Analysis of Wide Temperature Range and Low Temperature Coefficient Bandgap Reference

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Abstract. The bandgap reference (BGR) provides a stable output voltage to the circuit, which keeps almost the whole electrical system in normal working condition. It is extremely important to design a BGR that is less affected by external factors, especially temperature. This analysis delves into the performance of different compensation circuits like temperature drift coefficient and the operating temperature range. This report lists some optimizations for the classic structure and an innovative and proven feasible circuit with progressive features. The primary aim is to identify a BGR with a wider operating range under the condition of a relatively low temperature coefficient. Following the principle of finding an appropriate method to reduce the temperature coefficient and then expand the temperature range, this study compares the advantages and disadvantages of different compensation methods. It provides suggestions for future specific circuits that can be optimized and improved.

Keywords: Bandgap Reference, Low Temperature Drift Coefficient, Wide Working Temperature Range.

1. Introduction

As the global mobile communication is coming to the 5G era, the requirements for the performance of chips become higher. Bandgap Reference (BGR) is the core of an integrated circuit, providing an accurate and reliable reference voltage for the whole system. It plays a vital role in chips such as digital-to-analog converters and memory. However, electrical parameters are affected by temperature. Therefore, the characteristics of BGR will change, leading to output voltage drift and eventually inaccuracy of the circuit, which is called the temperature drift phenomenon. So, finding a high-stability BGR is crucial for enhancing the total reliability of the circuit. Such a BGR should meet the requirements of low temperature drift coefficient, high power supply rejection ratio, low power consumption, and wide temperature range. Notably, a low temperature drift coefficient ensures strong stability and reliability, while a wide temperature range enables more practical applications.

Nowadays, many researchers have developed new structures of BGR and their optimization. The most common way is to stabilize the output voltage by compensation effect. Zhang et al.

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[1] proposed a simple-structured high-precision bandgap reference. Taking advantage of the characteristics of the transistors at different temperatures, it forms different weight indices compensation current by arranging transistors with different layout areas. This bandgap reference has the properties of strong symmetry, ensuring high stability. Its accuracy is significantly improved by adding small components. On the other hand, a simple structure means some performance sacrifices. Actually, this bandgap reference can be only used within the specified temperature range of -40°C to 80°C. To extend the working temperature, Sun et al. [2] presented a piecewise compensation bandgap reference, which applies high-order compensation separately to the low-temperature and high-temperature sections, expanding the temperature range from -40°C to 150°C. By the way, the temperature drift phenomenon at low temperatures is not as obvious as the simple-structured bandgap reference. But this BGR not only complements the circuit but also needs transistors to work stably in sub-threshold regions. Minor mismatches could lead to serious consequences, meaning high requirements of techniques.

This paper will conduct a systematic review of the relevant research and conclude the possible optimization directions for a high-precision wide-temperature-range bandgap reference. This could both provide a theoretical reference for future optimization and clarify the existing shortage. And the development of a high-performance bandgap reference will provide a more stable working environment for the integrated chip. It is of great engineering value.

2. Traditional bandgap reference structure

The principle of BGR is to achieve a stable zero- temperature-coefficient reference voltage V_{REF} by combining negative and positive temperature coefficient power supplies together. Figure 1 shows the original BGR structure. The most classic one was designed by Widlar [3]. Taking advantage of the negative temperature dependence of the BJT base-emitter voltage, it reduces the influence of temperature by putting two BJT in different currents and weighting superposition. Based on this, Kuijk applied operational amplifiers (OPAMP) to force the voltage of two BJT to be equal, thereby enhancing the symmetry of the circuit. At the same time, the three-terminal BGR presented by Brokaw used the collector current sampling technique to alleviate the errors. Moreover, to solve the problem that traditional BGR could not work in low-pressure environments, Banba illustrated a method of current summation.

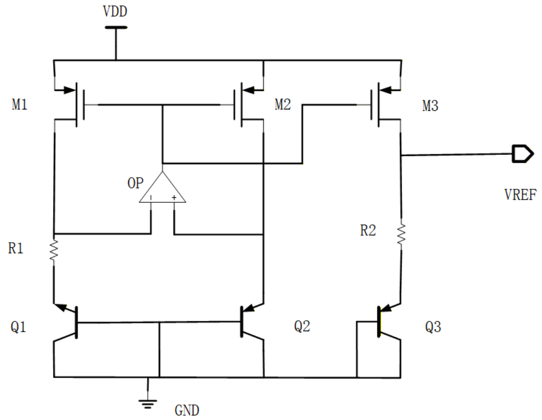

Figure.1. Classical Bandgap Reference(Picture credit : Original)

