Temperature-Independent Current Reference with Tunable Temperature Coefficient DAC

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***Abstract* - Modern automobiles increasingly support a variety of advanced features, with autonomous vehicle safety gaining heightened attention. This has created a growing demand for sensor technology that can accurately detect environmental changes. One of the critical challenges in automotive sensor technology is the need for a temperature-compensated reference. This paper focuses on designing a temperature-independent reference current source in this MPW. Conventional reference current sources are highly sensitive to environmental conditions, especially temperature fluctuations, leading to varying output values. Although several temperature-compensated reference current sources have been developed, effectively addressing the residual temperature coefficient resulting from process variations remains a challenge. To tackle this issue, we propose a circuit that compensates for residual temperature coefficients, enabling the creation of a stable, temperature-independent reference current source. This design aims to provide a reliable solution for the automotive sensor technology field, where maintaining accuracy across a range of environmental conditions is essential.**

***Keywords*—Current reference, Temperature compensation, Temperature coefficient, Tunable DAC, PVT-insensitive**

I. INTRODUCTION

As automobiles integrate more features and focus on safety increases, especially in autonomous vehicles, the demand for highly accurate sensor technology that remains reliable despite environmental changes is becoming increasingly important. While sensor accuracy is influenced by various factors, it fundamentally depends on a reference value, meaning the performance of the sensor is closely tied to the accuracy of the circuit providing this reference. These circuits include reference voltage sources, reference current sources, and reference frequency generators, with the sensor output indicating how much the input has deviated from these reference values. Despite the significant role this field plays, reference current sources have historically been more limited in circuit design options compared to reference voltage sources, which are commonly used in analog-to-digital converters (ADCs), or reference frequency generators, which serve frequency synthesizers [1]. Reference current sources, however, offer versatility in applications like current biasing and current-based DACs. Recognizing the importance of developing a reference current source that functions independently of environmental conditions, we proposed such a system. Among environmental factors, temperature fluctuations are known to particularly impact reference current sources. This is because generating current involves converting voltage into current, and the physical properties of the components used in this process (such as MOSFETs and resistors) are highly sensitive to temperature changes. Consequently, if a reference current source without temperature compensation is used in sensor applications, the output may vary with ambient temperature changes, even if the actual input remains constant. Thus, it is critical to employ a temperature-compensated reference current source.

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II. CURRENT REFERENCE

The proposed architecture is an expansion of the process, voltage and temperature (PVT) insensitive current reference proposed in [2].

A. PVT-Insensitive Current Reference

Fig. 1. shows the compensation voltage generator for current reference with process-insensitive temperature compensation [2]. This consists of a compensation voltage generator (CVG) and a current driver. The basic idea is to match the temperature coefficient (TC) of the resistance with the temperature coefficient of the compensation voltage V_{comp} to achieve a low TC.

The first-order temperature dependency of a resistor can be modeled as [3]

$$R(T) = R_0(1 + \alpha_{res}\Delta T) \quad (1)$$

where R_0 is the value of resistance at nominal temperature T_0 and α_{res} is its first order TC, which remains unaffected by process variations.

The current of M_1 and M_2 operating in the subthreshold region is as

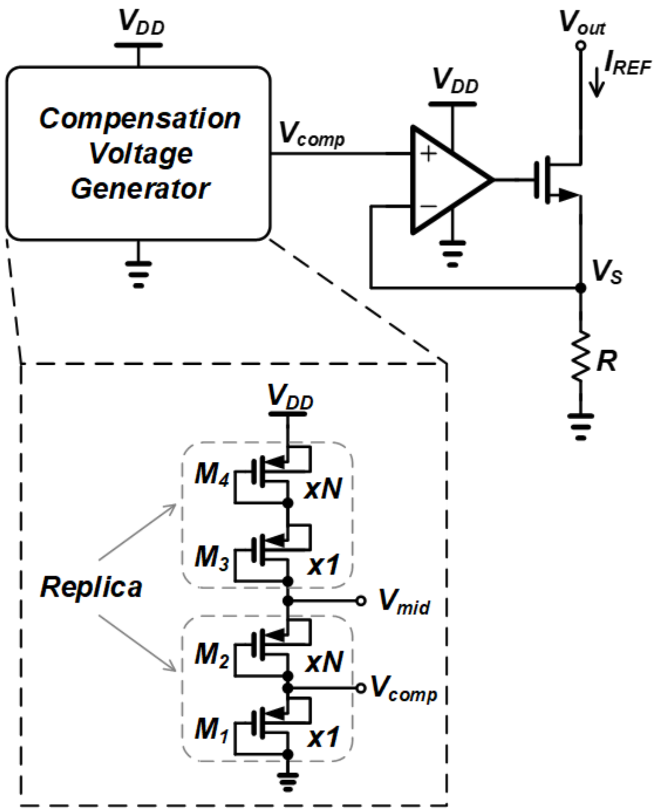


Fig. 1. PVT-insensitive current reference proposed in [2].

