A Design With High Order Compensation and low Temperature Drift Bandgap Reference Voltage Source

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Abstract. Based on the analysis of the conventional bandgap reference circuitry and the current IC of reference voltage source in the design of low voltage low power consumption and high power supply rejection ratio, a bandgap voltage reference with startup circuit and current compensation circuit is presented. It has a low temperature coefficient (<20ppm/℃), a temperature coefficient of 9.3ppm/℃ in the temperature range from -50℃ to 125℃, and a PSRR of -64dB at low frequency, which meets the requirements of bandgap reference for low voltage, low power and high PSRR.

1 Introduction

The voltage reference having little relation with temperature has been proven essential in many analog circuits, and it has a significant effect on the power and performance of the entire circuit, such as the voltage gain and noise of the operational amplifier. There are many kinds of reference sources, among which the bandgap reference voltage has been widely used due to its low power consumption, high power supply rejection ratio, and stability. In recent years, with the development of process technology, the structure of analog integrated circuit systems has become more complicated, and system-on-chip technology has been widely concerned by academics and industry, which poses higher requirements on the voltage, power consumption, accuracy and speed of basic modules in analog integrated circuits. At present, some scholars at home and abroad have begun to improve the conventional bandgap reference source. Most of them focus on improving the performance of the operational amplifier or compensating the absolute value of the reference, on the basis of the conventional bandgap reference structure [1].

In this paper, a novel voltage reference circuit with a relatively new structure is designed, based on the analysis of the conventional bandgap reference structure. The circuit has a start-up circuit and a high-order temperature compensation circuit that directly compensates the temperature of the reference output with a temperature variation of no more than 20ppm/℃.

2 Circuit Structure

2.1 Conventional Bandgap Reference Circuit

The working principle of bandgap reference is to generate a reference voltage by means of the characteristic that the bandgap voltage of the semiconductor material silicon is independent of the Supply Voltage and temperature. The mathematical model for generating the reference voltage is to find two variables \( V_1 \) and \( V_2 \) with opposite temperature coefficients, and make them have two appropriate coefficients a and b, so that \( a\frac{\partial V_1}{\partial T} + b\frac{\partial V_2}{\partial T} = 0 \). Studies have shown that the base-emitter voltage \( V_{be} \) of a triode has a negative temperature coefficient; in addition, it was found in 1964 that the...
base-emitter voltage difference $\Delta V_{be}$ has positive temperature coefficient when the two triodes operate at unequal current densities.

It may be derived as:

\[
V_{be1} = V_T \ln \left( \frac{I_1}{I_{ss1}} \right)
\]

\[
V_{be2} = V_T \ln \left( \frac{I_2}{I_{ss2}} \right)
\]

\[
\Delta V_{be} = V_{be1} - V_{be2} = V_T \ln \left( \frac{I_1}{I_2} \frac{I_{ss2}}{I_{ss1}} \right)
\]

According to the condition that the collector currents of two triodes are known to be the same, i.e. $I_1 = I_2$, the above formula may be simplified as:

\[
\Delta V_{be} = V_{be1} - V_{be2} = V_T \ln \left( \frac{I_{ss2}}{I_{ss1}} \right)
\]

If $N$ is the ratio of the emitter areas of transistors $Q_2$ and $Q_1$, then $I_{ss2} = N \cdot I_{ss1}$, the above formula may be simplified as:

\[
\Delta V_{be} = V_{be1} - V_{be2} = V_T \ln (N)
\]

The thermal voltage is known as $V_T = kT/q$, where $k$ is the Boltzmann constant ($1.38 \times 10^{-23} \text{J/K}$), $T$ is the absolute temperature, and $q$ is the electron charge ($1.6 \times 10^{-19} \text{C}$). Then, the following is derived:

\[
\frac{\partial \Delta V_{be}}{\partial T} = \frac{(k/q) \ln N}{T}
\]

Note that, $(k/q) \ln N$ is a constant independent of temperature.

Therefore, let $V_{ref} = aV_{be} + b\Delta V_{be}$, then $\frac{\partial V_{be}}{\partial T} \approx -1.5 \text{mV/}^\circ\text{K}$, $\frac{\partial V_T}{\partial T} \approx +0.087 \text{mV/}^\circ\text{K}$ at room temperature, so let $a=1$, so that $(\ln N)(0.087 \text{mV/}^\circ\text{K}) = 1.5 \mbox{ mV/}^\circ\text{K}$, that means, $\ln N \approx 17.2$, then the temperature coefficient of $V_{ref}$ may be zero \([2]\), and the zero temperature coefficient reference is:

\[
V_{ref} \approx V_{be} + 17.2V_T \approx 1.25V
\]

The circuit structure of the conventional bandgap reference voltage source is shown in Figure 1:

