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Performance enhancement techniques for bandgap reference voltage sources: a comprehensive review

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Abstract. The bandgap reference voltage source is a critical module in analog and mixed-signal integrated circuits, with its performance directly impacting the accuracy and stability of circuits such as ADCs, DACs, LDOs, power management systems, and sensor interfaces. As integrated circuits evolve toward lower voltage, lower power consumption, and higher precision, traditional bandgap references face increasing demands in terms of temperature stability, power supply rejection ratio (PSRR), and process compatibility. This paper reviews key performance enhancement methods for bandgap reference voltage sources. It begins by introducing the fundamental principles of traditional BJT-based bandgap references and fully CMOS voltage reference circuits, analyzing how CTAT and PTAT components complement each other to generate a stable reference voltage. Subsequently, recent typical reference source structures are categorized and compared across three aspects: temperature stability improvement, PSRR enhancement, and fully CMOS low-power implementation. In temperature compensation, methods such as segmented curvature compensation, exponential and logarithmic curvature compensation, resistor temperature coefficient compensation, subthreshold compensation, and base current compensation are emphasized. For PSRR improvement, techniques like pre-regulation, filtering, feedback enhancement, LDO stabilization, and transistor structure optimization are analyzed. Regarding fully CMOS voltage references, developments in MOS-only, subthreshold CMOS, 2-T structures, β-multiplier structures, and flexible substrate all-in-one reference circuits are summarized. Comparative results indicate that the design of high-performance bandgap references has shifted from single-compensation methods to joint optimization of multiple mechanisms, synergistically improving overall performance through temperature compensation, PSRR enhancement, low-power biasing, and process trimming. This review provides a reference for the design and optimization of low-temperature-drift, high-PSRR, and low-power bandgap reference voltage sources in future research.

Keywords: reference voltage source, bandgap reference, temperature compensation, power supply rejection ratio, fully CMOS voltage reference, low power consumption

1. Introduction

The reference voltage source is one of the key modules in analog and mixed-signal integrated circuits, widely used in analog-to-digital converters (ADC), digital-to-analog converters (DAC), low-dropout linear regulators (LDO), phase-locked loops (PLL), sensor interface circuits, and power management systems [1-3]. Its primary function is to provide a highly stable reference voltage or current for the system, ensuring that the circuit maintains high accuracy and reliability under conditions such as power supply fluctuations, temperature variations, and process deviations. Therefore, the performance of the reference source largely determines the precision, stability, and environmental adaptability of the entire system.

2. Basic principles

From the perspective of working principles, the core objective of a reference voltage source is to construct a reference signal insensitive to temperature variations. Since semiconductor device parameters typically vary with temperature, the key to high-precision reference source design lies in utilizing voltage or current components with different temperature coefficients for complementary compensation.The complementary combination of CTAT and PTAT currents is illustrated in Figure 1, while the conventional BJT-based bandgap reference circuit is shown in Figure 2.

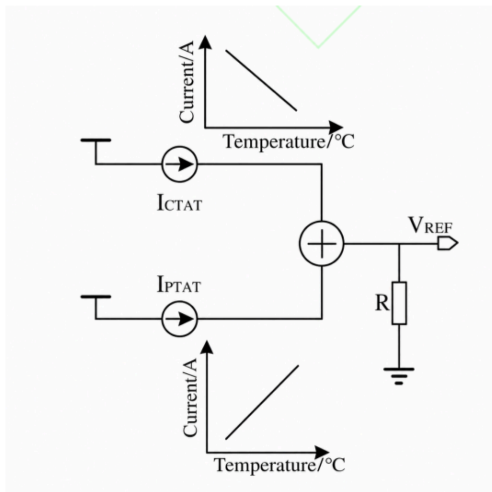

Figure 1. Schematic diagram of temperature compensation principle for reference voltage source

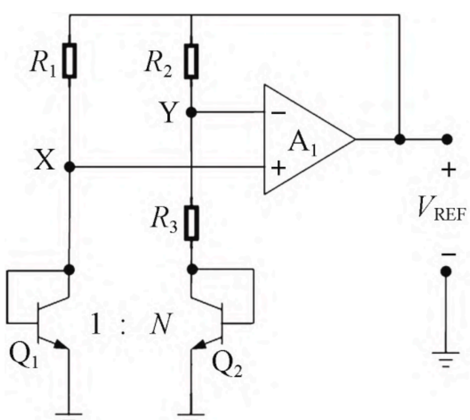

Figure 2. Structure of traditional bandgap reference circuit

Among them, the most classic and widely used is the bandgap reference (BGR) structure [4]. Traditional bandgap references are typically implemented based on bipolar junction transistors (BJTs) [4]. The basic idea is to superimpose a base-emitter voltage with a negative temperature coefficient and a voltage difference with a positive temperature coefficient in a certain proportion, thereby obtaining a reference voltage approximately independent of temperature. Specifically, the former decreases with rising temperature, exhibiting a CTAT (Complementary To Absolute Temperature) characteristic, while the latter, generated by BJTs with different emitter junction areas or current densities, increases proportionally with absolute temperature, showing a PTAT (Proportional To Absolute Temperature) characteristic. By appropriately designing the weight coefficients of these two components, the first-order temperature coefficient of the output reference voltage can be made close to zero, achieving stable reference output. Due to its clear principle, high accuracy, and minimal temperature drift, this structure has long been the mainstream solution for high-precision reference voltage design.

In traditional bandgap reference circuits, the reference voltage is typically obtained by superimposing the base-emitter voltage V_BE with a negative temperature coefficient and the ΔV_BE with a positive temperature coefficient, and its fundamental expression is

$$\mathrm{VREF} = \mathrm{VBE} + \mathrm{k}\,\Delta\,\mathrm{VBE}$$

Here, ΔVBE=VT ln n, where VT=kT/q is the thermal voltage. By adjusting the resistor ratio and transistor area ratio, the first-order temperature term can be canceled, resulting in a low temperature coefficient for the reference voltage near a specific temperature point.

However, as integrated circuit processes continue to advance toward lower voltages and power consumption, traditional BJT-based bandgap references also face certain limitations. On one hand, the output voltage of conventional bandgap references typically approaches the silicon bandgap voltage, around 1.2 V, which restricts their application under ultra-low power supply conditions [5-12]. On the other hand, the accuracy of parasitic bipolar transistor models, process consistency, and reliability in certain special environments can also impact the overall performance of reference circuits. Against this backdrop, fully CMOS references have gradually gained attention [5-12]. Unlike traditional bandgap references, fully CMOS references do not rely on bipolar transistors but instead utilize the gate-source voltage of MOS transistors and their differences to construct complementary temperature characteristics.The basic structure of a fully CMOS voltage reference circuit is shown in Figure 3.

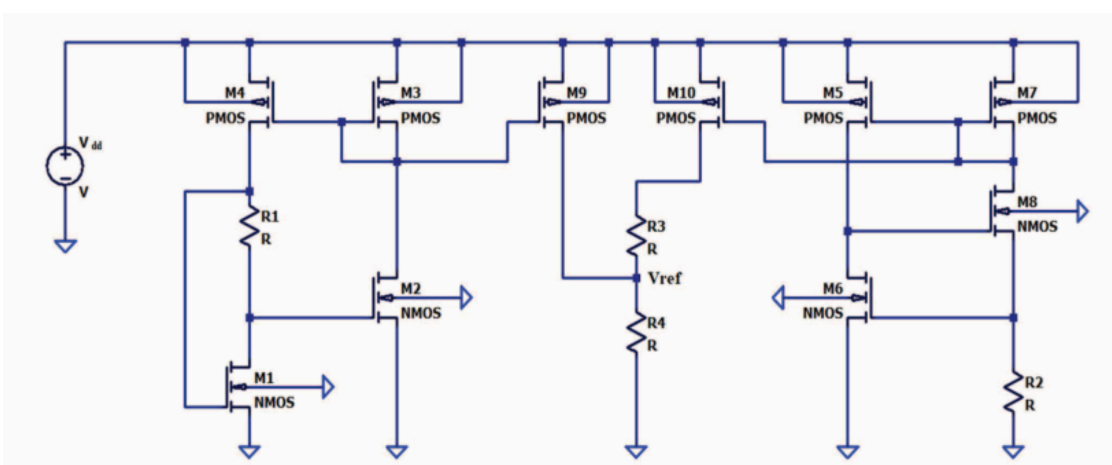

Figure 3. Basic structure of full CMOS voltage reference circuit

Among them, MOS transistors working in the subthreshold or weak inversion region typically exhibit a negative temperature coefficient for a single VGS, which can be used as a CTAT component; The difference in

VGS between two MOS transistors of different sizes, current densities, or threshold characteristics can be expressed as PTAT component. By combining VGS and △V in appropriate proportions, a temperature compensation effect similar to that of traditional bandgap benchmarks can be achieved.

From the perspective of structural characteristics, bandgap reference and full CMOS reference represent two typical reference voltage generation paths, respectively. The former uses BJT as the core device and obtains temperature stable output through complementary relationship with, which has the advantages of high accuracy and low temperature coefficient, but usually requires a high voltage margin; The latter uses MOS transistors as the core devices and generates reference voltage through complementary relationships with, making it more suitable for applications with low voltage, low power consumption, and compatibility with standard CMOS processes. With the development of applications such as the Internet of Things, wearable devices, biomedical electronics, RFID, and ultra-low power sensing nodes, full CMOS benchmarks have shown increasingly obvious advantages in low voltage and low power consumption, while traditional bandgap benchmarks still occupy an important position in high-precision and high stability scenarios [5-12].

Based on the above background, this article provides an overview of temperature stability and power suppression capability in reference voltage sources, with a focus on analyzing the basic principles, typical structures, and key performance improvement methods of traditional bandgap references and full CMOS references. On this basis, the development trends of different temperature compensation techniques and PSRR enhancement techniques are sorted out, and the differences in temperature coefficient, power consumption, complexity, and applicable scenarios of different schemes are compared with relevant literature, in order to provide reference for the design and optimization of high-performance reference voltage sources in the future.

