ICETIS 2021
Journal of Physics: Conference Series 1827 (2021) 012024 doi:10.1088/1742-6596/1827/1/012024

Design of a new voltage reference source

Xiaojiang Li, Qunfeng Huang
Zhonghuan Information College Tianjin University of Technology, Tianjin, China
*Corresponding author Email: tg778899@xzcstudio.com

ABSTRACT: Current reference is a very important module in analog circuits. The main purpose of this design is to provide a stable reference voltage for a switch magnetism-sensing circuit. Because of the inherent characteristics of the circuit, the reference voltage is set to 3.3V. In this paper, the reference voltage source is designed to have a wide input range, a stable output and a good temperature characteristic. In this paper, the simulation results of the reference voltage and the complete design layout are described, and a current reference is achieved, which is independent of process, voltage and temperature, with little area increases only. The simulation results based on a 4μm 25 V bipolar process verify the correctness of the theoretical analysis and the feasibility of the proposed methods.

1. INTRODUCTION
In recent years, the techniques around analog ICs have undergone big change. This places high demands on the voltage, power consumption, precision and response speed in an ASIC design. It is becoming increasingly difficult for the circuit structure of a traditional reference voltage source to meet the design requirement. At present, there are three main types of design for a reference voltage source: the buried Zener diode, the Extra Implanted Field-Effect Transistor (XFET), and the bandgap reference voltage source. The buried Zener diode and the XFET reference voltage sources have high precision and good stability. However, the buried Zener diode has a high power supply voltage and high power consumption, and XFET reference voltage source manufacturing is complex and is not compatible with the bipolar process. The traditional bandgap reference voltage source can be compatible with the bipolar process, and a circuit with high precision and low temperature coefficient. By adjusting the parameters of the emitter area and resistance, an output voltage with zero temperature coefficient can be achieved. However, the voltage is fixed at 1.25 V and cannot meet the switch magnetism-sensing circuit’s reference voltage circuit requirements; at the same time, the reference voltage will be affected by the op-amp input offset voltage.

On the basis of this analysis, we propose a novel reference voltage source structure. Our circuit has a small layout area, low temperature_coefficient and stable performance; it does not require changes to the original process (i.e. the original circuit can be smoothly upgraded).

2. ANALYSIS OF THE TRADITIONAL REFERENCE VOLTAGE SOURCE
2.1 Circuit analysis
Figure 1 shows a traditional reference voltage source circuit. The circuit is composed of differential amplifiers, PMOS M1 and M2, bipolar transistors Q1 and Q2, and resistors R1_R3. From Figure 1, we can obtain the equation $V_{\text{ref_conventional}} = V_{\text{be1}} + \frac{(R_2 V_T \ln n)}{R_3}$. The reference voltage with zero temperature coefficient is calculated by taking the derivative with respect to temperature; $V_{\text{ref_conventional}} = V_{\text{be1}} + 17.2$...
\( V_T \approx 1.25 \text{ V}, \ \partial V_{be}/\partial T \approx -1.5 \text{ mV/K}, \ \partial V_T/\partial T \approx 0.087 \text{ mV/K}. \) It can be seen that the traditional reference circuit \( V_{\text{ref, conventional}} \) is locked in at 1.25 V.

2.2 Defect analysis

The traditional reference voltage source circuit contains an operational amplifier, and its symmetry is not good. Therefore, the operational amplifier is affected by the input offset voltage, resulting in an error in the reference voltage. The input offset voltage can be quantified as \( V_{OS} \), and the new equations \( V_{be1} \pm V_{OS} \approx V_{be2} + R_3 I_2 \) and \( V_{\text{ref, conventional}} = V_{be2} + (R_3 + R_2) I_2 \) can be derived. So, \( V_{\text{ref, conventional}} = V_{be2} + (1 + R_2/R_3) (V_T \ln n \pm V_{OS}) \). As can be seen from the equation, \( V_{OS} \) is amplified by a factor of \( (1 + R_2/R_3) \). Thus, it is inevitable that an error exists in \( V_{\text{ref, conventional}} \). More importantly, \( V_{OS} \) changes with temperature, which increases the temperature coefficient of the conventional reference voltage source.

The previous analysis shows that the reference voltage \( V_{\text{ref, conventional}} \) is locked in at 1.25 V. Therefore, it cannot satisfy the reference voltage demand of the switch magnetism-sensing circuit.

