Research Progress of Bandgap Reference Circuit

Yuxuan Bao *

Portland Institute, Nanjing University of Posts and Telecommunications, Nanjing, China

* Corresponding Author Email: p21000828@njupt.edu.cn

Abstract. As an important part of integrated circuit design, bandgap reference circuit is widely used in various chips, among which ADC (analog-to-digital converter) and DAC(digital-to-analog converter) are typical examples. This paper introduces the bandgap reference circuit and its working principle in detail, and then systematically combs and introduces a variety of bandgap reference circuits. A conventional bandgap reference circuit consists of an op-amp, two bipolar transistors and multiple resistors; The CMOS bandgap reference circuit uses the common-source common-gate current mirror to provide the bias current to reduce the power consumption and the channel length modulation effect so that the circuit can work at a lower supply voltage. A bandgap reference circuit using PTAT (proportional to absolute temperature) current to generate reference voltages with different temperature coefficients can produce a simpler circuit structure than the traditional bandgap reference circuit. By summarizing and comparing these bandgap reference circuits, the latest trends and technical trends in this field are presented, providing guidance and inspiration for future research work.

Keywords: PTAT; bandgap reference circuit; cascode current mirror.

1. Introduction

In recent years, with the continuous development of technology and experience in the field of integrated circuits, band-gap reference circuits, as a kind of analog circuit design solution, have gradually assumed an important role in analog circuit design and precision measurement. Bandgap reference circuit is mainly used to generate reference voltage and are beneficial to the accurate and efficient control of multi-channel reference voltage. The band gap reference circuit can produce a stable reference voltage, and the output voltage has the characteristics of high stability, and low noise, it will not be affected by temperature changes. Thanks to these characteristics, it has been widely used in many fields, such as power management, temperature sensors, automatic gain control, etc.[1]

This paper will start with the analysis of the basic working principle of bandgap reference circuit, and deepen the understanding of bandgap reference circuit by introducing its core components and basic circuit model. Then, the common bandgap reference circuit design schemes are introduced and analyzed in detail, including the traditional operational amplifier and diode-based design schemes, CMOS process-based design schemes, and PTAT current-based design schemes. Finally, by combining some important progress made in the field of bandgap reference circuit research in recent years and the design scheme introduced in this paper, the future development trend of bandgap reference circuit research is forecasted to provide a reference for relevant researchers.

By summarizing and analyzing the research progress of bandgap reference circuits, researchers can better understand the latest trends and technical trends in this field. It is hoped that this paper can provide some reference for the relevant researchers in the field of bandgap reference circuit research, and promote the further development and application of this field.

2. Working Principle of Bandgap Reference Circuit

The bandgap reference circuit needs to provide a stable reference voltage and to provide a stable reference voltage or reference current meets at least the following three basic requirements: first, the reference voltage has nothing to do with the supply voltage. The static current is constant, and the dynamic power supply rejection ratio is as high as possible. Second, the reference voltage has nothing to do with the temperature. In a certain temperature range, the temperature coefficient is approximately zero.Third, the reference voltage has nothing to do with craft. The main performance is that it has nothing to do with V_{TH}, the most critical threshold voltage in the CMOS process, so the influence of process drift on the output can be overcome. Of these three requirements. The third one can be solved through the design process, for example, try to use the same type of pipe for experiments. Therefore, this paper will focus on the second one, how to make the reference voltage temperature independent.

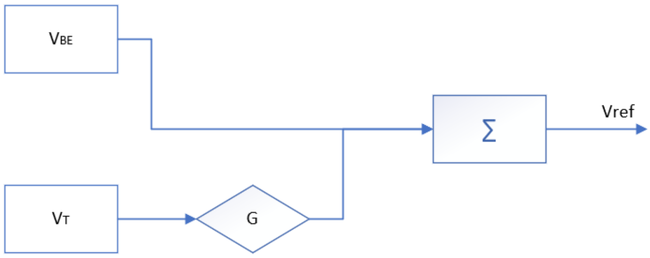

Figure. 1 Working principle of reference voltage source

As shown in Figure 1, to obtain a temperature-independent V_{ref}, it is necessary to find a voltage quantity with a positive temperature coefficient and a voltage quantity with a negative temperature coefficient, and then add the two together with some specific weight to compensate each other for temperature changes.[2] V_{BE} is the positive base-emitter voltage of the PN junction diode and has a negative temperature coefficient. The difference between the base-emitter forward voltage of two PN junction diodes at different current densities ΔV_{BE}, with a positive temperature coefficient. For a bipolar transistor with a negative temperature coefficient, the relationship between the collector current IC and the base-emitter voltage V_{BE} is:

$$V_{BE}=V_T \ln\frac{I_C}{I_S} \tag{1}$$

Where VT is the thermal voltage, expressed as $V_T=\frac{kq}{T}$,k is the Boltzmann constant; T is the absolute temperature; q is the size of the elementary charge.;

I_S can be expressed as: I_S=b$T^{4+m}exp^{\frac{-E_g}{kT}}$; I_C can be expressed as: I_C=$I_S exp(\frac{qV_{BE}}{kT})$ [3]