3. Development progress

The performance of a reference voltage source cannot be determined solely by a single indicator, but needs to consider factors such as temperature stability, power supply voltage stability, and power consumption simultaneously. Among them, temperature stability is usually represented by the temperature coefficient TC, with the unit of ppm/°C, which is used to measure the degree of change of reference voltage with temperature; The stability of power supply voltage is usually represented by PSRR, which is used to measure the impact of power supply disturbances on the output reference voltage; The power consumption directly determines whether the reference source is suitable for low-power systems. Therefore, a good reference source should strike a reasonable balance between low temperature coefficient, high PSRR, and low power consumption. Based on this, the following article will provide an overview from three aspects: improving temperature stability, enhancing PSRR, and achieving full CMOS low-power implementation.

3.1. Improve temperature stability

The principle and method of improving temperature stability using traditional benchmark structures were introduced earlier. However, due to the presence of high-order nonlinear terms such as T ln T in V_BE, traditional first-order compensation structures are difficult to achieve stable output over a wide temperature range. Its temperature characteristics usually exhibit a parabolic shape, deviating significantly from the room temperature point in both low and high temperature regions, thereby limiting further improvement in temperature stability.

3.1.1. Segmented curvature compensation technology

To address this issue, researchers have proposed segmented curvature compensation technology. The basic idea of this method is to introduce different compensation currents in different temperature ranges, and to reduce overall temperature drift by segmenting and correcting high-order temperature terms.

In 2022, the Institute of Microelectronics at Southwest Jiaotong University proposed a precise segmented compensation method [13], which uses an NMOS transistor as a temperature control switch to conduct the compensation current in a specific temperature range, thereby segmenting and correcting the bandgap output voltage. The simulation results show that the temperature coefficient of the circuit can be reduced to 0.48 ppm/℃ within the temperature range of -40 ℃ to 125 ℃.The resulting temperature-compensation characteristic and the corresponding circuit structure are shown in Figures 4 and 5, respectively.

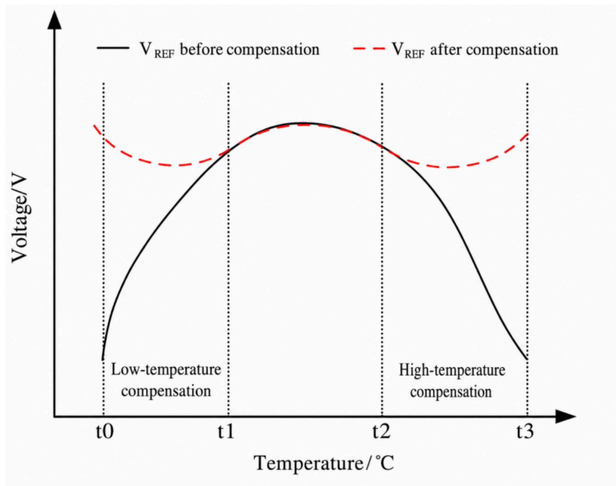

Figure 4. Precise segmented compensation bandgap reference temperature compensation curve

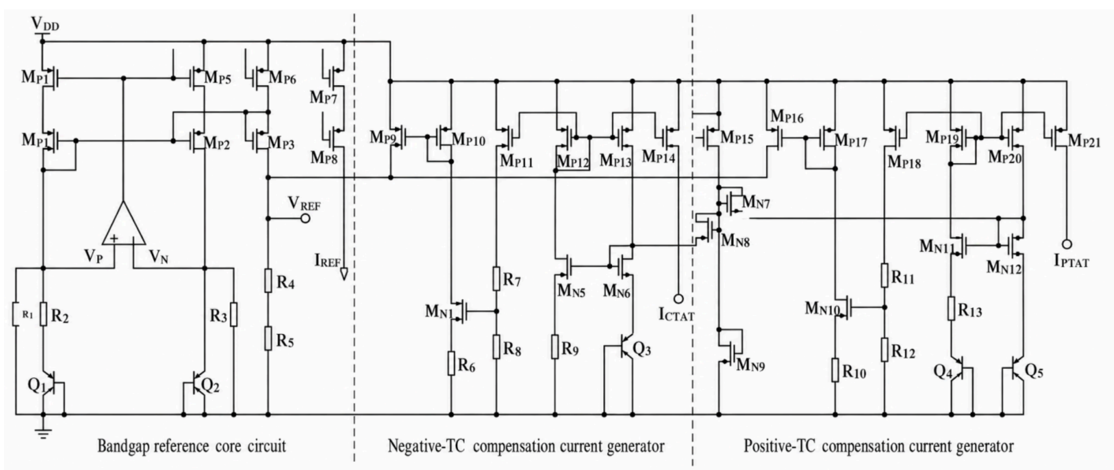

Figure 5. Structure of precise segmented compensation bandgap reference source circuit

In 2023, the School of Information Science and Engineering at Lanzhou University proposed a bandgap reference structure with segmented curvature compensation [14], which compensates for temperature curvature by extracting current in the low-temperature region and injecting current in the high-temperature region, reducing the temperature coefficient from 11.6 ppm/℃ to 1.137 ppm/℃. This method achieves multiple compensation extremum points within a wide temperature range of -75 ℃ to 125 ℃, significantly improving temperature stability.

In addition, in 2023, the School of Information Science and Engineering at Shenyang University of Technology proposed a high-order curvature compensation bandgap reference circuit [15], which further corrects the nonlinear temperature term by introducing high-order compensation branches into the traditional bandgap structure. This circuit utilizes additional temperature related currents to generate high-order compensation terms, effectively reducing the curvature error caused by the variation of bandgap voltage with temperature. The simulation results show that the circuit can achieve a temperature coefficient of about 1 ppm/℃ in the temperature range of -40 ℃ to 125 ℃, further improving the temperature stability of the bandgap reference circuit.

In 2024, the School of Science at Beijing University of Information Science and Technology introduced segmented compensation circuits and digital tuning techniques based on the Banba type bandgap structure to compensate for high-order terms over a wide temperature range, reducing the temperature coefficient of the reference source in the range of -40 ℃ to 150 ℃ to 0.98 ppm/℃ [16]. The variation in the segmented compensation current, the compensated output-voltage characteristic, and the corresponding circuit structure are presented in Figures 6–8, respectively.

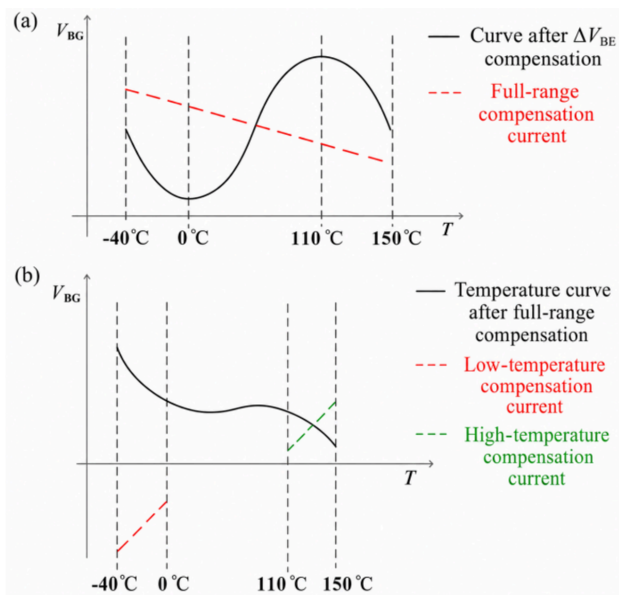

Figure 6. Schematic diagram of segmented compensation principle for wide temperature range

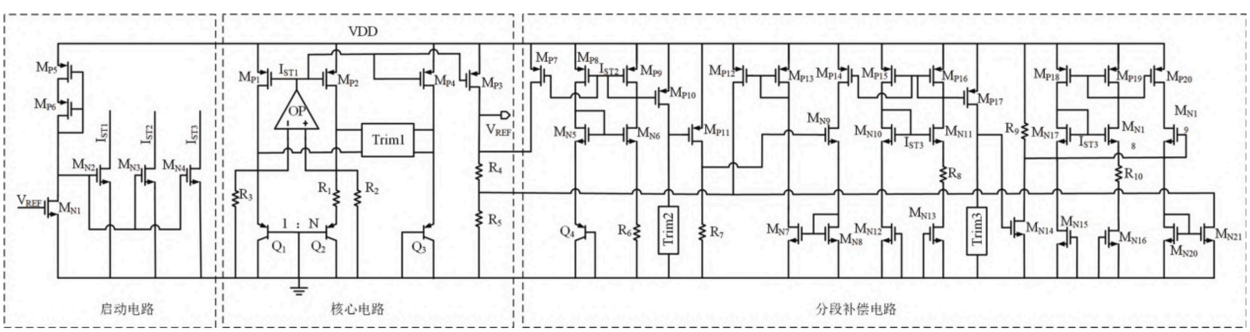

Figure 7. Structure of low temperature drift bandgap reference source circuit with wide temperature range

In 2024, the School of Advanced Manufacturing at Fuzhou University optimized the temperature coefficient of the bandgap benchmark through segmented compensation technology and combined it with a pre voltage stabilization circuit to improve the power supply suppression ratio, achieving a temperature coefficient of 1.3 ppm/℃ in the temperature range of -40 ℃ to 125 ℃ [17].The temperature-compensation characteristic and the corresponding circuit structure of the proposed low-temperature-drift, high-PSRR bandgap reference are shown in Figures 8 and 9, respectively .

