta \mathrm{V_{REF}}}{\mathrm{V_{REF}}\Delta \mathrm{T}} \times 10^6 \tag{1}$$

ΔV_{REF} is the difference between the maximum value V_{REFmax} and the small value V_{REFmin} of the electrical reference, ΔT is the difference between the maximum value T_{max} and the minimum value T_{min} of the temperature, and V_{REF} is the average value of the reference voltage in the temperature range. In many applications, the working environment temperature of the chip changes greatly, and the temperature difference will cause the output voltage to fluctuate. For a good performance voltage reference source, the temperature coefficient is an important index. In recent years, the conventional temperature compensation cannot meet the requirements of low temperature coefficient, and the temperature compensation technology is adopted in the all-MOS reference circuit to realize the low temperature coefficient voltage reference circuit. Therefore, further reducing the temperature coefficient has become a research hotspot of MOS electrical reference source. The first method, the temperature characteristics of the resistance is introduced into the reference output voltage, which can properly adjust the output voltage. The second method, find the key factors that the reference output voltage changes rapidly with the temperature, and carry out the corresponding voltage or current compensation.

2.3. High power supply rejection ratio

The power supply voltage ripple becomes one of the main factors of the instability and imprecision of the reference. Power supply ripple rejection characterizes the output to the power ripple rejection ability parameter, is the reference circuit isolated reference voltage ability parameter. The formula can be expressed as:

$$PSRR = 20\log\left(\frac{v_{ref}}{v_{dd}}\right) \tag{2}$$

Both v_{ref} and v_{dd} represent small signal changes, v_{dd} is the ripple of the power supply voltage at a certain frequency, v_{ref} is the change of the output voltage caused by the ripple drift of the power supply voltage.

2.4. Accuracy

Accuracy refers to the deviation between the actual test results of the reference voltage source and the design target value after the actual plate package, which is a relative error, generally expressed as a percentage of the deviation and the design value, and can be written as:

$$S = \frac{\Delta V_{REF}}{V_{REF}} \times 100\% \tag{3}$$

ΔV_{REF} represents the difference between the actual output result of the reference power supply and the design target, and V_{REF} represents the target design value of the output reference voltage. The level of initial accuracy is closely related to process Angle change, device mismatch, temperature gradient, process drift, system misalignment, uneven distribution of package pressure, etc. In the linear voltage regulator, flash memory circuit, the accuracy of the voltage reference source has high requirements. The accuracy is related to device mismatch, system misalignment, package and process angle. The use of repair technology can improve the accuracy, but the circuit complexity increases, the power consumption increases, the cost increases, and the realization of high precision circuit without the use of repair technology has become a hot research topic, the industry then put forward many high-precision technology, reduce the mismatch, improve the accuracy. Including automatic calibration, dynamic device matching [12], carousel structure [13] and so on.

3. Current-mode bandgap reference circuit

The circuit that was mentioned earlier creates a reference voltage by combining a voltage with a positive temperature coefficient and a voltage with a negative temperature coefficient. By adding the current whose temperature coefficient is negative and the current whose temperature coefficient is positive, a zero temperature coefficient current is generated, resulting in a voltage whose temperature coefficient is zero.

3.1. The basic principle of the current-mode bandgap reference circuit

Figure 1 displays schematic for universal reference circuit which bases on the current, which illustrates the topology of the reference source which bases on the current. The voltage of the base and emitter in bipolar transistors exhibits the coefficient whose temperature is negative, allowing for the generation of a current whose temperature coefficient is negative, known as I_{CTAT}. The ΔV_{BE} of two identical bipolar transistors which flow two values of current exhibits a temperature coefficient with a value which is positive, enabling the generation of a positive temperature coefficient current, known as I_{PTAT}. By using the current-mode bandgap reference voltage calculation formula $I_{REF} = \alpha I_{CTAT} + \beta I_{PTAT}$, it can be observed that by adjusting the coefficients α and β, a zero temperature coefficient current can be obtained. This current can be directed through a resistor to generate a zero temperature coefficient voltage V_{REF}.

