Research On Temperature Compensation Technology in The Field of Band-gap Reference.

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Abstract. With the rapid development and wide application of analog integrated circuits, the development and application of band-gap reference circuits, as one of the most basic analog integrated circuits, has been attracting much attention. The band-gap reference circuit has the advantages of high accuracy, good stability, and high reliability. The temperature compensation technology has a significant effect in improving the accuracy, stability and reliability of the band-gap reference. However, the generation of a more stable reference voltage through temperature compensation technology is still one of the key research topics at present. In this paper, In this paper, the temperature compensation technology is studied on the principle and structure of the band gap source, and the concept and related theories of the first, second and higher order temperature compensation technologies are analyzed, showing how the temperature stability of the band gap source is improved and applied to a wider temperature range. Starting from the changing angle of different order temperature compensation technology, the development of temperature compensation technology of band-gap reference neighborhood is promoted.

Keywords: Band-gap reference; higher-order compensation; temperature coefficient.

1. Introduction

With the development and application of analog integrated circuits, their performance requirements need to be continuously improved. The voltage reference is a very important module in analog integrated circuits, which is widely used in analog and RF circuit systems, providing a stable reference voltage for the application system that is not affected by temperature and power supply voltage changes. However, in essence, external factors such as current, temperature, and voltage affect the working state of passive and active components in the circuit, change their electrical parameters, and weaken the relevant performance of the voltage reference. Band-gap reference neighborhood temperature compensation is a technique designed to offset the effect of temperature changes on the output of band-gap reference in order to maintain its stability.

In this paper, the basic principle of the band-gap reference circuit is analyzed, and the advantages and disadvantages of the traditional op-amplified band-gap reference and the non-op-amplified band-gap reference are compared, and their basic characteristics are shown. Then, starting from the first-order temperature compensation technology, the two ways of generating the reference voltage are described, and the reference voltage generated by it is more suitable for a certain range of temperatures, and the output voltage is not stable in harsh environments, so the temperature coefficient needs to be reduced. In this paper, the principle of second-order temperature compensation technology is analyzed, and the second-order temperature compensation technology can improve the accuracy, stability and reliability of the band-gap reference by comparing it with the first-order temperature compensation technology and promoting the development and application of the band-gap reference. Finally, this paper analyzes the high-order temperature compensation techniques with different band-gap references, and studies their principles, advantages and disadvantages, and it can be concluded that these techniques can maintain the stability of the output voltage in a wider temperature range, reduce the drift caused by temperature changes, and enable the band-gap reference to operate in a wider range of temperatures, including extreme high and low-temperature environments. This greatly enhances the applicability of the band-gap reference in a variety of applications, thereby improving the performance of the entire system.

2. Basic Principle and Structure of the Band-gap Reference Source

2.1. Basic Principle of the Band-gap Reference Source

In IC design, the band gap reference source is a very critical device, which is much more complex than the bias circuit and cannot be affected by temperature, supply voltage and process factors. Reference voltage is a very critical module, whose accuracy will directly affect the accuracy of the whole system [1]. Temperature coefficient, power supply suppression ratio, long-term stability, power consumption noise, and other related parameters are the basis for effectively evaluating the performance of the reference voltage source circuit. If the reference voltage source is used in a temperature-sensitive system, then the temperature coefficient will be a priority indicator.

As shown in Fig 1, the generation principle of the reference voltage is to combine two voltages with positive and negative temperature characteristics, so as to obtain a stable voltage output that does not change with the temperature.

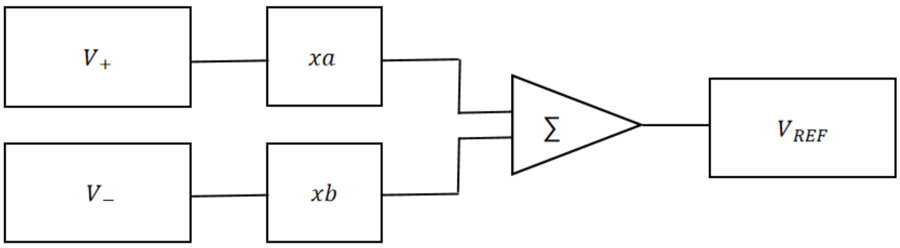

Fig. 1 The generation principle of the reference voltage

The expression for the reference circuit is:

$$V_{REF} = aV_{+} + bV_{-} \tag{1}$$

According to the above principle, select V_{BE} with a negative temperature coefficient and ΔV_{BE} with a positive temperature coefficient for a certain proportion of superposition, this results in a stable reference source that barely changes with temperature [2].