3. A NEW DESIGN FOR REFERENCE VOLTAGE SOURCE

We can get the following equation from Figure 2: \( V_{be1} = V_{be2} + I_o R_e \). \( Q_1 \) and \( Q_2 \) have the same
parameters; \( I_o \) is the output reference current. On the basis of the base-emitter voltage formula of the triode, \( V_{be} = V_T \ln(I_c/I_s) \), it is easy to derive Equation 1:

\[
I_o = \frac{V_T \ln \frac{I_{c1}}{I_{s1}} - V_T \ln \frac{I_{c2}}{I_{s2}}}{R_e} = \frac{V_T \ln \frac{I_{c1}}{I_{s1}} \times \frac{I_{c2}}{R_e}}{R_e}
\]

(1)

where \( V_T \) is thermal voltage \((V_T = kT/q, \text{ where } k = 1.38 \times 10^{-23} \text{ J is the Boltzmann constant, } q \text{ is the electron charge and } T \text{ is absolute temperature}); I_c \) is the collector current and \( I_s \) is the inverse saturation current. The parameters of triodes \( Q_1 \) and \( Q_2 \) are the same \((I_{s1} = I_{s2})\). According to Figure 2, \( I_{c1} \) of collector current can be replaced by \( I_{ref} \) if we overlook the function of the base current. Similarly, \( I_{c2} \) is replaced by \( I_o \) and we know that:

\[
I_o = \frac{V_T \text{Lambert}W(R_e I_{ref})}{R_e}
\]

(2)

\( I_o \) is the required current for our method and we can see that \( I_o \) is constant. Therefore a new reference voltage source circuit is designed based on this source circuit; the circuit is composed of a reference voltage source circuit, start-up circuit, isolating circuit, feedback loop and switch magnetism-sensing circuit, as shown in Figure 3. The switch magnetism-sensing circuit is not our focus, so we will not describe it further in this paper.

### 3.1 Zero temperature coefficient reference voltage source circuit

The reference voltage source circuit is composed of \( Q_1, Q_2, T_4, T_5, R_3, R_e, R_{ref}, R_6 \) and \( R_8 \). From Figure 3 we know that the voltage at point A is:

\[
I_o R_3 + V_{be-T5} = I_{ref} R_{ref} + V_{be-Q1}
\]

(3)

where \( V_{be-T5} \) and \( V_{be-Q1} \) approximately equal \( V_{be(on)} \). So:

\[
I_o = \frac{R_{ref}}{R_3} I_{ref}
\]

(4)

Substituting Equation 2 into Equation 4, we can obtain:

\[
\frac{V_T \text{Lambert}W(R_e I_{ref})}{R_e} = \frac{R_{ref}}{R_3} I_{ref}
\]

(5)

From Figure 3 we can get that \( V_A = I_{ref} R_{ref} + V_{be1} \), \( V_B = V_A + V_{be4} \). And as \( V_{ref} = V_{in}(R_6 + R_8)/R_8 \), \( V_{ref} \) can be shown as

\[
V_{ref} = \frac{R_3 V_T \ln \frac{R_6}{R_{ref}} + V_{be1} R_e + V_{be4} R_e}{R_e R_8 (R_6 + R_8)}
\]

(6)

The ratio of each resistance and zero temperature coefficient voltage of \( V_{ref} \) can be obtained by the derivative with respect to temperature. At the same time, the range of reference voltage is changed by adjusting the resistance of \( R_6 \) and \( R_8 \).

### 3.2 Start-up circuit

The function of the start-up circuit is to make the circuit avoid the zero state when the circuit starts, and enter the working state without disturbing normal function. The start-up circuit includes transistors \( T_1, T_2, T_3, T_9 \) and \( T_{10} \) and resistors \( R_1 \) and \( R_2 \). When the circuit is powered, the voltage at point E rises up and turns on the \( T_9, T_9 \) provides a path for the current mirror. When the current mirror composed of
T_1 and T_2 is turned on, the voltage at point C rises and T_3 turns on. The reference voltage regulator circuit (inside the red dotted box in Figure 3) starts to work.

3.3 Isolating circuit
Once the reference voltage regulator circuit is working, the voltage at point D rises and T_5 turns on. Then the voltage at point C is pulled low and T_3 turns off. The start-up circuit is separated from the reference voltage regulator circuit. The reference voltage can be set independently of the supply voltage.

4. SIMULATION
Based on the performance indexes of the relevant modules and the relative parameters of the existing commercial chips, the main technical indexes of the overall circuit and the reference voltage source circuit are determined, as shown in Table 1 and 2. The key point of the test is whether the design will affect the switch magnetism-sensing circuit, when the supply voltage varies between 4.5 and 24 V.

| Ambient temp. = 25 °C | Magnetic field | In-phase |
|-----------------------|----------------|----------|
| Supply voltage        | 4.5 - 24 V     |          |
| Output rise time      | 0.2 μs         |          |
| Output fall time      | 0.2 μs         |          |

Table 2 Performance indicators of reference voltage source.

| Supply voltage | 4.5 - 24 V |
|----------------|------------|
| Reference voltage stability | ±1% |
| Temperature coefficient | 20 ppm/°C |

In this paper, the circuit design provides a reference voltage for the switch magnetism-sensing circuit. Therefore, we first observe whether the overall circuit functions correctly.

Figure 4 Simulation results: (a) The output rise time, (b) The output fall time.