![Figure 1 Conventional Bandgap Reference Circuit](image)

In the bandgap reference voltage circuit shown in Figure 1, the bipolar transistor is normally connected, $R_1 = R_2$, $V_x = V_{be1}$, $V_y = V_{be2} + I_3 R_3$, and the operational amplifier make the circuit be in a deep negative feedback state, so $V_y = V_x$, thus the current flowing through resistor $R_3$ is:

\[
I_3 = \frac{V_{be1} - V_{be2}}{R_3}
\]

The output voltage reference is:

\[
V_{ref} = V_{be2} + I_3 (R_3 + R_2) = \frac{V_{be2}}{R_3} \cdot \frac{R_3 + R_2}{R_3} \cdot V_T \ln N
\]

Set the values of $N$ and $R_3$ as well as $R_2$. When $\ln N \cdot \frac{R_3 + R_2}{R_3} \approx 17.2$, the reference voltage $V_{ref}$ independent of temperature may be obtained.
The accuracy of the conventional bandgap reference voltage is affected by many factors: (1) the
temperature coefficient of the $V_{be}$ of the triode is a higher order function of the temperature $T$, and
the temperature coefficient $(k/q)^*\ln N$ of the $\Delta V_{be}$ is only a constant term. The temperature compensation
by superimposing the above two voltages is only a first-order approximation compensation, so the
high-order term in the temperature coefficient of $V_{be}$ is not eliminated, so the obtained reference
voltage is not quite accurate, and is still the high-order function of the temperature $T$. (2) In the actual
circuit, there is an offset voltage $V_{OS}$ at the input end of the operational amplifier. If the effect of the
offset voltage is considered, the output reference voltage should be modified to:

$$V_{ref} = V_{be2} + \frac{R3+R2}{R3}(V_T\ln N - V_{OS})$$

Since the $V_{OS}$ input to the operational amplifier may be as high as 20mV in a CMOS process, $V_{OS}$
has become one of the important factors limiting the accuracy of the output reference voltage. Under
the effect of the above factors, the accuracy of the simple CMOS bandgap reference voltage is
generally around 40ppm/°C [3].

2.2 Improved Bandgap Reference Voltage Source Circuit

The high-performance bandgap reference voltage source circuit designed in this paper adopts a
simple circuit structure consisting of a constant current source, a triode, a MOS transistor, and a
resistor. As the operational amplifier is omitted, thereby avoiding the output reference voltage error
due to the differential input offset. Another feedback branch consisting of resistors $R_1$, $R_5$ and $R_6$ as
well as transistor $Q_4$ is added to compensate for the effect of temperature-dependent high-order
components in $V_{be}$, thus the relatively accurate bandgap reference voltage is obtained. The circuit
structure is shown in Figure 2:

![Figure 2 Improved Bandgap Reference Circuit](image)

In the figure, the transistor $Q_1$ and the transistor $Q_2$ detect the bandgap reference voltage, and form
a negative feedback loop with the MOS transistors $M_7$ and $M_8$ to ensure the band gap is stable. The
emitter area of the transistor $Q_2$ is N times that of the transistor $Q_1$. The constant current sources $I_0$, $I_1$
and $I_2$ form a current mirror structure to ensure that the current density flowing through the transistor
$Q_1$ is N times that of the transistor $Q_2$ when the circuit is stable. $V_{be1}$ is the voltage difference between
the base and emitter of $Q_1$, $V_{be2}$ is the voltage difference between the base and emitter of $Q_2$, $V_{be3}$ is
the voltage difference between the base and emitter of Q3. The following may be derived:

$$V_{be1} - V_{be2} - I_6R_6 = I_3R_3$$

And then derived:
\[ \Delta V_{be1,2} = V_T \ln N = I_3 R_3 - I_6 R_6 \]

\[ I_3 = \frac{1}{R_3} \left( \frac{kT}{q} \ln N - I_6 R_6 \right) \]

The transistor M8 of the common source structure, as the gain in the above negative feedback loop, provides a relatively large gain for the entire circuit, ensuring that the feedback loop is in a deep negative feedback state, so that the base and emitter voltage \( V_{be3} \) of the transistor Q3 having a negative temperature coefficient is superimposed with \( \Delta V_{be1,2} \) having a positive temperature coefficient, resulting in a temperature-independent accurate bandgap reference voltage.

\[ V_{ref} = V_{be3} + I_3*(R_1 + R_2 + R_3 + R_4) \]

Substitute \( I_3 = \frac{1}{R_3} \left( \frac{kT}{q} \ln N - I_6 R_6 \right) \) in the above formula and we obtain:

\[ V_{ref} = V_{be3} + \frac{R_1 + R_2 + R_3 + R_4}{R_3} \left( \frac{kT}{q} \ln N - I_6 R_6 \right) \]