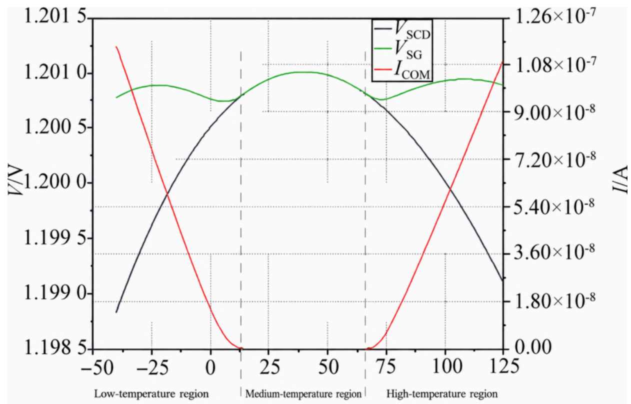

Figure 8. Low temperature drift PSRR bandgap reference temperature compensation characteristic curve

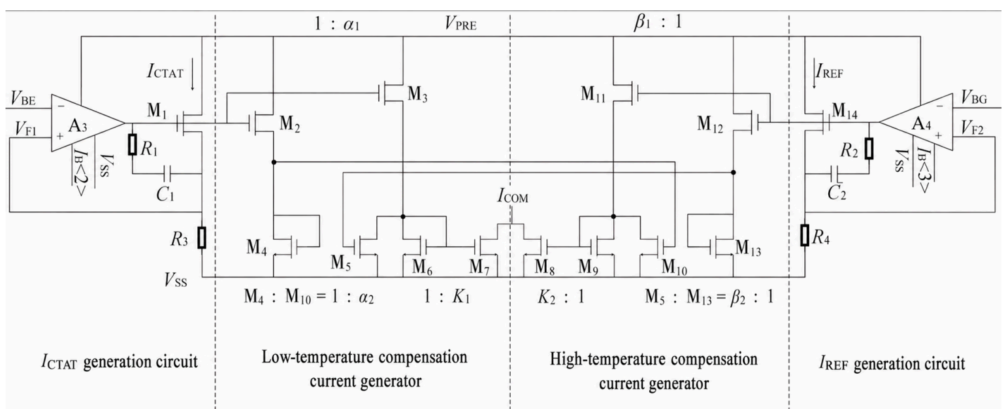

Figure 9. Low temperature drift PSRR bandgap reference source circuit structure

Overall, the segmented curvature compensation technique effectively weakens the high-order temperature nonlinearity of VBE by introducing different compensation mechanisms in different temperature ranges, thereby significantly improving the temperature stability of the bandgap reference circuit. In recent years, this method has become one of the important techniques for achieving sub ppm temperature coefficient bandgap benchmarks.

3.1.2. Exponential and logarithmic curvature compensation techniques

In addition to the segmented curvature compensation method, another common temperature compensation method is to generate high-order compensation terms through exponential or logarithmic function characteristics to offset the nonlinear temperature term in the bandgap reference. The traditional bandgap reference circuit mainly achieves first-order temperature compensation by superimposing the negative temperature coefficient VBE and the positive temperature coefficient Δ VBE, but the temperature characteristics of VBE still contain high-order nonlinear terms such as Tln (T). Therefore, after first-order compensation, there will still be curvature errors in the reference voltage with temperature changes, and it is necessary to further reduce temperature drift through exponential or logarithmic curvature compensation.

According to the temperature model of VBE, its expression can be written as:

$$VBE(T) = VG0 - [VG0 - VBE(Tr)] \cdot T/Tr - [\eta - \delta - bq/k] \cdot (kT/q) \cdot \ln(T/Tr)$$

Among them, VG0 is the bandgap voltage of silicon at 0 K, Tr is the reference temperature, and η, δ, and b are coefficients related to process parameters and collector current temperature characteristics. From this equation, it can be seen that in addition to constant and first-order temperature terms, VBE also contains nonlinear terms in the form of Tln (T). Therefore, the core idea of logarithmic curvature compensation is to construct a compensation voltage or current that is related to Tln (T) but of opposite polarity, to offset the residual higher-order temperature term in VBE.

In 2025, the National Key Laboratory of Integrated Circuits and Microsystems and other units proposed a curvature compensation method based on the Brokaw bandgap structure [18]. This method utilizes currents with different temperature coefficients to flow through bipolar transistors, causing the transistors to generate VBEs with different temperature characteristics, thereby forming Tln (T) compensation terms, which are used to correct the remaining temperature curvature after uniform order compensation. In the Brokaw benchmark core, two transistors with an emitter area ratio of N: 1 generate PTAT current, which is expressed as:

$$IPTAT = (VBE2 - VBE1)/R1 = VT\ln(N)/R1 = kT\ln(N)/(qR1)$$

Therefore, the bandgap reference voltage after first-order compensation is:

$$VBG = VBE2 + 2IPTAT \cdot R2$$

$$VBG = VBE2 + 2(kT/q)\ln(N) \cdot R2/R1$$

The second term in this equation is the positive temperature coefficient term, which is used to compensate for the first-order negative temperature coefficient term of VBE. However, due to the presence of Tln (T) nonlinearity in VBE, this paper further generates Tln (T) compensation terms with opposite trends through high-order compensation branches, thereby reducing temperature drift over a wide temperature range. The simulation results show that the circuit achieves a temperature coefficient of 1.4 ppm/℃ in the temperature range of -40 ℃ to 125 ℃, and obtains a power supply rejection ratio of -64 dB at 100 Hz.

In 2024, the Institute of Microelectronics at Southwest Jiaotong University proposed an exponential curvature compensation bandgap reference circuit [19]. This method utilizes the exponential characteristic of the current amplification factor β of bipolar transistors changing with temperature, and introduces an exponential nonlinear compensation term in the reference voltage. The article points out that the relationship between the transistor current amplification factor β and temperature can be approximately expressed as:

$$\beta(T) = \beta\infty \cdot \exp(-\Delta EG/kT)$$

Among them, β ∞ is the current amplification factor under ideal conditions, Δ EG is a parameter related to the narrowing of the bandgap width, k is the Boltzmann constant, and T is the absolute temperature. Due to the exponential relationship between β (T) and temperature, this characteristic can be utilized to generate exponential compensation current or compensation voltage.

In this method, the reference voltage after exponential curvature compensation can be expressed as:

$$\mathrm{VREF} = \mathrm{VBE1} + \mathrm{m1RT} + \mathrm{m2RT}/\beta(\mathrm{T})$$

After substituting β (T), it can be further expressed as:

$$\mathrm{VREF} = \mathrm{VBE1} + \mathrm{K1T} + \mathrm{K2T} \cdot \exp(\Delta\mathrm{EG}/\mathrm{kT})$$

Among them, K1T is a first-order PTAT compensation term, and K2T · exp (Δ EG/kT) is an exponential high-order compensation term. By using this index compensation term, the remaining nonlinear temperature error after uniform order compensation can be further corrected. The simulation results show that the circuit achieves a temperature coefficient of 5.46 ppm/℃ in the temperature range of -40 ℃ to 150 ℃, with a static current of only 2.3 μ A under a 5V power supply, and a DC power supply suppression ratio of -87 dB.

In 2024, the East China Institute of Optoelectronic Integrated Devices proposed a low temperature coefficient and low noise bandgap reference source [20]. This method also compensates for the nonlinear term Tln (T) in VBE by constructing a compensation current that is related to Tln (T) and has a downward opening to correct the curvature coefficient of the traditional bandgap reference after first-order temperature compensation. In traditional bandgap reference output, the reference voltage can be simplified as:

$$\mathrm{VREF0} = \mathrm{VBE} + \mathrm{K}\Delta\mathrm{VBE}$$

Among them, VBE is the negative temperature coefficient term, and K Δ VBE is the positive temperature coefficient term. On this basis, the article introduces a compensation current ICOMP related to Tln (T) to make the output voltage:

$$\mathrm{VREF} = \mathrm{VREF0} + \mathrm{ICOMP} \cdot \mathrm{R}$$

among which

$$\mathrm{ICOMP} \propto -\mathrm{Tln}(\mathrm{T})$$

Therefore, ICOMP · R can serve as a reverse compensation for the residual Tln (T) curvature term in VBE, thereby reducing temperature drift. At the same time, the article also uses a transistor as the input transistor of the differential amplifier to reduce the low-frequency noise caused by MOS transistor as the input transistor. The test results show that the circuit achieves a temperature coefficient of 1.49 ppm/℃ in the temperature range of -55 ℃ to 125 ℃, and an integrated noise of about 1 μ Vrms in the frequency range of 0.1-10 Hz. It is suitable for high-precision ADCs and other applications that require high noise and low temperature drift.

In 2025, the University of Electronic Science and Technology of China and the 24th Research Institute of China Electronics Technology Group Corporation proposed a low-temperature drift bandgap reference circuit with a wide input voltage range [21]. This article introduces a compensation transistor Q3 based on the traditional Brokaw bandgap reference, and uses the collector current IC3 generated by the gradual opening of the compensation transistor under high temperature conditions as a high-order compensation current to improve temperature drift in the high temperature region. When no compensation is introduced, the reference output voltage is:

$$\mathrm{VREF0} = \mathrm{VBE2} + 2\mathrm{I0}(\mathrm{R2} + \mathrm{R3})$$

because:

$$I0 = VTln(N)/R1$$

Therefore:

$$VREF0 = VBE2 + 2(R2 + R3)VTln(N)/R1$$

After introducing compensation transistor Q3, the output voltage becomes:

$$VREF = VBE2 + 2I0(R2 + R3) + IC3R3$$

It can also be written as:

$$VREF = VREF0 + IC3R3$$

Among them, IC3R3 is the nonlinear compensation term generated in the high-temperature region. Due to the decrease in the turn-on voltage of compensation transistor Q3 with increasing temperature, Q3 gradually enters the amplification region from the cutoff region under high temperature conditions, causing IC3 to increase with increasing temperature, thereby compensating for the curvature error of the reference voltage in the high temperature region. The simulation results show that the circuit achieves a temperature coefficient of 2.662 ppm/℃ within a wide input voltage range of 7-40 V and a temperature range of -40 ℃ to 125 ℃. At the same time, the power supply suppression ratio can reach -108.1 dB, and the static current is 14.77 μ A.

Overall, as shown in Table 1, exponential and logarithmic compensation techniques effectively counteract higher-order temperature terms in VBE by utilizing the exponential or logarithmic characteristics of semiconductor devices to generate nonlinear compensation currents. This allows for high-precision temperature compensation with a relatively simple circuit structure.