$$I_{M1} = \mu_p C_{OX} \frac{W}{L} {V_T}^2 \exp\left(\frac{V_{comp} - V_{TH1}}{mV_T}\right)$$

$$I_{M2} = \mu_p C_{OX} N \frac{W}{L} {V_T}^2 \exp\left(\frac{V_{mid} - V_{comp} - V_{TH2}}{mV_T}\right) \quad (2)$$

where μ_p is the mobility of carrier, C_{OX} is the gate-oxide capacitance, W and L are the channel width and length, respectively, N is the size ratio of M_1 and M_2, and V_{TH1} and V_{TH2} are the threshold voltages of M_1 and M_2, respectively, and V_T is the thermal voltage, and m is the subthreshold slope factor.

Since I_{M1} and I_{M2} are equal, V_{comp} can be expressed as follow:

$$V_{comp} = \frac{V_{mid}}{2} + \frac{mV_T \ln(N)}{2} + \frac{\Delta V_{TH}}{2}$$
$$= \frac{V_{mid}}{2} + \frac{mkT_0 \ln(N)}{2q} + \frac{\Delta V_{TH}}{2} + \frac{1}{2}\frac{mk}{q} ln(N)\Delta T$$
$$= V_{comp0} \times \left(1 + \alpha_{comp}\Delta T\right) \quad (3)$$

$$\alpha_{comp} = \frac{\frac{1}{2}\frac{mk}{q}\ln(N)}{\frac{V_{mid}}{2} + \frac{mkT_0 \ln(N)}{2q} + \frac{\Delta V_{TH}}{2}} \quad (4)$$

where $V_{comp0} = \frac{V_{mid}}{2} + \frac{mkT_0 \ln(N)}{2q} + \frac{\Delta V_{TH}}{2}$ and α_{comp} is TC of CVG. If condition $\frac{V_{mid}}{2} + \frac{\Delta V_{TH}}{2} \gg \frac{mkT_0 \ln(N)}{2q}$ is met, TC of V_{comp} can be controlled by the size ration N which is sorely independent of process variation.

Based on the above results, I_{ref} shown in fig. 1. can be expressed as

$$I_{ref} = \frac{V_{comp0}\left(1 + \alpha_{comp}\Delta T\right)}{R_0(1 + \alpha_{res}\Delta T)} = \frac{V_{comp0}}{R_0} \quad (5)$$

I_{res} remains unaffected by temperature variations on condition $\alpha_{comp} = \alpha_{res}$.

B. Proposed Current Reference

In order for the current reference from the previous section to achieve zero TC, α_{comp} and α_{res} must perfectly match. However, in practice, due to mismatches in size, threshold voltage, and subthreshold slope, α_{comp} and α_{res} may not match perfectly. Additionally, there is a dependency on the TC of the bandgap reference (BGR), which exhibits chip-to-chip variation, requiring a compensation circuit for the BGR′s temperature dependency. To address these issues and enable compensation for the BGR′s TC spread, we proposed TC-tunable current reference structure as shown in Fig. 2. This consists of a TC-tunable compensation voltage generator and a current driver.

Both the process variation of the TC for the poly resistor and the MIM capacitor are negligible; however, the resistance value of the poly resistor varies significantly with the process compared to the value of the MIM capacitance. Therefore, a switched capacitor-based resistor was used to improve the accuracy of the output current I_{ref}.

Through the same analysis as in the previous section, V_{comp} can be expressed as

$$V_{comp} = \frac{1}{2}\left(\frac{3V_{in}}{2} + \frac{mkT_0 \ln(N)}{q} + \Delta V_{TH}\right)$$
$$+ \frac{1}{2}\frac{mk}{q} ln(N)\Delta T \quad (6)$$

where V_{IN} is the input voltage of the TC-DAC, m is the subthreshold slope factor, k is the Boltzmann constant, q is the electron charge, and N represents the W/L ratio of the PMOS in the TC-DAC.