To simplify the analysis, I_C is assumed to be a fixed value, and the partial derivative of V_{BE} with respect to temperature T is obtained. The temperature coefficient of V_{BE} voltage can be obtained by bringing the above results into:

$$\frac{\partial V_{BE}}{\partial T} \approx \frac{V_{BE}-(4+m)V_T-E_g/q}{T} \tag{2}$$

When V_{BE} is approximately 750mV and T=300K, $\partial V_{BE}/\partial T \approx$-1.5mV/°C. For a positive temperature coefficient, connecting the base and collector of a bipolar transistor actually forms a diode, as shown in Figure 2 below, when Q1 and Q2 are the same,the emitter area $A_{e1}=A_{e2}$, and therefore Is1=Is2 in relation to the emitter area.

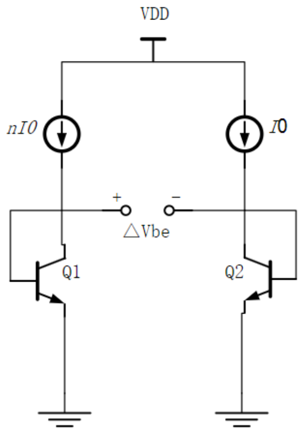

Figure 2 Schematic diagram of a circuit with a positive temperature coefficient

According to the above formula, $\Delta V_{BE}=V_{BE1}-V_{BE2}=V_T\ln(\frac{nI_o}{I_{s1}})-V_T\ln(\frac{I_o}{I_{s2}})=V_T\ln n$, Then take the first partial derivative of the temperature $\frac{\partial \Delta V_{BE}}{\partial T}=\frac{k}{q}\ln n$.Under the condition that n is greater than or equal to 1, it can be concluded that there is a positive temperature coefficient.

Now that the voltage quantity of the positive and negative temperature coefficients has been obtained,then let $V_{ref}=\alpha_1 V_{BE}+\alpha_2 V_T\ln n$ and find the partial derivative of V_{ref} with respect to temperature, get the following result:

$$\frac{\partial V_{ref}}{\partial T}=\alpha_1\frac{\partial V_{BE}}{\partial T}+\alpha_2\frac{\partial V_T}{\partial T}\ln n \tag{3}$$

Where $\frac{\partial V_{ref}}{\partial T}=-1.5\text{mV/K}$ $\frac{\partial V_T}{\partial T}=\frac{k}{q}=0.087\text{mV/K}$ $\alpha_1=1$ $\alpha_2=\alpha$. Bring the data into the above equation, it can be deduced that $\frac{\partial V_{ref}}{\partial T}=0$ $V_{ref}\approx1.25\text{V}$ when $\alpha\ln n=17.2$.

3. Analysis of Common Bandgap Reference Circuits

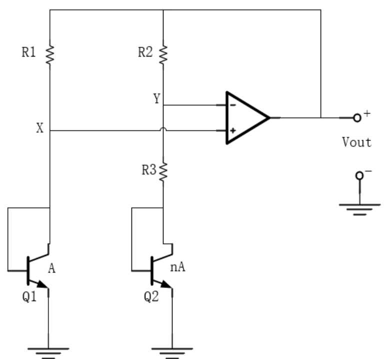

Figure 3. Traditional bandgap reference circuit

Figure 3 is the basic schematic diagram of the traditional bandgap reference circuit. An operational amplifier A1 is used in this structure, and $V_X=V_Y$ can be obtained due to the virtual short characteristic of this amplifier. If R1=R2, the voltage difference at both ends of R1 and R2 is the same, so the current flowing through R1 and R2 is equal, and the current flowing through the two branches is equal.From this, the researchers conclude that ΔV_{BE} is the voltage drop on R3.Since the currents of the two branches are equal, the following relationship can be obtained $\frac{V_{out}-V_X}{R1}=\frac{\Delta V_{BE}}{R3}$. Where $V_X=V_{BE}$, Sorting can obtain:

$$V_{out} = \frac{R1}{R3}\Delta V_{BE} + V_{BE} = \frac{R1}{R3}V_T \ln n + V_{BE} \tag{4}$$

According to the previous derivation, to obtain a zero-temperature voltage only need ream $\frac{R1}{R3}\ln n = 17.2$, By choosing the appropriate R1, R2 can satisfy the set requirement, and the value of n is usually set to 10.

The advantage of a traditional bandgap reference circuit is that the principle is simple, the correction is convenient, and the technology is mature. However, due to the existence of operational amplifiers, the performance index of this structure is limited to some extent by the off-balance voltage, PSRR, and other parameters, so researchers must use a new circuit structure to solve this problem.