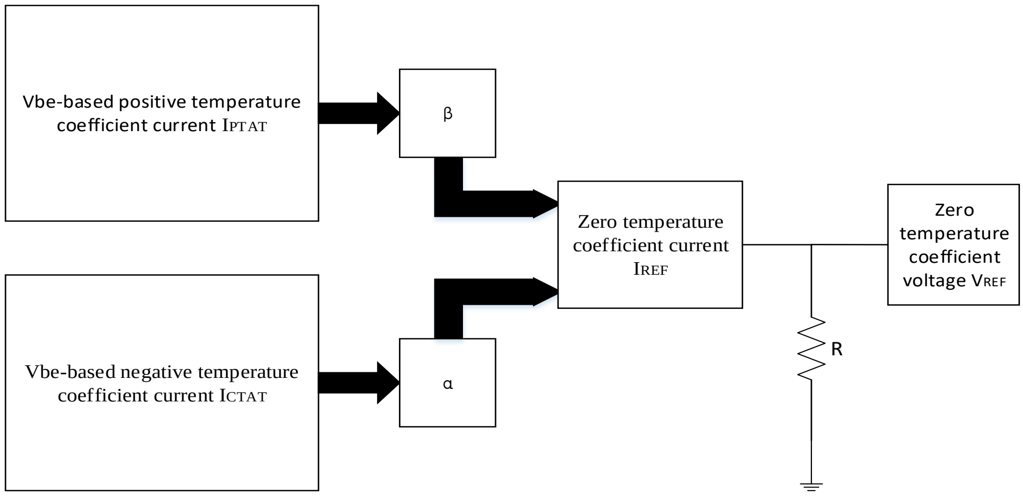

Figure 1. The schematic diagram of the current-mode reference source topology.

3.2. Analysis of Current-Mode Bandgap Reference Circuit Example

What circuit this section analyze is called Banba bandgap reference circuit and this kind of circuit's structure is shown in Figure 2. To satisfy changing market demands, circuit systems have started to evolve towards low power consumption. In 1999, Banba proposed a new low-voltage output bandgap reference source with an output voltage below 1V by converting the bandgap reference voltage into current form [14]. Compared to other bandgap reference sources such as the Widlar-type and Brokaw-type, which have output voltages around 1.2V, the Banba bandgap reference source has a smaller output voltage and lower power consumption. The Banba bandgap reference source consists of two bipolar transistors, three MOS transistors, four resistors, and a current mirror.

This circuit ensures that the input voltages at the X and Y terminals of the operational amplifier are equal through negative feedback. For stability considerations, the phase margin of the operational amplifier should also be sufficient, and Miller compensation can be designed in the operational amplifier to ensure stable operation [6]. Additionally, V_{R1} is equal to ΔV_{BE}, so the current which flows through R_1 is obtained by $I_1 = \frac{\Delta V_{BE}}{R_1}$. The Banba bandgap reference source utilizes the voltage between the base and emitter of this circuit's field effect transistors with proportional emitter areas to generate a current whose coefficient is positive [14]. Hence, the current through R_1 is a current whose coefficient is positive. Since M_2 and M_1 are in a mirrored relationship, the number of current of M_1 is same as the M_2's current's number. The current through R_2 on the right side is given by $I_2 = \frac{V_{BE2}}{R_2}$ if the resistance values of both R_2 are equal. Therefore, the currents through both resistors are negative temperature coefficient currents. Consequently, the current through M_2, I_{M1} can be expressed as $I_{M1} = \frac{V_{BE2}}{R_2} + \frac{\Delta V_{BE}}{R_1}$. By adjusting the relevant parameters, I_{M1} can be made into a zero temperature coefficient current, thereby making the current through R_3, I_3, a zero temperature coefficient current, which results in a zero temperature coefficient voltage across R_3. This type of bandgap reference source allows control of the output voltage by adjusting the resistance values.

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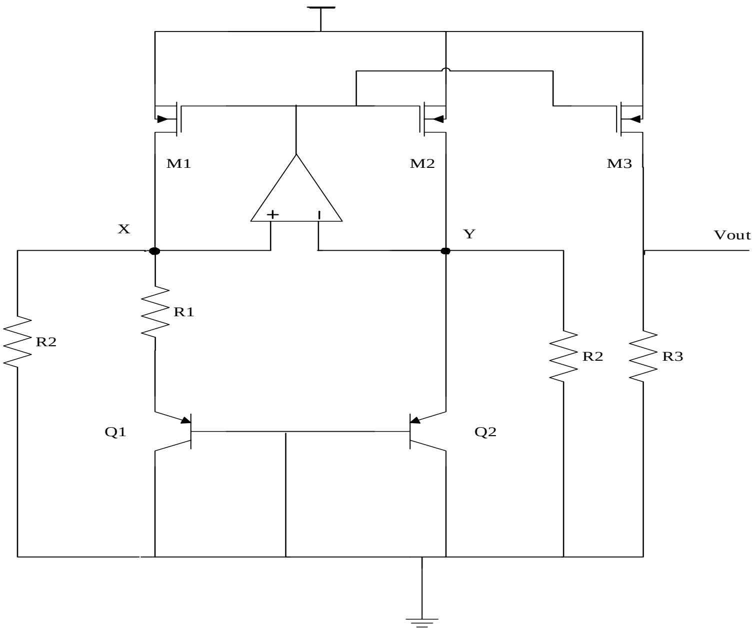

Figure 2. The Banba bandgap reference source.