Table 1. Comparison of performance metrics and compensation techniques for high-precision temperature sensors and voltage references across recent literature (2022–2025)

iterature	Year	Compensation Method	Temperature Range (°C)	Temperature Coefficient TC (ppm/°C)
He Hao	2022	Piecewise Curvature Compensation	-40~125	0.48
Ma Aning	2023	Piecewise Curvature Compensation	-75~125	1.137
Li Xin	2023	Higher-Order Curvature Compensation	-40~125	Approx. 1
Zhao Zhiyu	2023	Logarithmic Curvature Compensation	-40~125	1.4
Xiao Changzhi	2024	Piecewise Curvature Compensation + Digital Trimming	-40~150	0.98
Wang Luoyao	2024	Piecewise Compensation + Pre-regulation Structure	-40~125	1.3
Zhang Zujing	2024	Exponential Curvature Compensation	-40~150	5.46

Table 1. Continued

Chen Xiaojie	2024	Tln(T) Logarithmic Compensation	-55~125	1.49
Peng Lingchang	2025	Higher-Order Exponential Compensation	-40~125	2.662

3.1.3. Other temperature compensation methods and comparative analysis

In addition to segmented curvature compensation and exponential/logarithmic compensation methods, researchers have also proposed various temperature compensation techniques in recent years, including hybrid compensation, resistance temperature coefficient compensation, sub threshold compensation, and base current compensation. These methods are not completely independent, but are often combined with segmented compensation, curvature compensation, pre stabilization, or feedback techniques to introduce high-order compensation terms through the temperature characteristics of different devices or different circuit structures, thereby further reducing the temperature coefficient of the bandgap reference circuit.

The mixed compensation method achieves collaborative suppression of different temperature error terms by combining multiple compensation mechanisms. In 2025, the School of Microelectronics at Hefei University of Technology proposed a hybrid reference voltage source based on a combination of bipolar transistors and sub threshold MOS transistors [22]. This method utilizes a transistor to generate a negative temperature coefficient voltage, while a MOS transistor operating in the subthreshold region generates a positive temperature coefficient compensation term, thereby improving the temperature stability of the reference voltage under low power consumption conditions. The basic idea can be expressed as:

$$\mathrm{VREF} = \mathrm{VCTAT} + \mathrm{K} \cdot \mathrm{VPTAT} + \mathrm{VCOMP}$$

Among them, VCTAT is mainly generated by transistors or devices related to threshold voltage, with a negative temperature coefficient; VPTAT is a positive temperature coefficient compensation term; VCOMP is a high-order compensation term introduced by sub threshold MOS transistors or cascaded structures. For MOS transistors operating in the subthreshold region, their drain current can be approximately expressed as:

$$\mathrm{ID} = \mathrm{I0} \cdot \mathrm{K} \cdot \exp[(\mathrm{VGS} - \mathrm{VTH})/(\eta \mathrm{VT})]$$

Among them, I0 is a process related constant, K is the MOS transistor aspect ratio, VTH is the threshold voltage, η is the subthreshold slope factor, and VT is the thermoelectric voltage. Due to the exponential relationship between this current and VGS, VTH, and temperature, it can be used to generate nonlinear temperature compensation terms. The simulation results of this article show that within the temperature range of -20 ℃ to 140 ℃, the temperature coefficient of the circuit is 15.6 ppm/℃, and the total static current is only 24.3 nA, demonstrating good ultra-low power consumption characteristics. Overall, the hybrid compensation method can achieve a certain balance between low power consumption, process stability, and temperature stability, but its temperature coefficient is still higher than the sub ppm level high-precision bandgap benchmark.

The resistance temperature coefficient compensation method mainly utilizes the temperature coefficient differences of different types of resistors to achieve high-order temperature compensation. In 2024, the School of Big Data and Information Engineering at Guizhou University and other institutions proposed an ultra-low temperature drift bandgap reference source based on resistors with different temperature coefficients. This method is based on the Brokaw type bandgap reference structure and introduces a combination of Cr Si resistors and polycrystalline silicon resistors or diffusion resistors to generate a second-order temperature compensation term in the output voltage, thereby reducing temperature drift [23]. The temperature characteristics of a resistor can be expressed as:

$$\mathrm{R(T) = R0[1 + TC1(T - T0) + TC2(T - T0)2]}$$

Among them, R0 is the resistance value at the reference temperature T0, and TC1 and TC2 are the first-order and second-order temperature coefficients, respectively. When PTAT current flows through a resistor network with different temperature coefficients, a compensation voltage containing first-order and second-order temperature terms can be generated:

$$\mathrm{VR\ =\ IPTAT \cdot R(T)}$$

Since IPTAT is approximately proportional to temperature, VR will contain temperature terms related to T, T (T-T0), and T (T-T0)2 simultaneously. By adjusting the ratio of different resistors, the reference voltage can meet the following requirements:

$$\mathrm{dVREF/dT\ \approx\ 0}$$

$$\mathrm{d^2VREF/dT^2\ \approx\ 0}$$

Simultaneously reducing the first-order and second-order temperature drift near the reference temperature point. The compensation voltage provided in this article can be expressed as:

$$\mathrm{VR\ =\ [2VTln12/R37] \cdot \{R38 + R43[1 + (T - T0)TC1 + (T - T0)2TC2]\}}$$

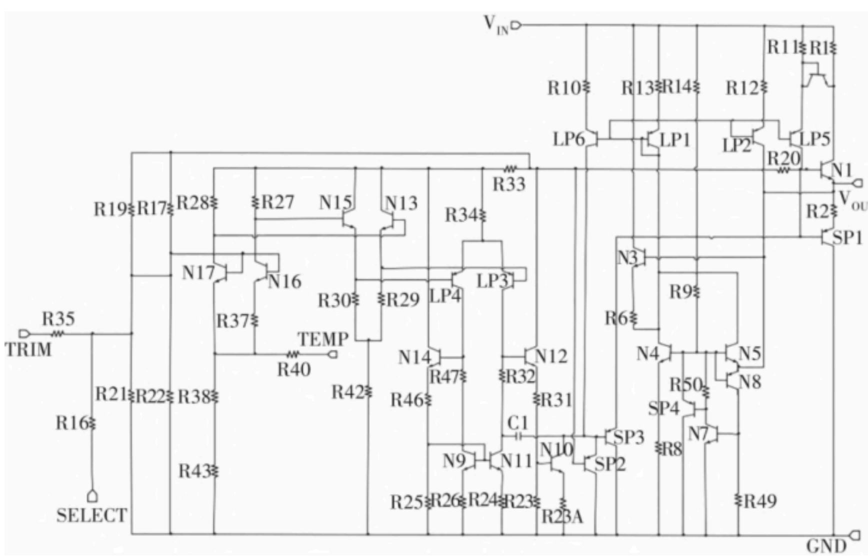

Figure 10. Circuit structure of ultra-low temperature drift bandgap reference source

This equation indicates that the temperature coefficient of diffusion resistance is introduced into the output voltage to compensate for high-order temperature nonlinearity in VBE. The actual test results show that within the operating voltage range of 4 to 36 V, the temperature drift coefficients of 2.5 V and 3 V output voltages are both less than 3 ppm/℃. This method has a relatively intuitive structure and is suitable for achieving ppm level temperature stability, but the compensation effect is highly dependent on the resistance temperature coefficient and process matching accuracy, so it requires high process consistency and adjustment accuracy.The circuit structure of the ultra-low-temperature-drift bandgap reference is shown in Figure 10 [23].

The sub threshold compensation method utilizes the exponential current characteristics of MOS transistors in the weak inversion region to construct a nonlinear temperature compensation term, which is one of the important methods for achieving low-power and high-precision bandgap references in recent years. When MOS transistor operates in the subthreshold region, its drain current can be expressed as:

$$\mathrm{ID} = \mathrm{I0} \cdot \mathrm{K} \cdot \exp[(\mathrm{VGS} - \mathrm{VTH})/(\eta \mathrm{VT})] \cdot [1 - \exp(-\mathrm{VDS}/\mathrm{VT})]$$

When VDS is large enough, the latter term can be approximated as 1, so the subthreshold current is mainly determined by VGS, VTH, and VT, and exhibits strong exponential temperature dependence characteristics. By utilizing this characteristic, compensation currents in different directions can be constructed in high or low temperature regions to offset curvature errors in the first-order bandgap reference.

In 2025, the School of Physics and Electronic Science at Changsha University of Science and Technology and other institutions proposed a high power suppression ratio low-temperature drift bandgap reference voltage source. This circuit smooths the temperature curve through a curvature compensation circuit, and combines a pre stabilization circuit and a low-pass filtering circuit to improve PSRR [24]. The temperature compensation approach can be summarized as adding additional compensation terms to the traditional bandgap output voltage:

$$\mathrm{VREF} = \mathrm{VBE} + \mathrm{K}\Delta\mathrm{VBE} + \mathrm{VCOMP}$$

Among them, VBE and K Δ VBE correspond to negative and positive temperature coefficient terms, respectively, and VCOMP is used to correct the residual high-order curvature error after first-order compensation. The simulation results show that the circuit achieves a temperature coefficient of 7.8 ppm/℃ in the temperature range of -40 ℃ to 125 ℃, and the PSRR can reach -147.1 dB. This article demonstrates that temperature compensation methods are often combined with pre stabilization and filtering techniques in practical circuits to optimize temperature stability and power suppression capabilities simultaneously.