2.2.Basic Structure of the Band-gap Reference Source

Traditional band-gap reference sources can be divided into op-amplified band-gap reference sources and op-amplified-free reference sources. Band-gap references typically take advantage of the "imaginary-short" and "virtual-off" characteristics of op-amps to clamp circuits, resulting in the accuracy of the band-gap output being affected by the offset voltage of the op-amp, while the design complexity, power consumption, and noise increase accordingly. The unloaded structure adopts the current mirror clamp circuit, which eliminates the constraint of the operational amplifier. However, the band-gap output voltage cannot be accurately measured due to the channel modulation effect, and the temperature coefficient is usually large [3].

Fig 2 (a) shows the structure of a traditional op-amp band-gap reference circuit [4]. In the fig, M_1, M_2 and M_3 constitute current mirrors, Q_1 and Q_2 are triodes proportional to the emission area, because the relationship between the operational amplifier and the resistance feedback network enables the circuit to form a deep negative feedback state, forcing the voltage balance at both ends of the transport and discharge, So the current flowing out from M_1 and M_2 is the same. Flow through the same current in Q_1 and Q_2, So that the voltage difference between Q_1 and Q_2 base-emitter is applied to the resistance, thus forming a PTAT current. This current is copied to the output end through the current mirror, converted into PTATvoltage via the resistance, and the reference output voltage can be obtained by superposition with the negative temperature coefficient voltage of Q_3.

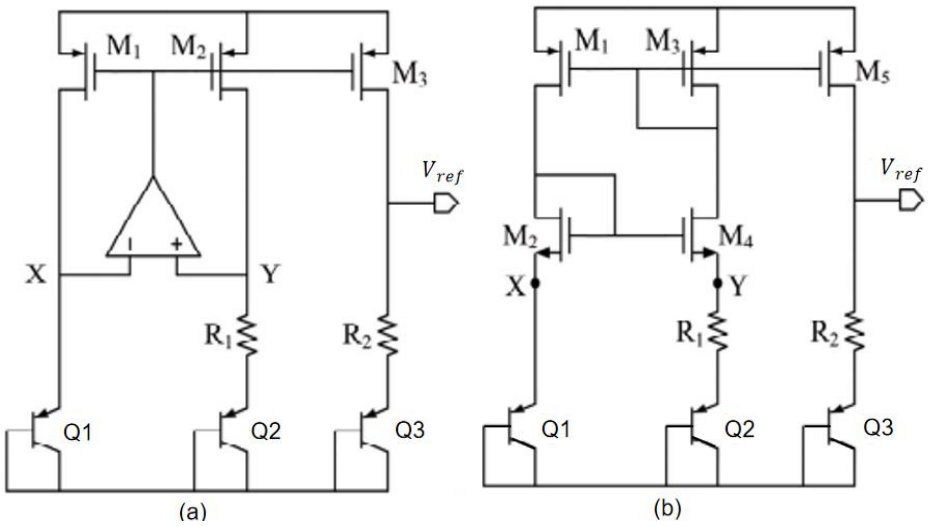

Fig. 2 Conventional op-amp and op-amp-free band-gap reference circuits [4]

Fig 2 (b) shows the structure of a conventional op-amp-free band-gap reference circuit [4], $\mathrm{M_1}$, $\mathrm{M_2}$ and $\mathrm{M_3}$ have the same width and length ratio, The aspect ratio of $\mathrm{M_2}$ and $\mathrm{M_4}$ is identical, different from the band-gap structure, conventional op-amp-free band-gap reference circuits uses a current mirror and a feedback loop composed of $\mathrm{M_1}$ to $\mathrm{M_4}$ to locate X and Y points. The relatively large influence on the band gap reference output is the ratio and N value of resistance $\mathrm{R_1}$ to $\mathrm{R_2}$, by selecting the appropriate ratio, the first-order band-gap reference voltage can be obtained.