Although this circuit that Banba created has the advantage of low power consumption, the resistance values in the circuit may not be precise due to manufacturing limitations, leading to resistor mismatch and impacting the accuracy. Channel modulation effects can cause deviations in mirror current, resulting in current mirror mismatch. Additionally, practical operational amplifiers may exhibit variations, leading to non-identical voltages at X and Y, thereby affecting the accuracy of this circuit.

To consider construction of a circuit that is a reference source for the bandgaps, it is necessary to think over the errors caused by these factors and find solutions. For example, increasing the transistor area ratio and using a cascode structure for the bipolar transistors can address the mismatch issue in the operational amplifier.

3.3. Temperature characteristics of the current-mode bandgap reference circuit

When operating with a voltage of 1.8V and a temperature range of 45°C to 85°C, it can be seen that the current source's temperature coefficient is 40ppm/°C [15]. What can be inferred is the bandgap current source has a higher temperature coefficient than bandgap voltage source circuit. This is because resistor R is more significantly affected by temperature under real-world conditions.

4. Comparative analysis

Voltage mode reference source for bandgap circuits and current mode bandgap reference source circuits are two commonly used reference source circuits, which differ in their basic principles, implementation methods, temperature characteristics, and application ranges.

In principle, the voltage mode bandgap reference source circuit generates a reference voltage by combining positive and negative temperature coefficient voltages. Typically, MOS transistors are used as key devices in this circuit, and to produce a reference voltage with a high power supply rejection ratio and a low temperature coefficient, temperature compensation techniques are used. On the other hand, the presently used bandgap reference source circuit generates the voltage used as a reference combining a current with temperature coefficients both positive and negative. By altering the necessary settings, this circuit principally uses a combination of bipolar devices and resistors to produce a reference current output with no temperature-related effect.

In terms of implementation, by cascading two voltage sources with opposing temperature coefficients and applying temperature compensation techniques, a voltage with a low temperature coefficient

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reference source is produced using the voltage mode bandgap reference source circuit. MOS transistors are used as key devices to achieve temperature compensation by leveraging the temperature characteristics of the opposite voltages. On the other hand, the current setting reference source for bandgap circuit modifies the current source's characteristics and by combining the current source and resistors to provide a reference current output with a zero temperature coefficient, the resistor ratio is calculated.

In terms of temperature characteristics, voltage mode bandgap reference source circuits typically exhibit a low temperature coefficient. With conventional temperature compensation circuit design, the temperature coefficient can be adjusted within the variety of 60 ppm/°C to 210 ppm/°C. This suggests that over the temperature range, the voltage of the output voltage reference source varies very little, providing a relatively stable and accurate reference voltage. In contrast, the reference to the current mode bandgap source circuit has a relatively large temperature-related factor since the strong temperature reliance on the resistance in the Circuit with current source. In practical applications, specific adjustments and compensation are necessary to achieve the desired temperature characteristics.

By way of applications, voltage mode bandgap reference source circuits are suitable for applications that require high voltage accuracy, such as linear voltage regulators and flash memory circuits. This is because voltage mode references provide a relatively stable and accurate reference voltage output. Current mode bandgap reference circuits are more suitable for applications requiring high current accuracy, such as sensor current sources and reference current sources for ADCs. This is due to the ability of current-mode reference sources to provide a stable current output with zero temperature coefficient.

However, there are some issues with both voltage mode reference source for bandgap circuits the present mode bandgap reference source circuits. For voltage mode bandgap reference source circuits, traditional temperature compensation techniques may not meet the requirement for a poor heat transfer coefficient. For reference to the current mode bandgap source circuits, the coefficient of temperature can be influenced by the temperature of the resistor, which is a challenge to address. Therefore, further research and improvement are needed.

Several solutions have been proposed to address these issues. For voltage mode bandgap reference source circuits, further research and improvement of temperature compensation techniques are necessary to explore new methods that reduce the temperature coefficient and enhance operational accuracy. Consideration could be given to introducing the features of temperature of the resistor to match the features of the temperature in the output voltage, or identifying and compensating for the key factors causing the output voltage variation with temperature. For reference source for the present mode bandgap circuits, the impact of resistance on the temperature coefficient can be diminished by optimizing the selection and design of resistors. Additionally, the design and optimization of the current source circuit are crucial, and more precise bipolar devices or other devices can be considered to enhance the stability and temperature coefficient of the current source.