In terms of sub threshold compensation, in 2025, the Institute of Microelectronics at Southwest Jiaotong University proposed a segmented curvature compensation low-temperature drift bandgap reference source [25]. This method utilizes MOS transistors operating in the sub threshold region to generate high-temperature compensation current IHT and low-temperature compensation current ILT, respectively, to compensate for the high-temperature and low-temperature regions. In the high-temperature compensation branch, the gate voltage of M18 is:

$$\mathrm{VG18} = \mathrm{I1R6} + \mathrm{VBE3}$$

The corresponding high-temperature compensation current is:

$$\mathrm{IHT} = \mathrm{I0} \cdot \mathrm{K18} \cdot \exp[(\mathrm{VGS18} - \mathrm{VTH18})/(\eta \mathrm{VT})]$$

In the low-temperature compensation branch, the gate voltage of M20 is:

$$\mathrm{VG20} = \mathrm{I1R7}$$

The corresponding low-temperature compensation current is:

$$\mathrm{ILT} = \mathrm{I0} \cdot \mathrm{K20} \cdot \exp[(\mathrm{VGS20} - \mathrm{VTH20})/(\eta \mathrm{VT})]$$

The final reference voltage expression is:

$$\mathrm{VREF} = [(\mathrm{VBEQ1}/\mathrm{R1}) + (\mathrm{VBEQ1} - \mathrm{VBEQ2})/\mathrm{R2}] \cdot (\mathrm{R4} + \mathrm{R5}) + (\mathrm{IHT} + \mathrm{ILT}) \cdot \mathrm{R4}$$

From this equation, it can be seen that the first half is the first-order bandgap reference output, and the second half is the additional compensation voltage generated by the high-temperature compensation current and low-temperature compensation current on the resistor. The simulation results of this article show that the temperature coefficient decreases from 9.85 ppm/℃ to 1.58 ppm/℃ within the range of -40 ℃ to 125 ℃. This method actually includes the ideas of sub threshold compensation, segmented compensation, and resistance temperature coefficient compensation, reflecting the characteristics of combining multiple compensation methods. In 2025, the Institute of Microelectronics at Southwest Jiaotong University proposed a low-power, low-temperature drift amplifier without bandgap reference source [26]. This method introduces a curve correction circuit based on the traditional Brokaw structure, which reduces the curvature error caused by the temperature variation of the output reference voltage by extracting temperature compensation current from the first-order bandgap reference circuit. The output voltage of the traditional Brokaw structure can be expressed as:

$$\mathrm{VREF0} = \mathrm{VBE1} + (\mathrm{IC1} + \mathrm{IC2})\mathrm{R1}$$

Among them, IC1 and IC2 are the collector currents of two BJT branches. because:

$$\mathrm{IC1} = \mathrm{IC2} = \mathrm{VTlnn}/\mathrm{R0}$$

Therefore, the first-order output voltage can be written as:

$$\mathrm{VREF0} = \mathrm{VBE1} + \mathrm{2R1VTlnn}/\mathrm{R0}$$

After introducing the curve correction circuit, the temperature compensation current IC is extracted from the node, and the output voltage becomes:

$$\mathrm{VREF} = \mathrm{VBE1} + [\mathrm{2VTln8}/\mathrm{R0} - \mathrm{IC}]\mathrm{R1}$$

Among them, IC is the temperature compensation current generated and extracted by the curve correction circuit. By adjusting the aspect ratio of the relevant MOS transistors, the size of the IC can be changed to maximize its compensation for the convex temperature curve of the first-order bandgap output voltage. The simulation results show that the circuit achieves a temperature coefficient of 2.76 ppm/℃ in the range of -40 ℃ to 130 ℃, with an overall static current of only 4.7 μ A, and the curve correction circuit consumes only

0.05 μ A. This method demonstrates that in low-power design, good temperature stability can be achieved through a non operational amplifier structure and a low current curve correction circuit.

The base current compensation method mainly compensates for the errors introduced by the base current in bipolar transistors due to changes in process and temperature. In the traditional bandgap reference, the collector current IC and base current IB of a BJT satisfy:

$$\mathrm{IB} = \mathrm{IC}/\beta$$

Among them, β is the forward current gain of BJT. Due to the variation of β with temperature, process angle, and device mismatch, the base current IB will also change, further introducing additional reference voltage errors. If no compensation is made, the base current error will affect the bandgap core current through the resistor network and current mirror, resulting in a deviation of the output reference voltage.

In 2025, the Department of Integrated Circuits at Xi'an University of Electronic Science and Technology proposed a low offset, low-noise, high-precision bandgap reference voltage source for high-precision ADCs [2]. On the one hand, this article adopts feedback boosting technology to reduce the impact of operational amplifier offset and low-frequency noise on the output. On the other hand, it proposes high-precision base current compensation technology to reduce the reference voltage offset caused by process angle changes and device mismatches. The current mode bandgap core output of this circuit can be expressed as:

$$\mathrm{VREF} = [(\mathrm{VTlnN})/\mathrm{R1} + \mathrm{VBE1}/\mathrm{R3}] \cdot \mathrm{R2}$$

Among them, the first term is PTAT current, and the second term is CTAT current. After the two currents are superimposed, they are converted into a reference voltage through resistor R2. When considering the base current error, the output voltage error can be approximated as:

$$\Delta\mathrm{VREF} \propto \mathrm{IB} \cdot \mathrm{R}$$

Also, due to:

$$\mathrm{IB} = \mathrm{IC}/\beta$$

Therefore:

$$\Delta\mathrm{VREF} \propto (\mathrm{IC}/\beta) \cdot \mathrm{R}$$

It can be seen that as β varies with temperature and process, the error caused by the base current will also change accordingly. The core of base current compensation is to accurately replicate the base current through auxiliary transistors and current mirrors, and inject compensation current into the bandgap core, so that:

$$\mathrm{ICOMP} \approx \mathrm{IB}$$

Thereby reducing the impact of base current on the output reference voltage. The test results show that the circuit outputs a reference voltage of 0.6 V at a power supply voltage of 1.2 V, with a static current of 31 μ A. The integrated noise is 2.79 μ Vrms in the range of 0.1-10 Hz, and the temperature coefficient is 3.6 ppm/℃ in the temperature range of -40 ℃ to 125 ℃.The circuit structure of the low-offset, low-noise reference voltage source for high-precision ADCs is shown in Figure 11.

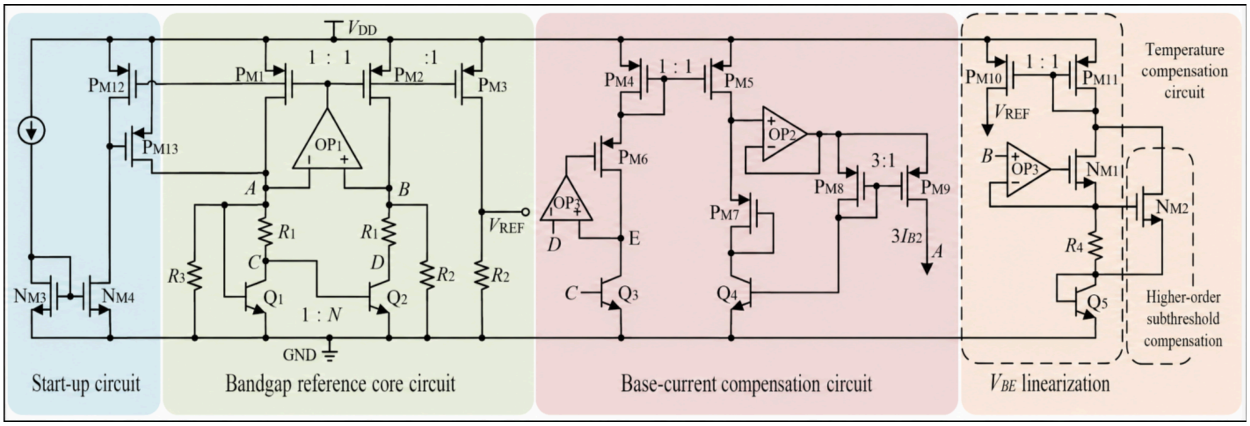

Figure 11. Structure of low offset and low noise bandgap reference voltage source for high-precision ADC

From the above methods, it can be seen that there is a clear trade-off between temperature stability, power consumption, and circuit complexity for different temperature compensation techniques. The hybrid compensation method is suitable for low-power applications, but has a high temperature coefficient; The structure of the resistance temperature coefficient compensation method is simple, but it is highly dependent on the process; The sub threshold compensation method has a good compromise between low power consumption and high accuracy, but its stability is greatly affected by the process; The base current compensation method can effectively improve accuracy and process robustness, but the circuit complexity is relatively high. Overall, bandgap reference temperature compensation technology is gradually developing towards multi mechanism collaborative compensation, achieving the optimal balance between temperature stability, power consumption, and circuit complexity by integrating multiple compensation methods.

It should be noted that different temperature compensation methods are not completely independent in practical circuits, and many high-performance bandgap references often use a combination of two or more compensation mechanisms. For example, the segmented curvature compensation low-temperature drift bandgap reference proposed by Qi Haihong et al. appears to belong to the segmented curvature compensation method, but its compensation current is generated by two exponential currents generated by MOS transistors operating in the subthreshold region, which are used for high-temperature and low-temperature compensation, respectively. Therefore, this method actually combines both the ideas of "segmented compensation" and "subthreshold exponential compensation". For example, the low-temperature drift PSRR bandgap reference source proposed by Wang Luoyao et al. uses segmented compensation technology to reduce the temperature coefficient, and introduces a pre voltage stabilization structure to enhance the power supply suppression capability. Therefore, this circuit is not a single temperature compensation method, but a combination design of "segmented temperature compensation+pre voltage PSRR enhancement".

In addition, the wide temperature range low-temperature drift bandgap reference source proposed by Xiao Changzhi et al. also reflects the characteristics of multi mechanism synergy. This design is based on the Bamba type bandgap structure, introducing additional transistor branches and compensation resistors to counteract the high-order effects of VBE. At the same time, a segmented compensation circuit is added to expand the temperature compensation range, and digital tuning is used to reduce the impact of process deviations. Therefore, it can be summarized as a composite compensation scheme of "high-order curvature compensation+segmented compensation+digital tuning". For example, Liu Xunxi et al. used a reference voltage source for high-precision ADCs, and adopted feedback boosting technology to reduce operational amplifier offset and low-frequency noise. They also introduced high-precision base current compensation technology to reduce output offset caused by different process angles and device mismatches. Therefore, this circuit also belongs to the comprehensive optimization structure of "feedback boosting+base current compensation+temperature compensation".