The traditional band gap reference structure puts forward very high requirements for the design of the amplifier, requiring the amplifier to have the characteristics of high gain and low disorder, and its own frequency compensation function brings difficulties to the design. The band-gap reference circuit without an operational amplifier will have no additional power loss because the current from the entire line is used to generate a reference voltage. This method does not use complex operation and saves the chip area. However, in the band gap reference point without transport discharge, the linear tunability is poor due to the different voltage of the tube leakage end.

3. First-order Temperature Compensation

3.1. The Reference Voltage Generated through the Amplifier Output End

As shown in fig 3, the circuit forms a state of negative feedback. Because the operational amplifier has the characteristics of virtual short and break, the voltage of X point is equal to the voltage of Y, and because the resistance value of $\mathrm{R_1}$ and $\mathrm{R_2}$ is equal, then the current flowing through $\mathrm{R_1}$ and $\mathrm{R_2}$ is equal. At this time, the emitter area of $\mathrm{Q_1}$ and $\mathrm{Q_2}$ is not equal, so there is a voltage difference between $\mathrm{Q_1}$ and $\mathrm{Q_2}$ applied to $\mathrm{R_3}$, finally, the reference voltage can be obtained by the superposition of the operational amplifier [5].

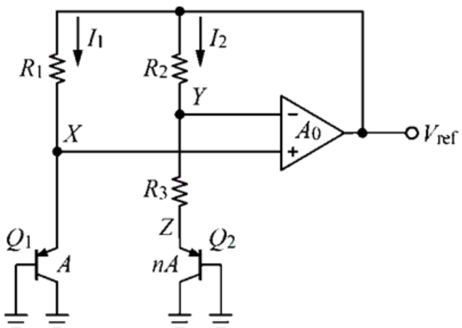

Fig. 3 Conventional amplifier feedback structural band gap reference [5]

Reference voltage expression:

$$V_{REF} = V_{BE2} + GV_T = V_{BE2} + [(1 + R_2/R_3)\ ln^n]V_T \quad (2)$$

However, the structure uses an operational amplifier. Due to asymmetric factors, the input end of the operation will be affected by the "imbalance", and the imbalance voltage is amplified by $1{+}R_2/R_3$ times, which will lead to the error of the output voltage and increase the temperature coefficient of the output voltage.

3.2. Generated by Using the PTAT Current

In order to improve the power suppression ratio, the PTAT current source is used as a buffer, and then the PTAT current source is connected to the reference voltage output circuit, so that the power interference voltage is reduced by the buffer of the PTAT current source, thus achieving a high-power suppression ratio.

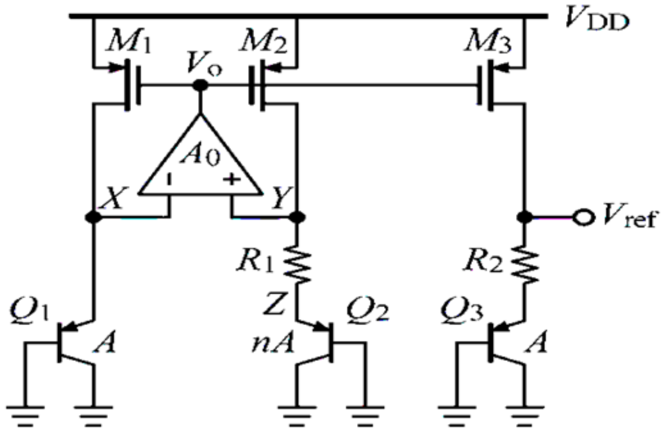

Fig. 4 The PTAT current source circuit [6]

As shown in Fig 4, since the current mirror structure of M_1, M_2 and M_3 in the circuit, the current of M_1 and M_2 of the MOS tubes changes synchronously, when the circuit works stably, the gate voltage of M_1 and M_2 is equal, if the current is too large, because there is a resistance R_1 below M_1, so the gate voltage change of M_1 will be less than the gate voltage change of M_2, At this point, the positive input of the operational amplifier is larger than the negative input, and the output voltage of the operational amplifier will increase, which leads to the output current of the current mirror to drop. The negative feedback loop is mainly working in the whole circuit, making the circuit more stable [6].