The switched capacitor resistor can be modeled as [4]

$$R_{eq} = \frac{1}{Cf_{XO}} \quad (7)$$

where C is the capacitance and f_{XO} is the switching frequency. Then I_{ref} shown in Fig. 2. can be expressed as

$$I_{ref} = V_{comp} \cdot C \cdot f_{XO} \quad (8)$$

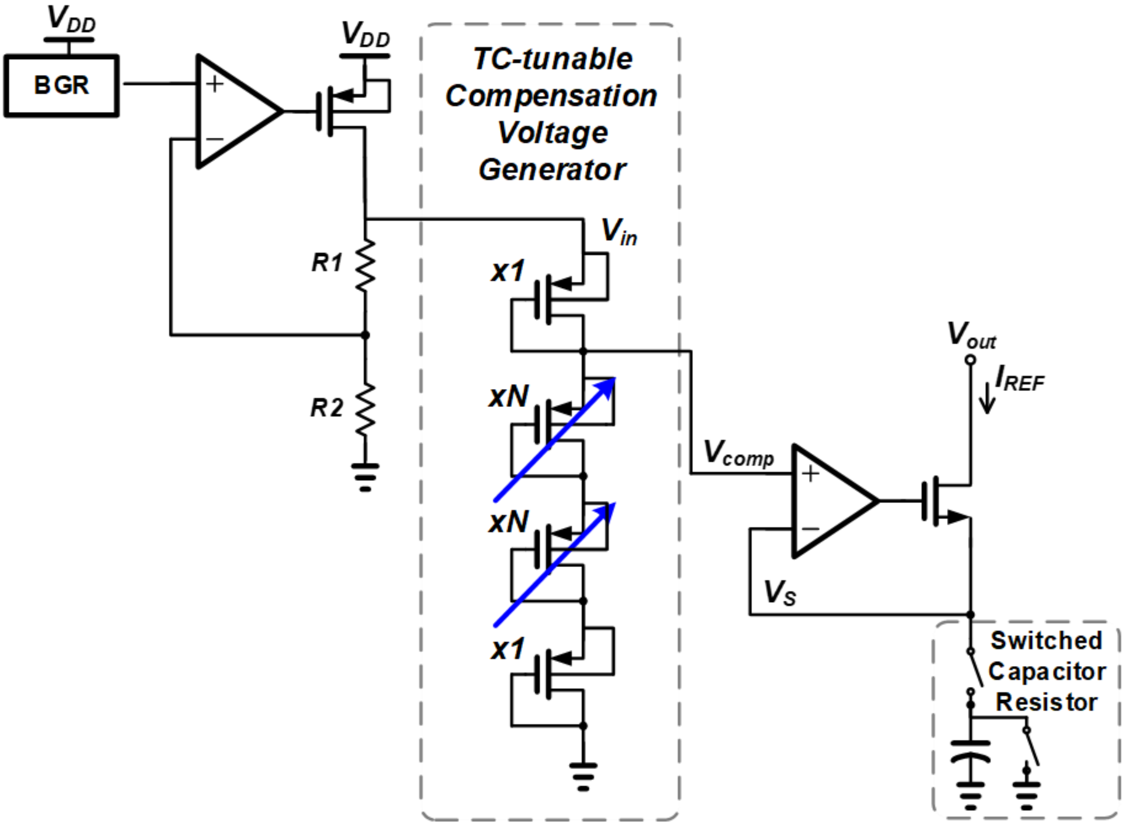


Fig. 2. Proposed temperature-compensated current reference with a tunable TC-DAC

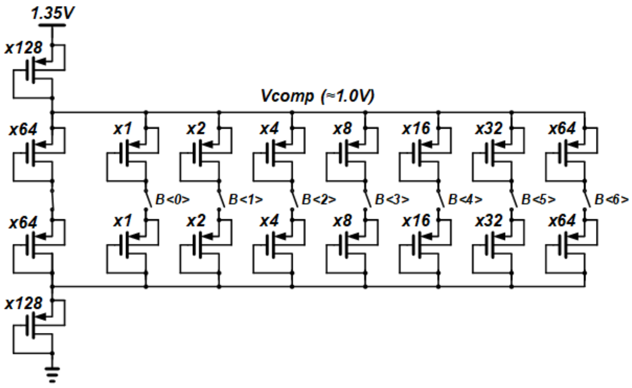


Fig 3. Proposed TC-DAC for post-cancellation of the residue temperature coefficient in the reference current after fabrication.

