

# A 46.468 $\mu$ W Low-Power Bandgap Voltage Reference

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**Abstract**—A low-power CMOS bandgap voltage reference is designed. This bandgap voltage reference adopted advanced startup circuit and sub-threshold technology. The circuit is simulated under SMIC 0.18 $\mu$ m CMOS process and 1.8V supply voltage. The simulation results show that it has significantly low power and low sensitivity to the temperature. The power is only 46.468  $\mu$ W, and the temperature coefficient is 16.33ppm/ $^{\circ}$ C in the temperature range from -40 to 125  $^{\circ}$ C.

**Keywords**- Bandgap-voltage-reference; low-power; sub-threshold technology

## I. INTRODUCTION

With growth in demand for electronic products, more and more Circuit systems have requests on low-power, small area and low cost<sup>[1]</sup>. Bandgap reference is one of the essential units in analog circuit systems. It offers the basic voltage reference to other circuit units. Its performance seriously hampered the performance of the entire signal processing system. For a long time, many people have been focusing on the research of bandgap reference. For example, “a novel current reference with low temperature and supply sensitivity and without any external component has been developed in a 0.25 $\mu$ m mixed-mode process”<sup>[9]</sup>. The circuit is based on a bandgap reference voltage and a CMOS circuit similar to a  $\beta$ -multiplier in [2]. Several kinds current and voltage reference were designed based on the sub-threshold MOSFETs with the SMIC 0.18 $\mu$ m standard CMOS process technique in [3] A current mode voltage reference was developed in which two currents with different temperature coefficient s were summed into a resistor to create a voltage reference. The output voltage can be easily changed as the resistor changes in [4],[5].

A low-power voltage reference consisting of pure CMOS is designed based on sub-threshold technology in this paper. Advanced startup circuit was adopted in the voltage reference to improve circuit precision and stability.

## II. CMOS VOLTAGE REFERENCE

Currently, the integrated voltage reference mainly had two types. One of them is based on diodes and parasitic junction transistors (BJTs). However, BJTs have several bipolar problems in the implementation of bandgap references at present. As the parasitic BJT in a CMOS process is usually not very well characterized, the output voltage of the bandgap reference is always fixed since the base of the parasitic transistor is grounded<sup>[6]</sup>. The other

voltage reference is consisted of MOS transistors without any BJTs. The MOS transistor has two primary regions of operation in which current flows from the source to the drain: the weak inversion region (sub-threshold region) and the strong inversion region. When MOS transistors work in the sub-threshold region, they have two opposite temperature dependent parameters:  $V_{GS}$  and  $\Delta V_{GS}$  which is the difference gate-source voltage between two MOS transistors, thus made the low-temperature-drift voltage reference possible.

When MOS transistors work in the sub-threshold region, they need smaller operating current, greater input common mode range and lower noise on low supply voltages. This will reduce the power consumption of the voltage reference.

The complete schematic of the proposed CMOS voltage reference is shown in Fig.1. It is composed of three sub-circuits:

- The startup circuit is consisted of MS1~MS6;
- The proportional to absolute temperature (PTAT) current generator is made up of M1~M4 and  $R_1$ , which is independent on the supply voltage;
- The complementary to absolute temperature (CTAT) current generator is formed by M5~M9 and  $R_2$ .  $C_C$  is the compensated capacitor.

### A. Startup Circuit

The PTAT current generator is a typical circuit, it is used to supply voltage independently. The difference with the classic design is M1 and M2 work in a sub-threshold region. There is an important problem about the circuit is the existent of “degeneration”<sup>[6]</sup>. So a startup circuit is necessary to drive the circuit to work. When the circuit is start, the startup part will be cut off.