4. Second Order Temperature Compensation

The conventional first-order temperature compensation band gap reference circuit is a circuit commonly used to provide a stable reference voltage and utilizes the temperature characteristics of the semiconductor device to maintain the stability of the output voltage under temperature changes. The key parameter is its temperature coefficient, and well-designed circuits usually have a lower temperature coefficient, which means that the output voltage changes relatively little when the temperature changes. The first-order temperature compensation band-gap reference circuit usually includes a temperature compensation circuit for correcting the effect of temperature changes on the output voltage. These compensation circuits may include resistance, capacitance or other temperature-sensitive elements to counteract voltage drift caused by temperature changes. The circuit also needs to consider its precision and cost, more accurate circuits usually require more complex design and more expensive components, while low-cost circuits may sacrifice a certain amount of precision.

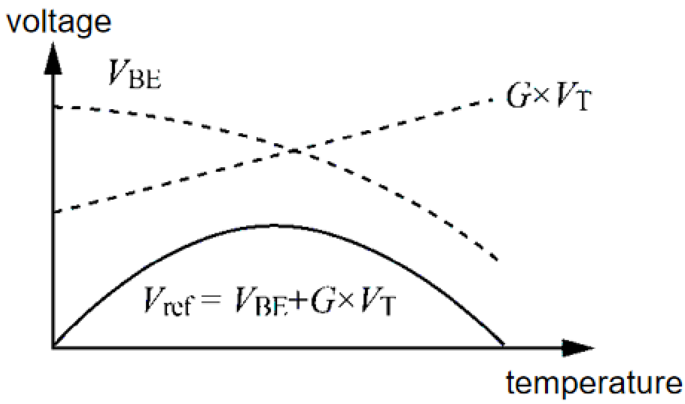

Fig. 5 Temperature characteristics of the actual first-order temperature compensation band-gap reference circuit

As shown in Fig 5, the temperature characteristics of the first-order temperature-compensated band-gap reference circuit are unstable at high temperatures. It is through the voltage V_{BE} with a nonlinear curve decreasing with rising temperature and with negative temperature characteristics, superimposed with voltage V_T with positive temperature characteristics to give the output voltage V_{REF}, the voltage is not a straight line with temperature, poor stability.

Traditional benchmark structure adopts the first-order low-temperature compensation principle, the circuit at room temperature can meet the daily needs, but as the chip working environment is more and more complex, the requirement of temperature is increasing, even requires it's in special bad cases can still work normally, this requires improving the high-temperature characteristics of the benchmark power supply.

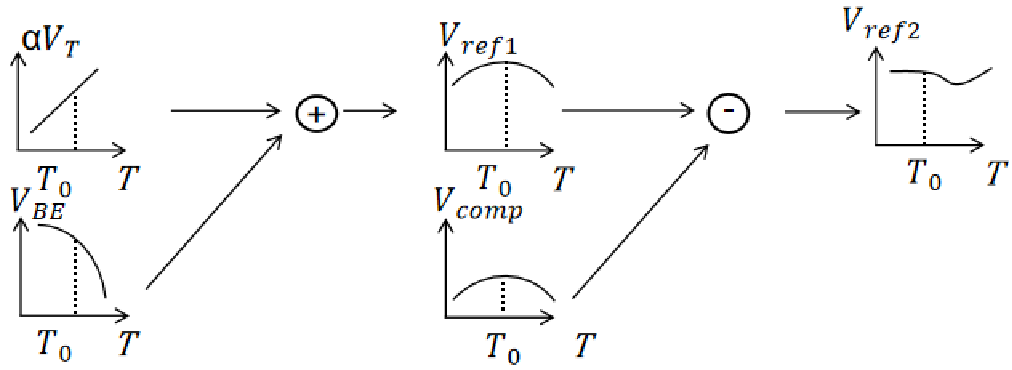

Fig. 6 Second-order temperature compensation band-gap reference compensation principle [7]

Fig 6 illustrates a compensation principle for a secondary temperature compensation band-gap reference voltage source with both positive and negative temperature compensation coefficients. a is the positive and negative temperature compensation coefficient. Then, the first-order reference voltage is compensated by the compensation voltage V_{COMP} generated at the MOS tube in the sub-threshold area operated by the voltage controlled by the negative temperature coefficient, this voltage has a similar curvature change to V_{REF}, and finally the two voltages are reduced to obtain the final second-order temperature compensation voltage[7].