3. Compensation by resistors

Taking advantage of temperature characteristic of resistance, Shao et al. [4] repalced traditional resistors with polycrystalline silicon resistors with larger second-order terms under the BCD process. This improvement succeeded in more precise second-order compensation. Besides this, the output voltage was further refined to reduce the temperature drift due to process deviations by combining parallel laser welding with small resistors. Meanwhile, replacing the conventional gate-input OPAMP (4.2 ppm/℃ at 5V) with a back-gate input OPAMP (2.4 ppm/℃ at 5V) not only decreased the working pressure, but also resulted in a lower temperature drift coefficient for the circuit under identical operating conditions. Combining polycrystalline silicon resistors with laser filaments, this reference has increased temperature stability and tunability. But polycrystalline silicon resistors mean complex circuit parameter debugging, while fuses rely on laser trimming technology in practical applications. Compared with the following one, this BGR takes a high cost and low production efficiency.

Zhao's invention [5] used resistors to compensate. The author adopted a folded cascode structure in OPAPM, achieving high stability by cascode current source. In the core of BGR, making use of the virtual short characteristic of OPAMP, he led two resistors to respectively achieve a linear relationship with temperature in terms of positive-temperature-coefficient current and voltage, then adjusted the resistance ratio to realize compensation. Beside this, he designed a high-order compensation circuir as figure 2 desmonstrates. After copying the reference voltage through the clamp effect of the amplifier, the voltage on the resistor is nonlinearly dependent on temperature by linearly adding. Then the reference voltage provided by the core circuit and the voltage generated by the high-order compensation circuit weighted and superimposed to output the final result. Their stimulation detected the temperature coefficient (TC) under the FF process angle is 14.00 ppm/°C, under the SS process angle is 18.8 ppm/°C, and under the TT process angle is 9.66 ppm/°C. It indicates that this BGR has higher process portability in comparision with the one in [4]. But the TC is not small enough that this circuit’s compensation is not adequate actually Subsequent studies could combine the advantages of both to develop a BGR with stable and low temperature coefficients under different processing angles.

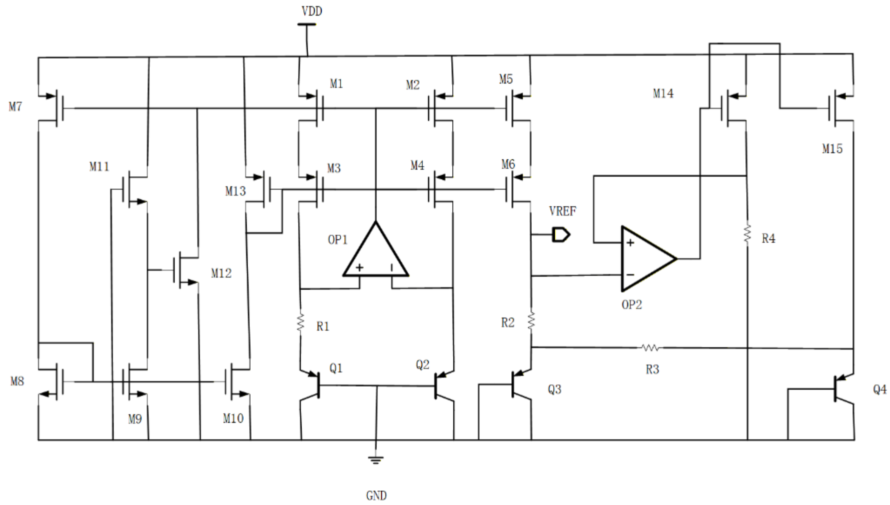

Figure.2. Case of different temperature characteristics resistors compensation circuit structure [5]

4. Automatic compensation

However, the method of compensating by resistors' temperature characteristics to lower temperature coefficients might generate leakage current,

$$I_{leakage} = \mu_n C_{ox}\left(\frac{W}{L}\right)(m-1)V_T^2 \exp\left(-\frac{V_{TH}}{m\,V_T}\right) \times \left[1 - \exp\left(-\frac{V_{DS}}{V_T}\right)\right] \quad (1)$$

effecting the output. To matigate the influence, Chi et al.[6] proposed a BGR combined with a switched-capacitor network. This circuit employs a voltage-dividing switched-capacitor to sample and generate an appropriate CTAT voltage coefficient, effectively mitigating the impact of leakage current on the temperature drift accuracy. Additionally, they integrated advanced compensation techniques, such as low-leakage buffers, into the process of sampling, avoiding the interference from the temperature-dependent voltage variations of the switched-capacitor on the CTAT. Another series-parallel switched-capacitor network is also used to sample and generate the PTAT coefficient. In contrast to the conventional approach of compensation, capacitor network requires fewer components and less area of chips. It also indicates the higher requirement of the accuracy of components in the circuit. After assembling the low-leakage buffer, the TC can reach 8 ppm/°C over the temperature range from -40°C to 120°C, satisfying wide temperature range and low temperature coefficient.