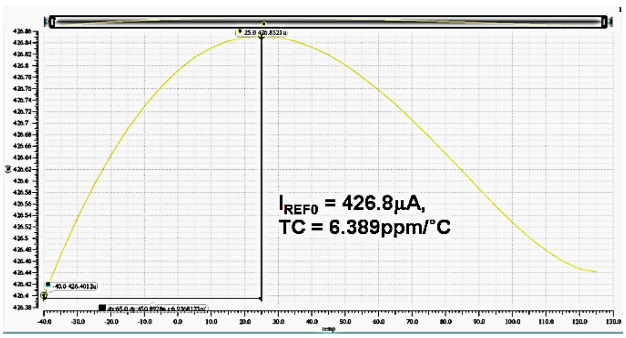


Fig 4. Simulated temperature independent current reference output versus temperature variation.

When using a crystal oscillator (XO) for the input frequency, its temperature coefficient is smaller than that of C and V_{comp} (less than 1 ppm/°C), allowing the output current to be represented by the following equation.

$$I_{REF} = f_{XO} \cdot C_o\left(1 + \alpha_C \cdot \Delta T\right) \times V_{comp0}\left(1 + \alpha_{comp}(N) \cdot \Delta T\right) \quad (9)$$

where α_c is the TC of capacitor. Therefore, by adjusting the size ratio N to satisfy the following conditions, a zero TC current reference can be obtained.

$$\alpha_{comp}(N) = \alpha_C \quad (10)$$

Due to non-idealities during chip fabrication, the temperature coefficient of the I_{ref} may not be completely eliminated. This residual TC is mainly caused by the variation in the TC of the BGR and the additional TC introduced by the offset of the op-amp used in the current driver. To further compensate for this, we proposed a TC-DAC structure as shown in Fig. 3, which allows for additional compensation of the residual TC caused by process variation. The proposed TC-DAC includes a 7-bit TC control for post-fabrication TC compensation. It is designed to cover the full temperature coefficient range of the MIM capacitor. As a result, the output current of the proposed reference current source with temperature

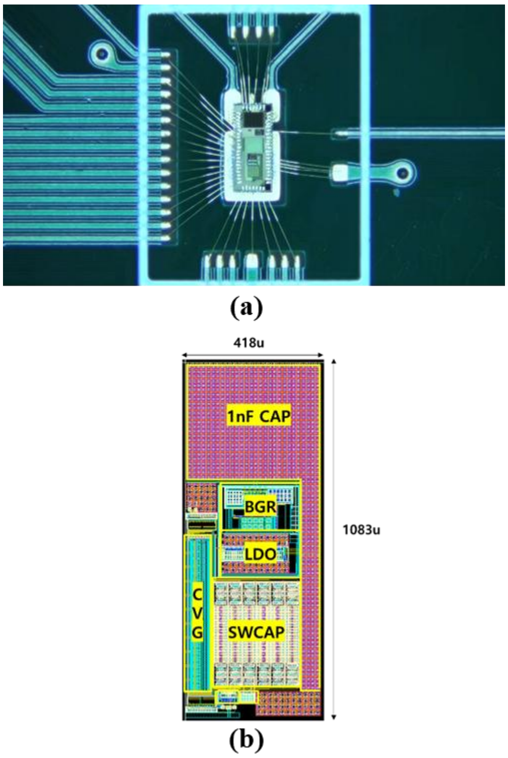


Fig 5. (a) Chip die photo after Chip-on-Board(COB), (b) Layout

variation is shown in Fig. 4. The output value of the reference current source at the nominal corner is 426.8 μA, with a TC of 6.389 ppm/°C across the automotive temperature range, demonstrating high thermal stability. Furthermore, even when residual temperature coefficients remain due to process variations, post-compensation can minimize the temperature coefficient.