It can be seen that the bandgap reference temperature compensation technology cannot be completely divided according to a certain method. Segmented compensation, exponential/logarithmic compensation, subthreshold compensation, resistance temperature coefficient compensation, base current compensation, and feedback enhancement methods are often used interchangeably in practical design. Different compensation mechanisms are optimized for temperature curvature error, process deviation, PSRR performance, or noise imbalance issues. The development trend of high-performance bandgap benchmarks is gradually shifting from a single compensation method to multi mechanism joint compensation, in order to improve temperature coefficient, power consumption PSRR 、 Achieve a better balance between process stability and circuit complexity.

3.2. Methods for improving the bandgap reference source PSRR

Power Supply Rejection Ratio (PSRR) is an important indicator for measuring the ability of bandgap reference circuits to suppress power supply voltage disturbances. It reflects the degree of impact of power supply voltage changes on the output reference voltage. It is usually defined as the logarithmic form of the ratio of output voltage change to power supply voltage change [3, 24], that is:

$$\mathrm{PSRR} = 20 \log \left[(\Delta\ \mathrm{VDD})/(\Delta\ \mathrm{VREF})\right]$$

The higher the PSRR value, the stronger the ability of the bandgap reference circuit to suppress power supply noise and voltage fluctuations. In practical applications, due to the presence of ripple, noise, and transient disturbances in the power supply voltage, if the PSRR performance of the bandgap reference circuit is insufficient, these disturbances will directly couple into the reference voltage, thereby affecting the accuracy and stability of the subsequent circuits (such as analog-to-digital converters, low dropout regulators, etc.).

In traditional bandgap reference circuits, changes in power supply voltage are mainly coupled to the output terminal through bias current sources, operational amplifiers, and current mirror structures, resulting in offset of the reference voltage. Therefore, improving PSRR performance has become one of the key issues in the design of bandgap reference circuits. In recent years, researchers have proposed various improvement methods to address this issue, including pre stabilization techniques, RC filtering enhancement methods, device structure optimization methods, LDO multiplexing pre stabilization methods, and feedback regulation methods. Below, we will systematically analyze the methods for improving the bandgap reference PSRR according to different technical paths.

3.2.1. Pre stabilization method

The pre stabilization method introduces a stabilization module at the front end of the bandgap reference circuit to convert the input power supply voltage into a relatively stable internal supply voltage, thereby reducing the impact of power supply disturbances on the bandgap core circuit. It is one of the most commonly used methods to improve PSRR performance. The basic idea is to construct an intermediate stable node to cut off the direct transmission path of power noise to the bandgap reference output terminal, thereby improving the overall power suppression capability.

In 2025, the School of Science at Beijing University of Information Science and Technology proposed a bandgap reference source for high PSRR low dropout linear voltage regulators. The article points out that in LDO systems, the PSRR of the bandgap reference source significantly affects the mid frequency power suppression performance of LDO. Therefore, this design simultaneously introduces a pre voltage regulation circuit with charged voltage negative feedback, a capacitor multiplication circuit, and a low-pass filtering circuit in the bandgap reference source to suppress power ripple from both the input and output paths of the power supply [3].

The pre regulated piezoelectric circuit used in this article is composed of MOS transistors to form a negative feedback loop. When there is an instantaneous rise disturbance in the power supply voltage VDD, the voltage at the MOS transistor port connected to the power supply will rise accordingly; Subsequently, the negative feedback loop will cause a reverse change in the voltage of the relevant nodes, thereby offsetting the power supply voltage disturbance. Its essence is to weaken power disturbances before entering the bandgap core circuit through a negative feedback mechanism, allowing the core circuit to obtain a more stable internal power supply voltage. The article also points out that the output voltage of the bandgap reference core circuit can be expressed as:

$$\mathrm{VBG} = (\mathrm{Rout} / \mathrm{R3}) \cdot [\mathrm{VBE1} + (\mathrm{R3} / \mathrm{R1})\mathrm{VTlnn}]$$

Among them, VBE1 is the negative temperature coefficient voltage, VTlnn is the positive temperature coefficient voltage term, and Rout, R1, R3 are the resistance parameters. Due to the correlation between output voltage and output resistance Rout, when power disturbances are converted into leakage current changes through MOS transistors, they will further form output voltage disturbances on Rout, and therefore the value of Rout will also affect PSRR. The PSRR expression given in this article is:

$$\mathrm{PSRR} = 20\mathrm{lg}(\Delta\mathrm{Vout} / \Delta\mathrm{Vin})$$

Meanwhile, due to the output voltage satisfying:

$$\mathrm{Vout} = \mathrm{ID3} \cdot \mathrm{Rout}$$

Therefore, when the power supply voltage disturbance causes a change in ID3, the output voltage change Δ Vout will also increase with the increase of Rout, thereby reducing the power supply suppression performance. Therefore, in the design, it is not enough to rely solely on increasing Rout to improve the output voltage, but it is necessary to combine pre voltage regulation, capacitor multiplication, and filtering structure to optimize PSRR.

In addition, this article adopts a capacitance doubling structure to enhance the mid frequency PSRR. The equivalent capacitance of a capacitor doubling circuit can be expressed as:

$$\mathrm{Ceq} = (1 + \mathrm{k})\mathrm{C1}$$

Among them, C1 is the actual capacitance, and k is the amplification factor of the current mirror. By doubling the capacitance, a larger equivalent decoupling capacitance can be obtained without significantly increasing the chip area, thereby enhancing the filtering ability against power disturbances. For the high frequency range, an RC low-pass filter circuit is added to the output terminal in the article to further attenuate the ripple of the high frequency power supply. The simulation results show that the PSRR of the reference source reaches 137.9 dB, 93.6 dB, and 87 dB at 100 Hz, 1 MHz, and 3 MHz, respectively, which is about 50 dB higher than similar reference sources. This indicates that the combination of pre voltage regulation, capacitance doubling, and low-pass filtering can effectively improve the wideband PSRR.The complete circuit structure of the bandgap reference for a high-PSRR low-dropout linear regulator is shown in Figure 12.

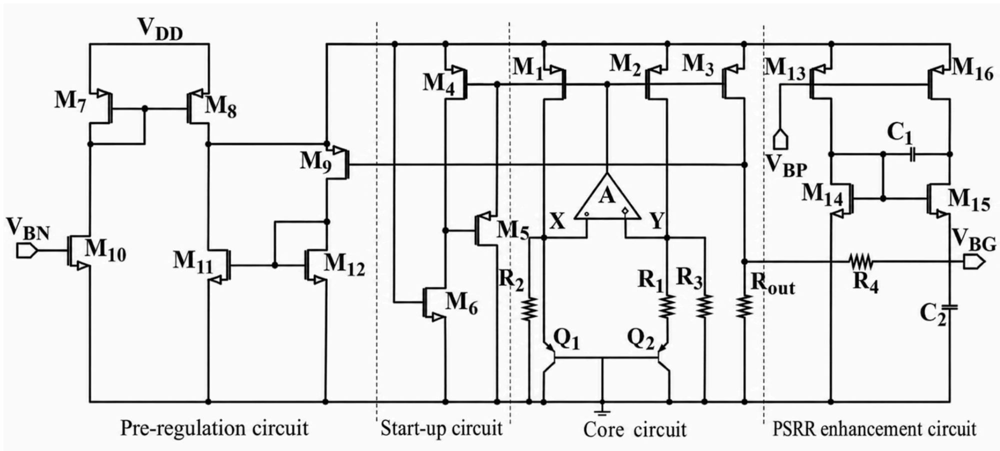

Figure 12. Bandgap reference source structure for high PSRR low dropout linear voltage regulator

On this basis, in 2025, the School of Physics and Electronic Science at Changsha University of Science and Technology improved the pre voltage stabilization structure from the perspective of current stability. This method uses a Wilson current source to construct a current negative feedback loop, allowing the reference current to be determined by the circuit's own constraints rather than relying on the power supply voltage, thereby weakening the impact of power supply disturbances on the circuit. On this basis, a stable internal power supply voltage is generated through a pre regulator to provide isolated power supply for the bandgap core circuit. This structure not only reduces the linear adjustment rate, but also significantly improves the PSRR performance. The simulation results show that the PSRR can reach -147.1 dB, demonstrating excellent power supply suppression capability [24].The circuit structure of the high-PSRR, low-temperature-drift bandgap reference voltage source is shown in Figure 13.

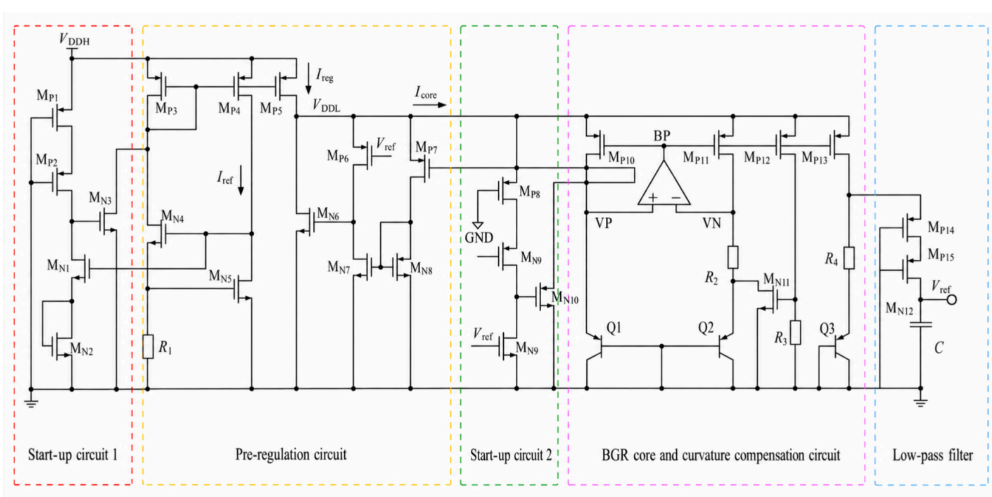

Figure 13. Structure of high power supply rejection ratio low temperature drift bandgap reference voltage source

In addition, for wide input voltage application scenarios, in 2025, the University of Electronic Science and Technology of China and the 24th Research Institute of China Electronics Technology Group Corporation proposed a pre voltage stabilization structure based on Zener diodes. This method generates a stable voltage through a Zener transistor and combines it with a source follower structure to generate an internal supply voltage, thereby avoiding high voltage directly acting on the bandgap core circuit and achieving isolation of power supply noise. This structure can still operate stably within a wide input voltage range of 7-40 V and achieve PSRR performance of approximately -108.1 dB [21].