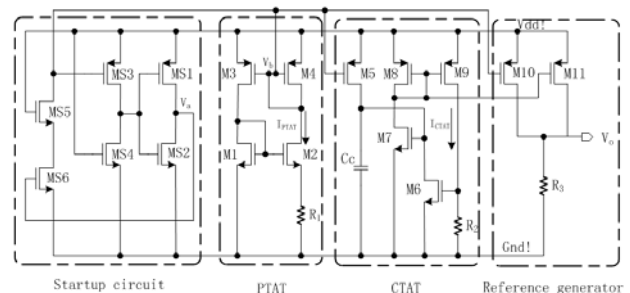


Figure 1. The schematic of the proposed CMOS voltage reference

As shown in Fig.1, the startup circuit is consisted of MS1~MS6. We can see it contains two invertors and two transistors. MS3 and MS4 form the 1<sup>st</sup> invertor. MS1 and MS2 form the 2<sup>nd</sup> invertor. At the moment when the supply is on, the circuit is under start and  $V_b$  is high. For the start circuit, the 1<sup>st</sup> invertor output low. So the voltage of  $V_a$  is high. Then MS5 and MS6 open, And  $V_b$  get lower which leads the PTAT circuit starts. When  $V_a$  is low enough to conduct MS3, make the output of the 1<sup>st</sup> invertor be high. MS6 will be cut off. The PTAT circuit starts.

We can see the 1<sup>st</sup> invertor is equal to two resistors when MS3 conducts. So the dimension of MS3 should be large enough and MS4 small enough so as to make  $V_a$  low and MS6 cut off. And which will make a low current leakage.

### B. PTAT Circuit

The PTAT current generator is made up of M1~M4 and R1 as shown in Fig.1. M1 and M2 operate in the sub-threshold region. M3 and M4 work in saturated region. The basic idea is that  $I_{PTAT}$  can be formed by the difference gate-source voltage between M1 and M2. As they work in sub-threshold region, the  $\Delta V_{GS1,2}$  of M1 and M2 has a positive temperature coefficient<sup>[3]</sup>. As illustrated in [7],[8], the current is in direct proportion to absolute temperature.

$$I_{PTAT} = \frac{\Delta V_{GS}(T_0)}{R_1} \cdot \frac{T}{T_0} \quad (1)$$

Where

$$V_{GS}(T_0) = \frac{kT_0}{Aq} \ln \frac{S_2 S_3}{S_1 S_4} \quad (2)$$

$S_1 \sim S_4$  are dimensions of M1~M4. M3 and M4 copy  $I_{PTAT}$  as enantiomorphous tube. Which made the current of M3 is equal to  $I_{PTAT}$ . In order to copy the current accurately, the channel length of M3 and M4 should be sufficiently long. So the channel length modulation effects may be negligible.

### C. PTAT Circuit

The CTAT current generate circuit consists of transistors M5~M9,  $R_2$  and  $C_C$ . M6 operates in the sub-threshold region. M5 is used to copy current from M4 and offers a fixed low current to M6 to guarantee it work in sub-threshold region. So the  $V_{gs,M6}$  has a negative temperature coefficient, thus made a CTAT current. As shown in (3), the value of  $I_{CTAT}$  is decided by  $R_2$ . And it is because that the voltage of  $R_2$  is fixed in  $V_{gs,M6}$  due to the negative feedback<sup>[3],[4]</sup>.

M7~M9 build up a negative feedback loop to ensure the circuit work in a general way. The higher gain the feedback is the higher precise the current is. So a compensated capacitor is necessary for the stabilization of the circuit<sup>[4]</sup>.

$$I_{CTAT} = \frac{V_{gs,M6}(T)}{R_2} \quad (3)$$

### D. Voltage Reference Generator

The voltage reference generator is made up of the transistors M10, M11 and the resistor R3, as it shown in Fig.1. M10 is used to copy the PTAT current, and M11 to copy the CTAT current. If two of the opposite temperature coefficient currents were added in a proper ratio, the added current flowing through  $R_3$  will generate a low-temperature-drift reference voltage<sup>[3]</sup>, as shown in (5).

$$I_{R3} = \frac{S_{10}}{S_4} I_{PTAT} + \frac{S_{11}}{S_9} I_{CTAT} \quad (4)$$

$$V_{ref} = I_{R3} R_3 \quad (5)$$

$S_9 \sim S_{11}$  are dimensions of M9~M11. The current temperature coefficient was tested from -40 °C to 125 °C. The dimension ratio of M10 and M11 can be prospected by the opposite current temperature coefficients.