Later, this team presented a sub-microwatt auto-calibration BGR [7], filling the gap in the calibration of process deviations compared to the model they proposed previously [6]. He pointed out that saturation current (IS) deviation introduces a PTAT-type error, forward emission coefficient (ηF) deviation introduces a CTAT-type error, and common-emitter current gain (βF) deviation introduces a quasi-PTAT-type error. Together, these three factors result in considerable error even after conventional single-point adjustment, which is not only inefficient but also powerless in dealing with ηF and βF deviation. The digital-assisted auto-calibration loop, using the relationship between IS, ηF and βF, eliminates errors by adjusting the PTAT and CTAT coefficients Δm and Δn. The designed circuit will start the calibration engine, automatically adjusting the coefficients after reading the I_{PTAT} and I_{CTAT} generated by BGR. The 1σ error decreased from ±0.53% to ±0.12% with adjustment. But this technique does not become a mainstream solution due to the complexity of circuits.

There is also a technology of automatic zero setting developed by Yu[8], focusing on offseting voltage cancellation of OPAMP to reduce the deviation of the reference voltage. The work of OPAMP is divided into two stages by two clock signals. At the first stage, the transistor that stores the OPAMP offset voltage is turned on. Then after the clock signal conversion it turned into the second stage. During this period, another transistor turns on while the original one turns off. They generate the voltage and current that offset cancellating component respectively when the input voltage is pressed on. TC decreases by several times after offset cancellation. But it is to be noted that the charge on the capacitor will leak, thereby affecting the effectiveness of the offset cancellation. It means that TC of the circuit will increase after long time working and the performance of BGR will degrade.

Regardless of the auto techniques of capacitive adjusting, digital calibration, or OPAMP zero setting, they are all adding automatic compensation on the basis of the existing compensation structure with good performance. This makes these BGRs both precise by multiple compensations and featuring extremely high adaptability. But these structures are quite limited in practical for too large lay area and too much time to launch than the conventional ones.

5. Compensation by transistor

It is also a common way to provide curvature correction compensation for the wide temperature range by the exponential characteristic of transistors operating in the sub-threshold region. Proposed by Qi et al. [9], negative feedback loop could take the place of OPAMP in the core circuit of BGR to reduce the influence brought by OPAMP. At the same time, they take advantage of the negative temperature characteristic of the transistor and the characteristic of MOS transistor operatng in the linear region, build an current mirror to ensure that the current of the MOS transistor is always less than the mirrored current. Thereby, the MOS transistor will work in the linear region and its current will be linear with its drain-source voltage. In low temperature area, the current into the MOS transistor is not large enough to open the compensation circuit. As the temperature climbs up, the diodes in the compensation circuit gradually conduct, generating a compensation current. TC with compensation is about 3.83ppm/℃~4.08ppm/℃.

Ye et al. [10] also presented a method that use metal oxide semiconductor (MOS) transistors to replace metal oxide semiconductor field-effect (MOSFET) transistors. This not only reverses the capacity of transistors to achieve high power supply rejection ratio through zero TC characteristic, but also avoids cost waste caused by extra adjustment of the temperature reduction. In the core of BGR, the authors used self-biased cascode current mirror to connect the mirror current of the PTAT to the curvature compensation circuit. As the temperature goes high, NMOS transistor will work in the sub-threshold region, generating current to reduce mismatch, while PMOS transistor injects compensating current at low temperatures. Eventually, the simulation demonstrated that the error of the reference voltage is controlled within 0.7% under different processing angles, and TC is 5.5ppm/℃ under FF processing angle.

All of these two BGRs give up traditional OPAMP, but to realize voltage clamping by MOS transistor and current mirror. They have strong production compatibility due to the optimization of circuit structure. However, both circuits require transistors to work in specific area, components to match well and temperature suitable. In the extreme condition of temperature, the stability of MOS transistor decreases thus TC increases.

6. Piecewise compensation

Last but not least, piecewise compensation is a critical way to lower TC. It uses different methods in different temperature ranges that these methods could fully exert their capabilities in the corresponding periods. This not only brings out the performance advantages of each method but also expands the working temperature range.