Based on the above research, it can be seen that the pre stabilization method effectively blocks the transmission path of power disturbances to the bandgap reference core circuit by constructing stable internal power supply nodes. Among them, the pre stabilization structure based on voltage negative feedback has a good PSRR enhancement effect in a wide frequency range; The structure based on Wilson current source further enhances the anti-interference ability by stabilizing the current, making it suitable for high-precision design; The pre stabilization method based on Zener diodes is more suitable for wide input voltage application scenarios. Overall, the pre stabilization method is the fundamental technology for improving the bandgap reference PSRR performance, but it still needs to be combined with filtering or feedback techniques in the high frequency range to achieve better performance.

3.2.2. Other methods

In addition, in addition to the pre stabilization method, methods such as filter, transistor structure improvement, LDO stabilization, and feedback enhancement are also commonly used to improve the PSRR of bandgap reference sources. Filters are mainly used to suppress high-frequency power supply noise, while transistor structure improvements reduce the coupling of power supply disturbances from within the bandgap core. LDO stabilization isolates external power supply fluctuations by stabilizing the internal power supply voltage, while feedback law reduces the impact of power supply disturbances at the output end by enhancing the loop feedback capability. Below, we will analyze the above methods in detail by combining several typical circuits.

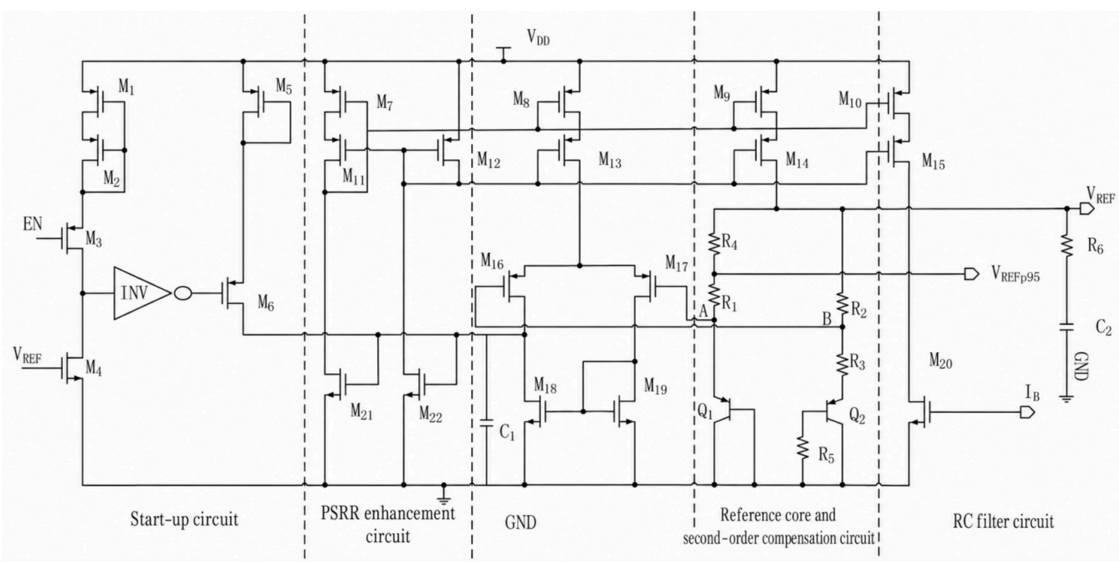

Figure 14. Structure of high PSRR low temperature drift bandgap reference source for temperature sensor

In 2024, the School of Electronic Information and Artificial Intelligence at Shaanxi University of Science and Technology introduced a design method combining RC high-frequency filtering circuit and PSRR enhancement circuit based on the traditional bandgap reference structure. In this structure, the RC filtering network introduces a pole between the power supply and the reference output, thereby forming a zero compensation effect in the PSRR frequency response, effectively improving the power supply suppression performance in the high-frequency region. At the same time, in order to solve the problem of slow charging speed of capacitors in RC filtering circuits, a fast charging circuit was designed in the paper, which enables the filtering capacitors to establish a stable voltage in a short time, thereby avoiding the problem of long startup time [27]. The circuit structure combining an RC filter and a PSRR-enhancement circuit is shown in Figure 14.

The simulation results show that with the introduction of RC filtering network, the PSRR of the bandgap reference circuit can reach over 100 dB in the full frequency range (1 Hz~1 GHz), and even reach -134 dB at high frequency (about 1 GHz), which is significantly improved compared to the case without adding filtering network.

In addition, this article further improves the power supply suppression capability by combining PSRR enhancement circuits. This enhanced structure separates the output of the operational amplifier from the current mirror control terminal, so that the gate source voltage of the key MOS transistor does not change with the power supply voltage, thereby ensuring that its operating current is basically not affected by power supply disturbances, and further suppressing the transmission of power supply noise to the bandgap core circuit. This "current stabilization" mechanism reduces the impact of power supply changes on circuit bias points from the source, thereby improving PSRR performance without significantly increasing circuit complexity.

Overall, the RC filtering method mainly suppresses high-frequency noise by introducing a frequency selective network, while the PSRR enhancement circuit reduces power coupling by stabilizing the critical current path. The combination of the two can significantly improve the PSRR performance of the bandgap reference over a wide frequency range. Among them, the RC filtering structure has significant advantages in the high frequency range, while the PSRR enhancement circuit provides additional suppression capability in the mid low frequency range. The two complement each other, making the circuit exhibit high power suppression capability in the entire frequency range.

In addition to improving PSRR performance through external circuits such as pre stabilization and filtering, researchers have also improved the bandgap reference core circuit structure in recent years to reduce the coupling path of power supply disturbances from the source, thereby achieving an improvement in PSRR performance. Among them, optimizing the connection method and working mechanism of bipolar transistors (BJTs) has become one of the important technical paths to improve PSRR.

In traditional bandgap reference circuits, the output voltage is mainly affected by the power suppression capability and resistance ratio of the operational amplifier, and its PSRR performance is largely limited by the performance of the operational amplifier itself. When the power supply voltage changes, disturbances will couple to the output terminal through the operational amplifier and bias current path, thereby reducing the stability of the reference voltage. Therefore, simply increasing the gain of the operational amplifier to enhance PSRR often increases circuit complexity and has limited effectiveness.

In response to this issue, in 2025, the School of Information Science and Engineering at Wuhan University of Science and Technology achieved dual suppression of power supply disturbances and operational amplifier offset voltages by changing the connection method of the transistor based on the traditional bandgap structure. Specifically, this method connects the base of one transistor to the drain (or collector node) of another transistor, thereby changing the current path and forming a certain negative feedback structure inside the circuit, reducing the impact of operational amplifier offset voltage on the output, and weakening the coupling effect of power supply voltage changes on key nodes [28].

In this structure, the bandgap reference output voltage is still composed of the superposition of V_BE and Δ V_BE, but due to the redistribution of current paths, the dependence of voltage changes across the resistor on the power supply voltage is reduced, thereby improving the overall PSRR performance. Through theoretical analysis, it can be concluded that this structure weakens the strong dependence of the traditional bandgap on the PSRR of the operational amplifier, so that the power suppression capability not only depends on the performance of the operational amplifier, but also on the transconductance and resistance ratio of the transistor, thereby improving the overall anti-interference ability of the system.

The simulation results show that the PSRR of this structure can reach -110.1 dB under low frequency conditions (10 Hz), and can still maintain a PSRR performance of -70.9 dB at 10 kHz, demonstrating good power supply suppression capability. At the same time, the circuit maintains low power consumption (about 6 μ A) and low temperature coefficient (about 6.08 ppm/°C) while achieving high PSRR.

In addition, the design also introduces a low-temperature compensation branch to correct the output voltage by utilizing the high-order temperature characteristics of the transistor base current, thereby improving PSRR while also considering temperature stability. This method indicates that through structural optimization, not only can the power suppression performance be improved, but also the comprehensive performance of the bandgap benchmark can be enhanced.

Overall, the transistor structure improvement method fundamentally reduces the impact of power supply disturbances on key nodes of the circuit by changing the current path and device connection method. It is an effective method to improve PSRR without significantly adding additional circuit modules. Compared with pre stabilization and RC filtering methods, this method does not rely on additional filtering or stabilization modules, has a more compact structure, and is suitable for applications with limited area and power consumption. However, the PSRR enhancement capability of this method is still limited by circuit parameter design and is sensitive to device matching and process changes. It is usually necessary to combine it with other PSRR enhancement techniques to achieve better overall performance.

The LDO pre stabilization method, which does not require additional circuits, typically requires an additional reference voltage circuit to provide a reference voltage for the stabilization module. This not only increases circuit area and power consumption, but also increases design complexity. In response to this issue, researchers have proposed an LDO pre stabilization method in recent years that does not require additional reference circuits. By reusing the output of the bandgap reference circuit itself as a stabilization reference, adaptive regulation of the power supply voltage can be achieved, thereby improving PSRR performance without adding additional modules.

In 2025, the School of Advanced Manufacturing at Fuzhou University and other institutions proposed a low-temperature drift high PSRR bandgap reference circuit, which introduces an LDO pre stabilization technology that does not require an additional reference voltage based on the traditional structure. This method utilizes the bandgap reference output voltage as the reference voltage for the LDO, while the LDO output voltage in turn supplies power to the bandgap core circuit, forming a "self powered closed-loop structure" [17].