## III. ANALYSIS AND SIMULATION RESULTS

The voltage reference generator which supposed to be used in signal processing system was successfully implemented under the process of SMIC 0.18 $\mu$ m and 1.8V supply voltage. The output voltage of the reference is 0.9V.

As it mentioned in [5],[6], the temperature coefficient of the resistors will be cancelled if all of the three resistors are the same kind of resistor, while it has a higher temperature coefficient when different kinds of resistors were used. In this paper, two kinds of resistors were used, as it shown in Tab.1.

TABLE I. RESISTOR TYPES AND TEMPERATURE COEFFICIENTS

Resistor	Type	Temperature coefficient(ppm/°C)
R <sub>1</sub>	Rpdifsab	$1.4 \times 10^{-3}$
R <sub>2</sub> & R <sub>3</sub>	Rpposab	$-1.65 \times 10^{-4}$

They have the opposite temperature coefficients, and they are used in opposite current generator. The resistor's type rpdifsab, which has a positive temperature coefficient was used in PTAT current generator, while rpposab which has a negative temperature was used in CTAT current generator.

The resistor temperature coefficient participate in the operation of the current generation, this makes the coefficient more stable. The temperature coefficient of CTAT current is -5.483nA/°C and 2.531nA/°C for PTAT current as it shown in Fig.2.

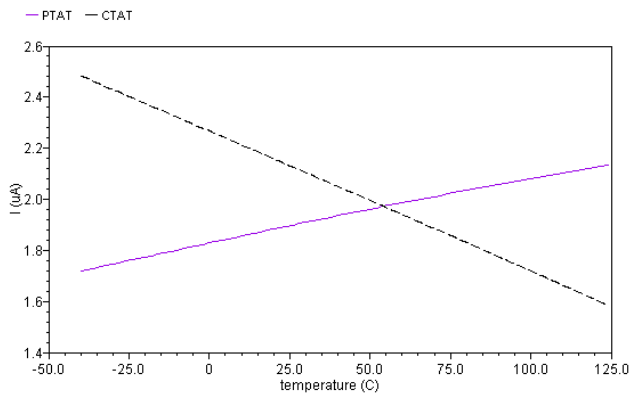


Figure 2. CTAT current and PTAT current temperature drift curve

The temperature coefficient of the voltage reference is 6.33ppm/°C under typical process with temperature ranges from -40 to 125°C. The result is shown in Fig.3.

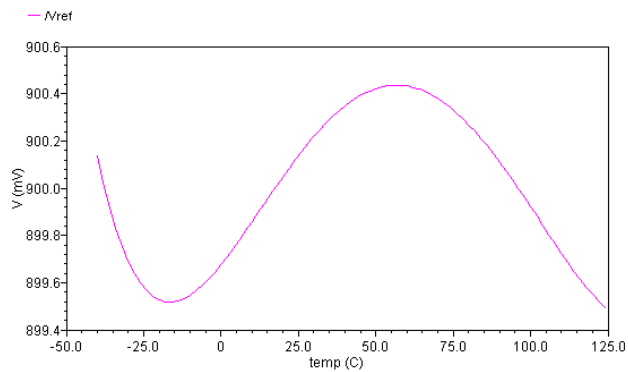


Figure 3. Temperatur drift curve

This is much better than the results from reference 5 and 6 is 115.4ppm/°C and 31ppm/°C separately, as it shown in Tab. II.

TABLE II. THE COMPARE OF TEMPERATURE COEFFICIENT

	Resistor type	Temperature coefficient(ppm/°C)
Ref.[5]	same	115.4
Ref.[6]	same	31
This paper	difference	16.33

The circuit current is 25.81μA and makes the power consumption is 46.468μW. This attributes to MOS tube work in the sub-threshold region.

#### IV. CONCLUSIONS

A pure CMOS voltage reference based on sub-threshold technology is designed in this paper. Two opposite temperature coefficient current which based on CMOS process sub-threshold region were created to add, in order to obtain low-temperature-drift voltage reference. At the same time, this achieves low power consumption, which is only 46.468μW. Unlike the other references, two different types of resistors were used in the design, which makes a low temperature coefficient: 16.33ppm/°C in the temperature range from -40 to 125 °C. The voltage reference is applicable to low-power and high-precision circuit systems.

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