As demonstrated in Figure 3, Wang et al. [11] divided the first-order TC compensation circuit, which was an inverted parabola into ascending zone, stable zone, and descending zone three regions. In ascending zone, the positive TC of BGR is greater than the negative one, thus the circuit compensates negative TC current I_{CTAT}, in descending zone the opposite operation will be carried out while nothing will be done in stable zone. The key of the compensation circuit is to determine the critical point, dividing different areas for different operations. The core of the design is to compare the voltage across two different resistors operated by the mirror current I_{PTAT} with preset voltage respectively through two comparators. Corresponding compensation of low or high temperature will add into the core when the comparator meets requirements. This design is featuring of simple circuit and low power consumption. But robustness of process is poor as setting the reference point and compensation current is done manually. TC under TT processing angle is 1.141ppm/℃, meaning a relatively high-precision BGR with low cost.

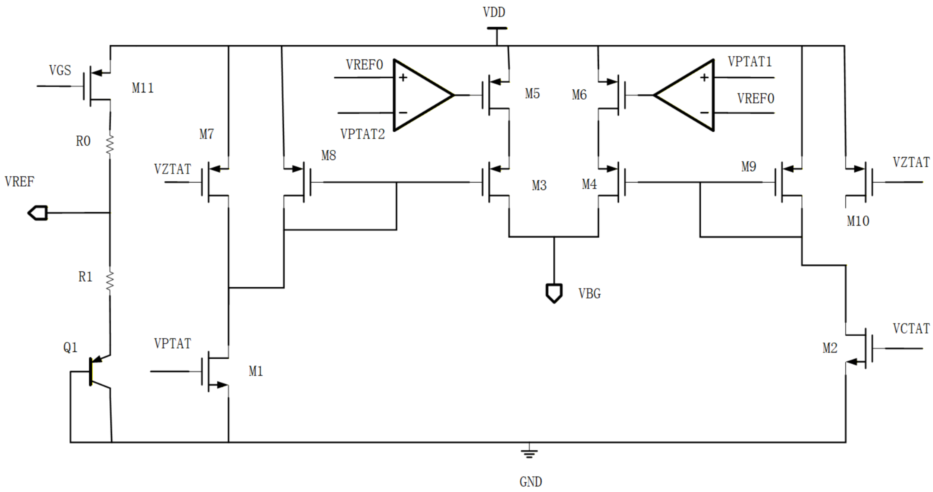

Figure.3. Piecewise Compensation Circuit of Wang [11]

According to An and Wu [12], piecewise compensation could be connected with high-order compensation. In comparision with the previous one [11], their setting of the segment points is optimized that it is unnecessary to set the reference threshold manually. Taking intrinsic voltage as the critical points, compensation will be trigged automatically by the variation of node voltage. The authors used Banba non-amplifier circuit structure in the core of BGR, and cascoded current mirror to replace the OPAMP clamping function. This procedure has already carried out first-order compensation and avoided offset errors caused by OPAMP. To the compensation circuit, they used the MOS transistors in the sub-threshold region to do high-order nonlinear compensation. And piecewise compensation is emphasized in the falling region. The current mirror will generate extra current compensation to counteract the extreme decline of V_{BE} in high temperature, thereby the BGR will not lose its perfermance in a considerable high temperature environment. The practical samples' TC reaches 7.2ppm/℃ range from -40℃ to 160℃, breaking the traditional upper limit of 125℃. It satisfied both the requirement of high precision and wide temperature range, but has an excessive power consumption, which could be optimized later.

Gu developed an advanced BGR with multi-segment and fine compensation [13]. After dividing the high and low temperature region into multiple subintervals, the circuit generates multiple first and second compensation currents separately in the two large temperature regions, then it activates more compensation current paths in the sub-intervals with higher or lower temperatures. Each compensation current exhibits a piecewise-linear characteristic and different thresholds correspond to different slopes. Then they superimposed to form a high-order-like compensation current to deal with the curvature error precisely in different temperature regions. The difference value of I_{CTAT} and I_{PTAT} forms the different slopes of each threshold. Therefore, there is no requirement for external biasing circuits like CMOS transistors. Not only does it refine the circuit but also enhanced its stability. It is worth noting that the design ensures that the injection current is much larger than the leakage current, preventing the correction failure and accuracy decline that may occur due to leakage current in the traditional process. But the circuit structure might be complex due to the multiple usage of current mirror in compensation circuits while the cost of designing process parameters such as the ratio of I_{CTAT} and I_{PTAT} and their optimization. In practical applications, some branch compensation currents could be deleted to optimize the circuit according to the actual working range of chips.