Where, the current \( I_6 \) flowing through the resistor \( R_6 \) is a constant current source, so \( I_3 R_6 \) is a constant. When the temperature rises, the positive temperature current \( I_3 \) increase, which will make the reference voltage \( V_{ref} \) increase. At the same time, the base and emitter voltage \( V_{be4} \) of the transistor Q4 will increase, causing the transistor Q4 to be connected, and the current flowing through the resistor \( R_5 \) is no longer 0, so the following may be derived:

\[ \Delta V_{be1,2} = I_3 R_3 - (I_5 + I_6) R_6 \]

From the above formula, it can be seen that when the temperature increase is large, the resistors \( R_5, R_6 \) and the transistor Q4 will introduce a negative feedback loop of the positive temperature coefficient current and start working, thereby introducing a high-order component opposite to \( V_{be3} \) in the positive temperature coefficient current, thus the temperature coefficient of the bandgap reference voltage is reduced \(^4\).

In summary, as long as appropriate \( R_1, R_2, R_3, R_4, R_5, R_6 \) and \( N \) are selected, a temperature-independent \( V_{ref} \) can be obtained.

The startup circuit and the bias circuit are introduced as shown in Figure 3. When the circuit is started, \( M_1 \) is connected, \( M_3 \) and \( M_4 \) are cut off, X point potential is raised, \( M_5 \) is connected, Z point potential is lowered, \( M_2 \) and \( M_6 \) are connected, and Y point potential is raised, so \( M_3 \) and \( M_4 \) are connected, the X point potential slowly drops to less than the turn-on voltage of \( M_5 \), \( M_5 \) is cut off, and the startup of the entire circuit is completed.

\[ \text{Figure 3 Circuit Diagram of Bandgap Reference Voltage Source designed in this Paper} \]
3 Circuit Simulation and Results

The reference source simulation conditions are set as: temperature range -55~125°C; Supply Voltage range 0~5V. The simulation was carried out using the ST3000 process library of Shanghua. The results are shown in Figure. 4 and Figure. 5.

![Figure 4](image)

**Figure 4** Relationship between Reference Voltage and Temperature

From the simulation results in Figure 4, it can be seen when the temperature changes from -55°C to 125 °C, the output bandgap reference voltage reaches the maximum when it is near 25°C, the maximum voltage is 1.205V, and the minimum voltage is 1.201V, $\Delta V_{ref} = 4mV$.

\[
T CF = \frac{\Delta V_{ref} * 10^6}{T \cdot V_{ref}} = \frac{0.004}{180+1.203} * 10^6
\]

=18.5 ppm/°C

![Figure 5](image)

**Figure 5** Relationship between Reference Voltage and Supply Voltage

As seen from Figure 5, when the supply voltage varies between 0V and 5V, and when the supply voltage is 0.4V or above, the output bandgap reference voltage remains stable at 1.2V, and there is almost no change, which indicates that the reference source can work normally when it is above 0.4V. The circuit has a wide operating voltage range and is suitable for low voltage and low power-consumption systems.
Figure 6 Reference Voltage PSRR

Figure 6 shows the power supply rejection ratio simulation results for this circuit. It can be seen that PSRR is about -64dB and has a good power supply fluctuation rejection.

Figure 7 Actual Layout Results of Circuit

The actual layout result of the whole circuit is shown in Figure 7. The layout area (excluding the pad) realized by CSMC 0.5μm bcd process is 675*482μm. The bandgap reference voltage source circuit designed in this paper has been applied in the actual circuit.

Table 1 Measured Bandgap Reference

| Measured Bandgap Reference | TEM | -55 | -15 | 25  | 65  | 105 | 125 |
|----------------------------|-----|-----|-----|-----|-----|-----|-----|
| VREF                       | 1.1929 | 1.1934 | 1.1949 | 1.1939 | 1.1931 | 1.193 |

From Table1, it can be seen that the measured bandgap reference voltage is very close to the simulation result and meets the expected target requirements.

4 Conclusion

CMOS bandgap reference source is widely applied in integrated circuits because of their comprehensive advantages. It can satisfy different reference voltages required by different environmental requirements, and can maintain a relatively low temperature drift coefficient and stable voltage. Therefore, it is very significant to study the CMOS bandgap reference voltage with higher accuracy and lower temperature drift coefficient [5].

A high performance low temperature drift coefficient CMOS bandgap reference voltage source is designed in the paper when the conventional bandgap reference voltage source design is discussed. The simulation and measured results show that this circuit meets the design requirements, and has the
characteristics like high accuracy, low temperature drift coefficient, and high power supply rejection ratio, showing a wide application prospect.

References

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