When the power supply voltage V_DD increases, according to the polarity relationship, the LDO output voltage V_PRE will correspondingly decrease, thereby reducing the power supply voltage of the bandgap core circuit; Vice versa. This' reverse regulation mechanism 'cancels out power disturbances before entering the core circuit, thereby achieving stable control of the supply voltage and effectively improving PSRR performance.

In addition, there is a typical self-locking problem in this structure, that is, when VPRE=0, it will cause VBG=0, thereby preventing the establishment of V_PRE. Therefore, a specialized startup circuit was designed in the article to force the LDO output to approach the power supply voltage during the initial power on stage, enabling the bandgap core circuit to start normally; After the establishment of VBG, the pre stabilization loop enters a stable working state.

The simulation results show that the temperature coefficient of the structure is 1.3 ppm/ ℃ in the temperature range of -40 ℃ to 125 ℃, and the lowest low-frequency PSRR can reach -131.7 at all process angles dB@10 Hz， Under 1.8 V power supply conditions, it can even achieve PSRR performance of -136.5 dB.

Overall, this method achieves a pre stabilization design without the need for additional reference circuits by deeply coupling the LDO pre stabilization structure with the bandgap reference circuit, significantly reducing circuit complexity and power consumption while maintaining high PSRR performance. Compared with traditional pre stabilization methods, this method avoids the introduction of additional reference voltage circuits and is more suitable for integrated circuit designs with limited area and power consumption. However, due to the existence of a self powered closed-loop, this structure imposes higher requirements on the starting circuit and loop stability. At the same time, careful handling of self-locking issues and dynamic response characteristics is required during the design process.

In addition to methods such as pre stabilization, filtering, and structural optimization, feedback method is also one of the important technical paths to improve the suppression ratio of bandgap reference power supply. The basic idea is to improve the accuracy and PSRR performance of the reference output by increasing the feedback coefficient of the bandgap core circuit, weakening the equivalent amplification effect of operational amplifier offset voltage, low-frequency noise, and power supply disturbance at the output terminal. Compared with relying solely on increasing the gain of the operational amplifier, the feedback method can improve the anti-interference ability of the bandgap core from a system level perspective, and has therefore received widespread attention in high-precision and low-noise bandgap reference design in recent years.

In 2023, Liao et al. proposed a low-frequency noise/offset cancellation technique based on current mode bandgap reference. This method reduces the equivalent gain of low-frequency noise and offset at the output end of the operational amplifier by changing the feedback path, and further introduces PTAT resistance feedback technology to reduce the low-frequency noise and offset error introduced by the current mirror. The analysis in the article shows that in the traditional current mode bandgap structure, the low-frequency noise and offset of the operational amplifier will be amplified by about times when equivalent to the output terminal. However, the proposed feedback structure further reduces this influence, significantly reducing the low-frequency noise/offset. The test results show that the circuit outputs a reference voltage of 0.6 V under a 1.2 V power supply, with an integrated noise of only 3.5 at 0.1-10 Hz and a DC accuracy of 0.21%, exhibiting good low noise and high precision characteristics [1].

On this basis, in 2025, Guangxi Key Laboratory of Brain Computing and Intelligent Chips and other units further proposed a high-precision bandgap reference voltage source with high power supply suppression ratio. This method improves the bandgap core architecture, designs offset suppression and feedback enhancement structures, and utilizes the characteristics of PMOS current mirrors and feedback loops to enhance PSRR performance while suppressing the offset effects of operational amplifiers. Compared with the traditional Bamba architecture, this structure improves the feedback coefficient by changing the feedback path and equivalent impedance relationship, thereby reducing the transmission effect of power supply voltage fluctuations at the output terminal [29].

In 2025, the Department of Integrated Circuits at Xi'an University of Electronic Science and Technology proposed a low offset, low-noise, high-precision bandgap benchmark with feedback enhancement technology for high-precision ADC applications. This method significantly improves the core feedback coefficient by changing the connection method of the bandgap core circuit, compressing the offset voltage and low-frequency noise of the operational amplifier to about 1/23 of the original when equivalent to the reference output, thereby significantly improving the output accuracy and anti-interference ability. At the same time, the article also combines high-precision base current compensation technology to further reduce the impact of process angle variations and device mismatch on the reference output. The test results show that the circuit outputs a reference voltage of 0.6 V under a 1.2 V power supply, with a static current of 31 μ A, an integrated noise of 2.79 at 0.1-10 Hz, and a temperature coefficient of 3.6 ppm/℃ in the range of -40~125 ℃. It has low noise, high accuracy, and strong robustness [2].

Overall, the core advantage of the feedback method is that it does not simply rely on additional filtering or pre stabilization modules, but directly reduces the impact of misalignment, power disturbances, and low-frequency noise on the output by improving the feedback capability of the bandgap core itself. Therefore, it is particularly suitable for high-precision, low-noise reference voltage source design. Compared with the pre stabilization method, the feedback method focuses more on suppressing internal errors in the core circuit; Compared with the RC filtering method, its improvement on low-frequency noise and misalignment is more significant; Compared with structural improvement methods, feedback methods typically achieve higher accuracy and better system level robustness. However, feedback methods typically require more complex loop design and stability analysis, with higher requirements for the design of operational amplifiers, current mirrors, and compensation networks. Therefore, in practical applications, they are often combined with pre stabilization, filtering, or base current compensation techniques to achieve better overall performance.

3.3. Full CMOS voltage reference circuit

In addition to traditional BJT based bandgap references, full CMOS voltage reference circuits have also been an important research direction in the design of low-voltage and low-power reference sources in recent years. Traditional bandgap references typically utilize the VBE and Δ VBE of BJTs to construct CTAT and PTAT components, while full CMOS references primarily utilize the VGS and Δ VGS of MOS transistors to achieve similar temperature compensation. Due to the fact that the all CMOS structure does not rely on parasitic BJTs, it is better compatible with standard CMOS processes and more suitable for low power supply voltage and low-power applications. Therefore, in the Internet of Things RFID 、 Wearable devices and special environmental electronic systems have high research value.

When the MOS transistor operates in the sub threshold region, its drain current can be approximately expressed as:

$$\mathrm{ID} = \mathrm{I0} \cdot \exp[(\mathrm{VGS} - \mathrm{VTH})/(\eta \mathrm{VT})]$$

Among them, VTH is the threshold voltage of MOS transistor, η is the sub threshold slope factor, and VT=kT/q is the thermal voltage. From this equation, we can obtain:

$$\mathrm{VGS} = \mathrm{VTH} + \eta \mathrm{VT} \cdot \ln(\mathrm{ID}/\mathrm{I0})$$

Due to the fact that VTH usually decreases with increasing temperature, the VGS of a single MOS transistor generally exhibits a negative temperature coefficient and can be used as the CTAT component. On the other hand, for two MOS transistors operating under the same current conditions but with different aspect ratios, the gate source voltage difference can be expressed as:

$$\Delta VGS = VGS1 - VGS2 = \eta VT \cdot \ln[(W/L)2/(W/L)1]$$

Due to the proportionality between VT and absolute temperature T, Δ VGS exhibits a positive temperature coefficient and can be used as a PTAT component. Therefore, the basic form of a full CMOS voltage reference can be written as:

$$VREF = VGS + K\Delta VGS$$

Among them, K is a coefficient determined by the circuit size ratio, current ratio, or resistance ratio. This formula indicates that the compensation concept of the full CMOS reference is consistent with that of the traditional BJT bandgap reference, both of which obtain a temperature stable reference voltage by canceling out the negative temperature coefficient term and the positive temperature coefficient term. However, the former uses the VGS and Δ VGS of MOS transistors, while the latter uses the VBE and Δ VBE of BJTs.

Recent advances from 2022 to 2025 highlight a clear trend toward extreme power efficiency and expanded functionality. Key research includes resistor-less designs achieving nanowatt power consumption, voltage-doubler integrated architectures enabling operation at ultra-low supply voltages down to 0.32 V, and simplified 2-T structures that minimize circuit complexity. Furthermore, specialized applications have driven the development of radiation-hardened designs for high-energy physics and "all-in-one" voltage/current references for flexible electronics using IGZO TFT technology. While early works focused on basic PTAT/CTAT compensation, subsequent studies have introduced sophisticated techniques such as ββ-multipliers, negative feedback loops, and digital trimming to improve Temperature Coefficients (TC), Power Supply Rejection Ratio (PSRR), and line sensitivity. Despite these improvements, all-CMOS references still generally face trade-offs between precision and power, with TCs often remaining in the tens to hundreds of ppm/°C range. Consequently, the field is evolving toward achieving higher precision and robustness while maintaining the inherent advantages of minimal supply voltage and power consumption, positioning all-CMOS architectures as a versatile alternative to BJT-based references in energy-constrained and specialized environments.

4. Conclusion

This study explores the landscape of voltage reference design, focusing on the trade-offs inherent in BJT-based bandgap and all-CMOS architectures. Achieving reliable operation amidst thermal and supply fluctuations requires more than just low temperature coefficients; it demands a holistic optimization of PSRR, power consumption, and silicon area. Although standard BJT references effectively cancel first-order drift by combining VBE and ΔVBE components, reaching high-precision targets necessitates addressing high-order nonlinearities through hybrid curvature compensation—integrating piecewise, exponential, or logarithmic methods. Furthermore, robust PSRR is typically achieved through a combination of pre-regulation and enhanced feedback loops that isolate the reference core from external noise. For energy-constrained applications like RFID or IoT, all-CMOS topologies offer a compelling nanowatt-power alternative, though they often rely on post-fabrication trimming to mitigate process sensitivity. The current trajectory in the field points toward multi-mechanism strategies and the deployment of CMOS references in extreme environments, such as radiation-hardened systems. Moving forward, the challenge lies in balancing these competing performance metrics through digital-analog co-design, ensuring that next-generation references meet the increasingly stringent reliability standards of modern electronics.

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