III. SIMULATION AND MEASUREMENT RESULTS

The proposed current reference is designed and fabricated in a 180-nm CMOS process. The die photo is shown in Fig. 5. At a supply voltage of 1.8V, the power consumption is 391.41 μW, with a detailed breakdown provided in Fig. 6. Most of the power consumption occurred in the BGR, and it is expected that power consumption can be reduced by adopting a different voltage reference structure. The proposed current reference was measured with the setup shown in Fig. 7. A function generator was used instead of a crystal oscillator, and I_{ref} was measured using a source meter over a temperature range of -25°C to 125°C. The simulation results for the proposed structure across different corners are shown in Fig. 8. As shown in Fig. 8, simulations confirmed that the controllable TC range of the proposed TC-DAC can cover the switched capacitor TC variation across all corners. Therefore, after fabrication, zero-TC can be achieved by matching the TC of the switched capacitor resistor and the CVG TC through foreground calibration.

The TC-DAC control code can be adjusted according to the process corner as shown in Fig. 9. The proposed structure can only cancel the first-order TC, leaving a second-order TC after compensation, which limits the ability to achieve perfect zero-TC.

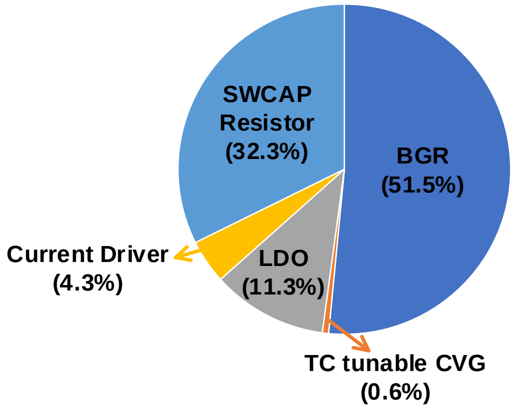


Fig 6. Power breakdown

Fig 7. Measurement setup

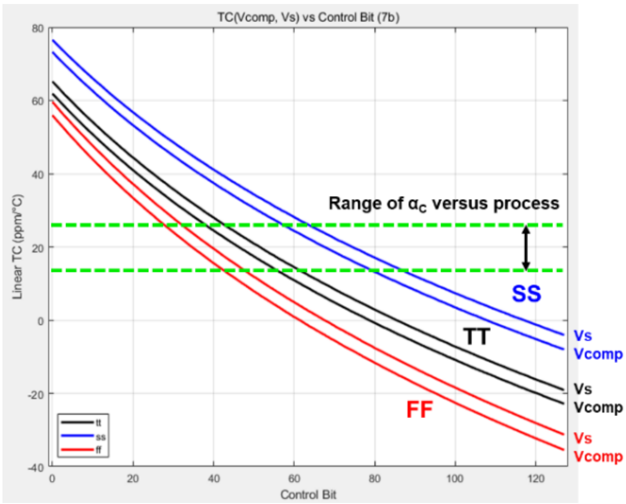
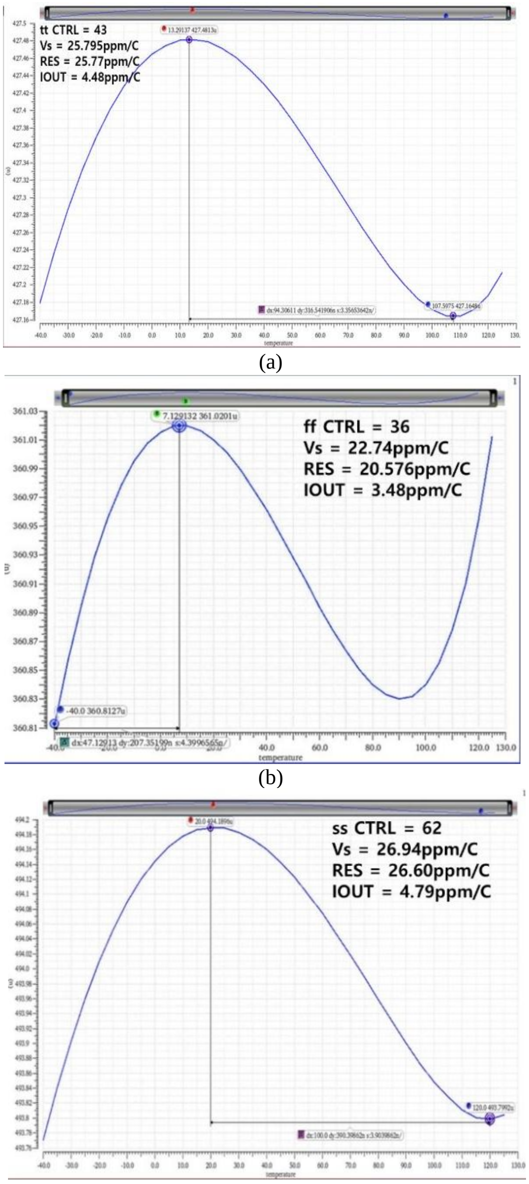


Fig 8. Simulated TC of V_{comp} vs 7-bit control of proposed TC-DAC.