5. Conclusion

Voltage mode bandgap references and current mode bandgap references are two commonly used reference source circuits. Voltage mode bandgap references generate a reference voltage by superimposing voltages with positive and negative temperature coefficients, resulting in a low temperature-related factor. They are suitable for applications that require high voltage accuracy. Contrarily, the current mode bandgap references generate the benchmark voltage by superimposing currents with positive and negative temperature coefficients, requiring proper resistor matching and compensation. They are suitable for applications that require high current accuracy. However, both types of reference source circuits have certain issues that need to be addressed. In the event that voltage mode bandgap citation source circuits, the conventional temperature compensation techniques may no longer meet the requirements for a low temperature coefficient. Therefore, there is a need to explore new temperature compensation techniques to improve the temperature stability and accuracy of these circuits. Similarly, the current mode's temperature coefficient bandgap reference source circuits is greatly

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influenced by the resistance in the circuit. To solve this problem, it is required to improve the performance of these circuits' design and compensation. Overall, in practical applications, it is crucial to select the appropriate reference source circuit based on the specific accuracy and stability requirements. Continuous research and improvement of related technologies are necessary to enhance the performance and accuracy of these reference source circuits, ensuring they can meet the demands of practical applications.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

References

[1] Liu Lingyan, Gao Tongqiang, Cai Gang, et al. A voltage source CMOS bandgap reference circuit for biomedical sensing [J/OL]. Microelectronics and Computers, 2023 (09): 1-7 [2023-09-25]. DOI: 10.19304/J.ISSN1000-7180.2022.0692

[2] Guo Wei, Feng Quanyuan, Zhuang Shengxian, et al. Design of a novel high power suppression bandgap reference circuit [J]. Science and Technology and Engineering, 2016,16 (28): 199-203

[3] Dong Dawei. A high-precision reference source circuit [J]. Electronic Technology Application, 2015,41 (06): 45-46+50. DOI: 10.16157/j.issn.0258-7998.2015.06.012

[4] Zhong Zhaoyang, Li Yan, Wang Weiguang, et al. Review of low-power and high-precision reference sources [J]. Microelectronics and Computers, 2022, 39 (02): 1-8. DOI: 10.19304/j.issn1000-7180.2021.0138

[5] Yingjing Research on the Design and Improvement Technology of Low Temperature Drift Bandgap Reference Source [D]. Xi'an University of Electronic Science and Technology, 2021. DOI: 10.27389/dcnki.gxadu.2021.000564

[6] DE VITA G, IANNACCONE G. Ultra-low-power temperature compensated voltage reference generator [J]. Microelectronics Journal, 2006, 37(10): 1072-9.

[7] SUL H, JUN Y H, KONG B S. A temperature-stabilized voltage reference utilizing MOS body effect; proceedings of the 2010 IEEE Asia Pacific Conference on Circuits and Systems, F 6-9 Dec. 2010, 2010 [C].

[8] HASSAN A, GOSSELIN B, SAWAN M. Ultra-low power CMOS voltage reference for high temperature applications up to 300°C; proceedings of the 2015 IEEE International Conference on Electronics, Circuits, and Systems (ICECS), F 6-9 Dec. 2015, 2015 [C].

[9] GOMEZ C J A, KLIMACH H, FABRIS E, et al. High PSRR nano-watt MOS-only threshold voltage monitor circuit; proceedings of the 2015 28th Symposium on Integrated Circuits and Systems Design (SBCCI), F 31 Aug.-4 Sept. 2015, 2015 [C].

[10] LUONG P, CHRISTOFFERSEN C, ROSSI-AICARDI C, et al. Nanopower, Sub-1 V, CMOS Voltage References With Digitally-Trimmable Temperature Coefficients [J]. IEEE Transactions on Circuits and Systems I: Regular Papers, 2017, 64(4): 787-98.

[11] MAGNELLI L, CRUPI F, CORSONELLO P, et al. A 2.6 nW, 0.45V Temperature-Compensated Subthreshold CMOS Voltage Reference [J]. IEEE Journal of Solid-State Circuits, 2011, 46(2): 465-74.

[12] MEIJER G C M, GUIJIE W, FRUETT F. Temperature sensors and voltage references implemented in CMOS technology [J]. IEEE Sensors Journal, 2001, 1(3): 225-34.

[13] DAQIAN H, JIAQI Q, XIAOXU Y, et al. A Low-temperature-coefficient Bandgap Voltage Reference for Sar Adc [J]. Journal of Physics: Conference Series, 2022, 2219(1): 012032.

[14] Zhang Zonghang,Zhao Yiqiang,Geng JunfengA second-order curvature compensation bandgap voltage reference source [J]. Microelectronics and computer engineering,2012,29(05): 15-19. DOI:10.19304/j.cnki.issn1000-7180.2012.05.004.

[15] Wang Jian. Research and applications of CMOS bandgap reference sources [D]. Tutor: Zhang Ying. Nanjing University of Posts and Telecommunications,2016