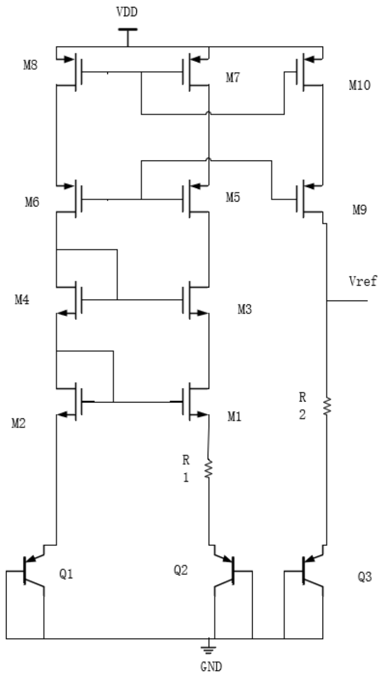

Figure 4. Using a cascode current mirror to provide bias current

As shown in Figure 4, this structure first uses a cascode current mirror to make the current of the left and right branches equal, and then uses the same structure to embed VX=VY.So the current on R1 is $\frac{\Delta V_{BE}}{R1}$, And since the left and right currents are the same, the current copied to R2 through the cascode current mirror is also $\frac{\Delta V_{BE}}{R1}$. Vref can therefore be expressed as:

$$V_{ref} = \frac{R2}{R1}\Delta V_{BE} + V_{BE} \tag{5}$$

Compared with the operation amplifier, the use of cascode current mirror has two main advantages: First, it can effectively suppress the current mismatch caused by the channel length modulation effect and reduce the mirror current error. Second, the output current is somewhat independent of the power supply voltage, which is easier to achieve. However, due to the extensive use of Mos tubes in this structure, based on the characteristics of Mos tubes, lattice vibration scattering is strengthened and carrier mobility is reduced when the temperature is increased, which leads to a decrease in transconductance and a corresponding decrease in bandwidth. Changes in these parameters may lead to changes in the positive temperature coefficient voltage of the bandgap reference circuit, for which a reference voltage can be generated using the PTAT (proportional to the absolute temperature) current to maintain the overall characteristics of the circuit.[4]

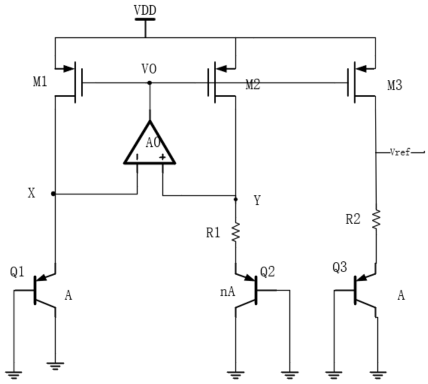

Figure 5. The reference voltage is generated by PTAT (proportional to absolute temperature) current

As shown in Figure 5, a reference voltage with a certain temperature coefficient is generated by generating PTAT current proportional to temperature. As $V_X=V_Y$, due to the action of the op amp, the voltage difference on R1 can be obtained as ΔV_{BE}, and the branch current of R1 is $\frac{\Delta V_{BE}}{R1}$, Since M1 and M2 used are the same, the left and right branches have the same current, and the current mirror is used to copy Vo to M3 to generate an output current, whose value is $\frac{\Delta V_{BE}}{R1}$. V_{ref} can be expressed as: $V_{ref} = \frac{R2}{R1} V_T \ln n + V_{BE}$.In order to reduce the power consumption of the circuit, the overall structure can also be optimized, as shown in Figure 6.

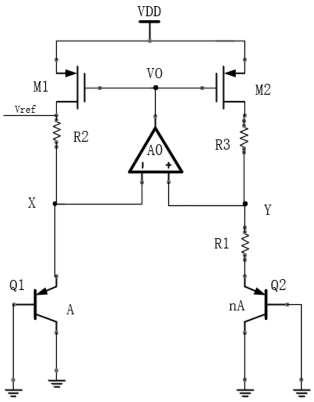

Figure 6. Optimizing the circuit

The basic principle is the same as above, but R2 and R3 are directly connected, and the role of the new resistance R3 is mainly to balance the current of the two branches.The expression of V_{ref} does not change: $V_{ref} = \frac{R2}{R1} V_T \ln n + V_{BE}$. However, as mentioned earlier, the utilization of operational amplifiers still imposes limitations on the power supply rejection ratio (PSRR) of the overall bandgap reference circuit. To address this issue, an active load inverter can be employed to adjust the PSRR by introducing operational noise and incorporating specific resistors. The design of this circuit can be used as a correction technology to eliminate the errors caused by the manufacturing process to a certain extent. At the same time, this adjustability greatly enhances the applicability of the design in specific situations, so that it can be more widely used. However, due to the increase of branches and required devices, this circuit may require greater power consumption than traditional PTAT circuits[5]. Due to the intricate nature of the design process involved, it is beyond the scope of this article to delve into further details.

4. Conclusion

This paper introduces the basic concept of bandgap voltage reference in detail and further analyzes its basic working principle and process. Three different bandgap reference circuits are compared and analyzed. The advantages and disadvantages of these bandgap reference circuits in practical analog circuit applications are discussed. This paper presents an improved idea that the power supply voltage rejection ratio can be adjusted by using the combination of active load inverter and resistor. This paper mainly summarizes some theories and achievements of previous bandgap reference circuits and compares and analyzes them but lacks the design and simulation of specific circuits. It is hoped that future researchers can give their own design and data analysis on the basis of this paper to further promote the development of related fields.

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