By adding the second-order temperature compensation circuit, the temperature coefficient of the reference voltage can be significantly reduced, the temperature range of the reference voltage can be expanded, and the accuracy of the reference voltage can be improved.

5. Higher Order Temperature Compensation

The traditional bandgap reference sources are based on Widlar, Kuijk, Brokaw, and Banba, among which Kuijk, Brokaw, and Banba are the band gap reference sources with transport and release, with the advantages of simple structure and temperature stability, However, the first-order temperature compensation technology cannot compensate for its high-order nonlinearity, and the temperature coefficient can reach tens to hundreds of ppm/℃, which can not meet the requirements of high-precision chips. Therefore, to obtain a lower temperature coefficient, a new temperature curvature compensation technique or circuit structure is needed. To realize a reference voltage source with a llow-temperaturecoefficient, multiple temperature compensation techniques are proposed to partially or completely eliminate the nonlinear temperature term of V_{BE}. Its common high-order temperature compensation techniques iinclude$PTAT^2$, resistance ratio and exponential curvature.

5.1.PTAT^2 Compensation Technique

The nonlinear term in the V_{BE} voltage term compensates the second order term. This compensation method is to add the voltage $PTAT^2$ to the output end of the first-order band-gap reference voltage source, that is a voltage that is squared-related to the absolute temperature. A nonlinear term with a negative temperature coefficient in the voltage V_{BE} is offset by a nonlinear voltage with a positive temperature coefficient [8].

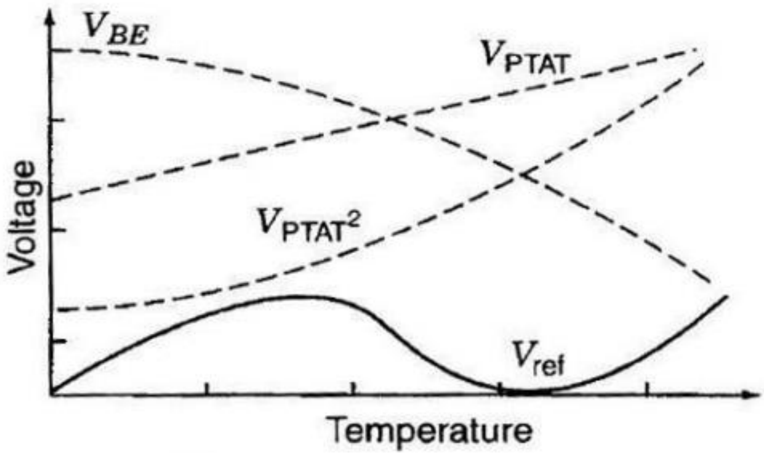

Fig. 7 $PTAT^2$Basic principle of compensation technology [8]

Fig 7 shows the general principle of a curvature-corrected band-gap reference voltage source such as $PTAT^2$. When the temperature is low, the reference voltage is mainly voltage V_{BE} and linear voltage PTAT. In this interval, the reference voltage reflects the curvature characteristic of the first-stage band-gap reference voltage source. The voltage $PTAT^2$ increases with the temperature increase to compensate for the negative temperature characteristics of the voltage V_{BE} in the high temperature region. Using the curvature correction technique, the reference voltage temperature coefficient reaches $1-20$ ppm/℃.

5.2.Resistance Proportional Compensation Technology

Resistance proportional compensation technology can compensate for the influence of temperature change on the band gap reference source by adjusting the resistance value. By introducing the resistance proportional compensation network into the circuit, the temperature drift can be offset more effectively, thus improving the temperature compensation effect of the band-gap reference source. Resistance proportional compensation technology uses the temperature characteristics of different resistances to construct higher order terms with resistance elimination voltage V_{BE} with different temperature coefficients. This method can be achieved only by adding a reverse temperature coefficient resistance to the original circuit [9].