The simulation results are shown in Figure 4, and the magnetic signal is simulated with a sinusoidal
signal. When the magnetic field intensity is higher than the upper limit threshold, the circuit output will be HIGH, and when the intensity is lower than the lower limit threshold, the circuit output will be LOW. The performance index conforms to design requirements. The output rise time $t_r$ is the time interval for the response curve to increase from 10% to 90%: $T_{M0} - T_{M2} \approx (1.91809 - 1.91794) \text{ ms} = 0.05 \mu\text{s}$, as shown in Figure 4a. The result is less than 0.2 $\mu\text{s}$, which conforms to the requirements of the design. The output fall time $t_f$ is the time interval for the response curve to fall from 90% to 10%: $T_{M1} - T_{M3} \approx (1.91809 - 1.91794) \text{ ms} = 0.05 \mu\text{s}$, as shown in Figure 4b. Again, the result is less than 0.2 $\mu\text{s}$, which conforms to the requirements of the design.

Next, we need to verify whether the design will be affected by the reference voltage source circuit and the switch magnetism-sensing circuit, when the supply voltage varies from 4.5 to 24 V.

![Figure 5 Simulation results of voltage reference](image)

Figure 5 Simulation results of voltage reference: (a) Under the condition of 25°C, (b) Under the temperature changes from 0°C to 150°C.

The output voltage stability is an important basis for reference circuit performance. According to the above analysis, by substituting relevant design parameters into Equation 6, we can see that the reference voltage value is approximately 3.3 V. At a temperature of 25 °C, the simulation result for reference voltage $V_{ref}$ is shown in Figure 5a (DC scan of the reference voltage). The output voltage only changes by 87.0304 mV when the input voltage changes from 4.32 to 24 V, and the output error is 0.47%, which is far lower than 1%; thus, it meets the performance requirements.

Another important indicator of the reference source is its stability over a wide temperature range. Temperature coefficient (TC) is an important parameter in measuring the temperature change of the output voltage of a bandgap reference voltage source. The simulation result is shown in Figure 5b. The reference voltage changes 9.23102 mV when the temperature changes from 0 to 150 °C and $V_{DD} = 10$ V. The TC of the voltage reference source is 18.65 ppm/°C, which meets the design requirement.
In this paper, the design of the chip layout is completed using a BCD 4 μm 25 V bipolar process. Figure 6 shows the chip layout and the location of the reference voltage source. The layout is connected by a single layer of metal wire, with an area of 1.225692 mm² (length × width = 1,164 μm × 1,053 μm). In this chip, the layout area of the reference voltage source is 635 μm × 236 μm, and the decoupling capacitance is connected to the ground at the output end of the reference voltage. A test circuit and test environment is built for the sample.

The chip test results are shown in Table 3 and demonstrate that the simulation and experimental results have good consistency. The test results show that as the supply voltage changed from 5 to 25 V, the operating point (BOP), release point (BRP) and hysteresis (BHY) of the chip remained about the same. That is to say, the chip can work normally under a 5–25 V supply voltage.

Table 3 Chip test results.

| Ambient | Supply voltage (V) | Magnetic field (GS) | BOP (GS) | BRP (GS) | BHY (GS) |
|---------|-------------------|---------------------|----------|----------|----------|
|         | 5                 | 0 500               | 149.7    | 100.03   | 49.67    |
|         | 10                | 0 500               | 150.4    | 100.01   | 50.39    |
|         | 15                | 0 500               | 150.3    | 100.02   | 50.28    |
|         | 20                | 0 500               | 149.0    | 100.08   | 48.92    |
|         | 25                | 0 500               | 150.2    | 100.05   | 50.15    |

Compared with the traditional reference, we can see that the improved chip supports a wider supply voltage range, its layout area is smaller, and its reference voltage is higher.

5. CONCLUSION

This design provides a stable reference voltage for the switch magnetism-sensing circuit. The simulation results show that the output voltage only changes 87.0304 mV when the input voltage changes from 4.32 to 24 V, and the output error is only 0.47%. At the same time, the reference voltage changes 9.23102 mV when the temperature changes from 0 to 150 °C, and the temperature coefficient is 18.65 ppm/°C.

REFERENCE

[1] Allen, P.E. & Holberg, D.R. (2005). CMOS analog circuit design second edition (2nd ed.). Beijing: Publishing House of Electronics Industry.

[2] Bilotti, A., Monreal, G. & Vig, R. (1997). Monolithic magnetic Hall sensor using dynamic quadrature offset cancellation. Solid-State Circuits, 3(6), 829-836.

[3] Gray, P. & Meyer, R. (1993). Analysis and design of analog integrated circuits. New York: Wiley.
[4] Hastings, A. (2004). *The art of analog layout*. Beijing: Tsinghua University Press.

[5] Huang, H.Y., Wang D.G & Xu, Y. (2015). A monolithic CMOS magnetic Hall sensor with high sensitivity and linearity characteristics. *Sensors* 15(10): 27359-27373.

[6] Qin, B., Jia, C. & Chen Z.L. (2006). A 1V MNC bandgap reference with high temperature stability. *Chinese Journal of Semiconductors*, 27,2035-2038.

[7] Zeng, Y.C., Xia, J.Y & Cui, J.J. (2018). Design of a high performance CMOS bandgap voltage reference with piecewise linear compensation. *Electronic Components & Materials*, 3, 73-77.