Compensation can be achieved by two separate and distinct circuits at both low and high temperatures. This method is presented by Guo [14]. Similar to Wang et al. [11], in low temperatures he used mirror current I_{PTAT} which decreased as the temperature increased as the compensation currents. He also pointed out that there was a flaw of large variation of mirror current in high temperature, thus another group of control structures should be added into the circuit besides conventional MOSFET control structures. The new structures control BJT transistors to gradually reduce current after reaching appropriate temperature point. But this leads to too complex circuits for integration. Not like traditional cascode current mirror, it is dynamic biased by the drain voltage as the figure 4 showed, broadening the swing range of the output voltage. As a result, the current mirror will keep excellent current replication accuracy within a wider output voltage range, further improving the replication accuracy and reducing the temperature drift caused by current mirror mismatch. The actual samples proved that this BGR could work range from -80℃ to 120℃, demonstrating the capability to work in extreme low temperature, while TC droped from $9.455ppm$/℃ to $1.1148p\ pm/$℃ after piecewise compensating. Although the TC is not small enough in extreme low temperatures, but this BGR further lowered the temperature limit, which represents innovation.

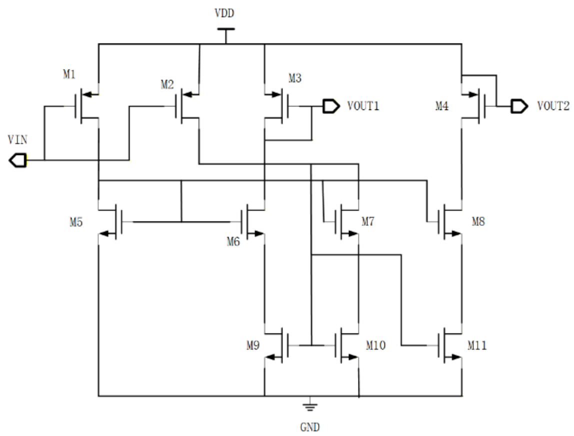

Figure.4. Two separate and distinct circuits to compensate in low and high temperatures [14]

For practical considerations, using a BGR designed for ultra-high-temperature operation is expensive and unnecessary. But the circuit can easily overheat to extremely high temperatures during operation. To protect the components and maintain normal output, He [5] presented a high-precision BGR with an over-temperature protection function, which would automatically disconnect the circuit when the temperature rises to a certain level. Based on the fundamental characteristics of remaining unchanged in V_{BE}, over-temperature protection section compares with the reference current I_{REF} through the V-I converter. It does not use a temperature sensor to avoid its effect on temperature drift. To ensure high precision, this circuit gives up extra independent compensation circuit which might interplay with over-temperature protection circuit [15]. Moreover, he used fuse resistors to ensure that new compensation currents would be generated when the process deviated from the standard. Eventually, TC of the BGR reaches 5.5ppm/℃. The core of BGR will stop working as soon as the temperature goes over 120℃, and will not start again untill the temperature is below 100℃. Innovatively employing the method of temperature over-limit blocking, this BGR, which directionally adapted chips that do not require high-temperature operation, not only ensures its low TC but also prevents chips from damage caused by high temperature.

7. Conclusion

Overall, BGR has evolved from the classic structure into various curvature compensation optimization and has an enhancement of temperature range. The common curvature compensation circuit takes advantage of temperature characteristics of resistors, charge storage capability of capacitors and the subthreshold operation characteristics of transistors. Piecewise compensation not only improves the fitness of each stage of the compensation curve but also extends the operating temperature range, which is particularly significant under extreme high temperature conditions.

Presently, BGR is developed in the direction of high precision, high robustness, low power consumption and wide operating temperature range. It provides a more stable reference voltage for precise circuits and lays the foundation for the development of high-performance chips. This plays a critical role in the stimulation of industries which have high standards for chips, such as automotive manufacturing, electronics, aerospace, and industrial control.

To be noticed, there is still temperature drift fluctuation when process and temperature vary jointly. Deeper studies to the synergic relationship of them should receive more attention in the future. Meanwhile, it is also a breakthrough to design more novel curvature-optimized circuits that can automatically generate compensation, which will reduce the cost of multiple simulation and debugging. New temperature compensation, innovative circuit structure, and deep integration with advanced techniques are expected to drive bandgap reference toward development with higher precision, wider application ranges, and stronger robustness.

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