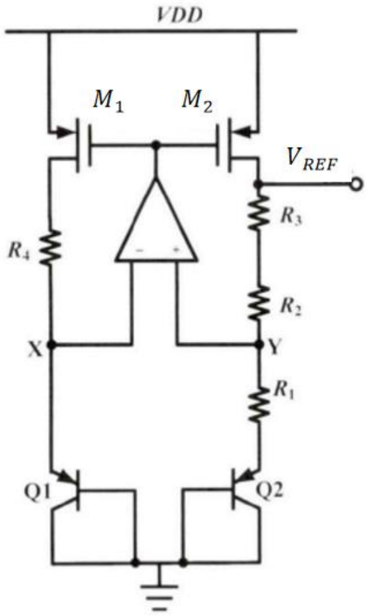

Fig. 8 Schematic of the resistance proportional compensation [9]

Transistors Q_1, Q_2, and resistors R_1 generate a positive temperature coefficient current, Conversion to PTAT voltage by flow through resistance R_2, R_3, and the emission junction voltage of the transistor Q_2 is superimposed to generate the output reference voltage. Where R_1, R_2 and R_4 are the polysilicon resistance and R_3 is the P-type diffusion resistance. As long as the appropriate ratio of R_1 to R_3 is selected, the reference voltage high order term can be eliminated, and then, the thermal effect of the device can be reduced, and the performance of the band gap reference power supply can be improved.

5.3.Exponential Curvature Compensation Technique

Exponential curvature compensation techniques play a key role in higher-order temperature compensation, especially in improving the performance of band-gap reference sources, reducing temperature drift and improving accuracy. The application of this technique is intended to more accurately compensate for the effect of temperature on the band-gap reference source output, especially under extreme temperature conditions. The exponential curvature compensation technique compensates the higher order temperature term of the voltage V_{BE} by using the exponential relation between the current magnification β and the temperature of the bipolar transistors [10].

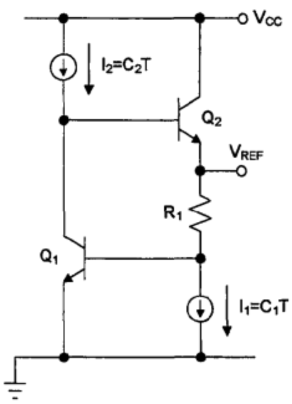

Fig. 9 Schematic of the exponential curvature compensation

The greatest advantage of this method over conventional secondary compensation methods is that no additional circuits are required to generate paranoid currents with curvature compensation. In the exponential curvature compensation technique, the base current of Q_1 is used as the source of curvature compensation, while the PTAT bias current used by Q_1 is very common in the first-order band-gap reference source. Therefore, when the exponential compensation technique is applied to the first-order band gap reference source, its topology is the same as the first-order band gap reference source, so that no major changes are necessary to the original circuit in compensation. The only work added was to adjust the current of the current source I_2 to minimize the nonlinear temperature drift of the V_{REF}.

6. Conclusion

This paper mainly analyzes the temperature compensation technology in the band gap reference field, clearly shows the principle and structure of the band gap reference source, and studies the principle and classification of the first order temperature compensation, second order temperature compensation and high order temperature compensation technology. At present, band-gap reference sources are still a very important and commonly used part in integrated circuits, especially in applications that require high precision and stability. Temperature compensation technology can cancel out the influence of temperature change on the output voltage in a certain range, eliminate the high-order nonlinear term of the reference voltage, and thus provide a more stable reference voltage, the band-gap reference source can be applied to a wider range of temperature work, and more functions and circuits can be integrated into a single chip, thus reducing system costs and improving performance. In conclusion, the high-order temperature-compensated band-gap reference source plays an important role in modern IC design, and its increasing accuracy, stability and function make it an indispensable part in many applications. Although the higher-order temperature-compensated band-gap reference solves many of the problems of traditional band-gap references, it requires more complex circuit design and additional power consumption, this increases the difficulty of manufacturing and maintenance, and the increase in temperature creates additional problems for temperature compensation, challenging its sensitivity and stability. In the future, the development direction of high-order temperature compensation band gap datum will mainly focus on improving the integration degree, reducing the power consumption, improving the anti-interference capability and intelligent algorithms, so as to meet the growing market demand and technical challenges.

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