TABLE I. Comparison of Different Current References

Table	This work	JSSC 2012[2]	ISSCC 2024[5]	TCAS-II 2020[6]	JSSC 2020[7]	ISSCC 2017[8]	CICC 2015[9]
Technology(nm)	180	180	180	180	180	180	180
IREF	406.24 uA	7.81 uA	10.9 uA	11.6 nA	1 nA	6.64 nA	10 uA
Temperature Range(ºC)	-25 to 125	0 to 100	-20 to 125	-40 to 120	-20 to 80	0 to 110	-40 to 80
Avg. TC (ppm/ºC)	20.89	24.9	11.4	169	265	283	130
Line Sensitivity(%/V)	*0.448	0.13	0.036	1.08	1.40	1.16	0.5
Area(mm^2)	0.2403	0.023	0.08	0.054	0.332	0.055	0.005
Supply (V)	*1.7 to 2.4	1 to 1.2	1.3 to 2.4	0.8 to 2	1.5 to 2.0	1.3 to 1.8	2.4 to 3.0

* Simulation

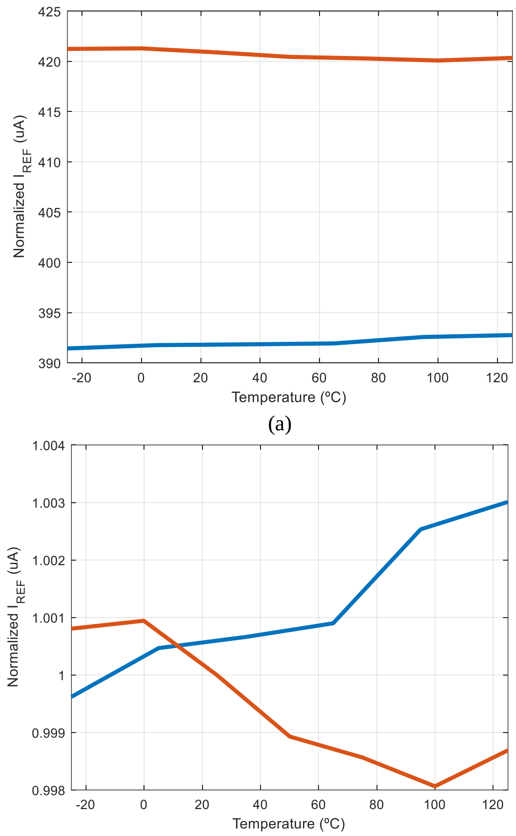


(a)

(b)

(c)

Fig 9. Simulation result of I_{ref} over process corners.



(a)

(b)

Fig 10. (a) Measured I_{REF} vs temperature variation (b) Normalized I_{ref} vs temperature variation.

To verify temperature stability, a temperature sweep was conducted, measuring the output current at 25°C intervals over a range from -25°C to 125°C while selecting the optimal code. A TC of 20.89 ppm/°C was achieved (Fig. 10).

The performance of the proposed current reference is summarized in Table I.

IV. CONCLUSION

In this paper, we have presented a design for a temperature-independent current reference with tunable temperature coefficient (TC) compensation. The proposed architecture addresses the challenges associated with process variations and residual temperature coefficients, which are critical issues in achieving reliable current sources in automotive sensor applications. Through the integration of a switched capacitor resistor and a TC-tunable compensation voltage generator, we successfully mitigated the effects of temperature fluctuations and process variations. The final design achieved a current reference with a temperature coefficient of 20.89 ppm/°C, demonstrating high thermal stability across a wide range of temperatures. This level of performance is well-suited for automotive and other high-precision applications where temperature independence is crucial. Future work may explore further optimization of the compensation techniques to enhance the robustness of the design under extreme environmental conditions.

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