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A High PSRR Voltage Reference for High Efficiency Power Management Circuit of MEMS Energy Harvesters

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Abstract

A high power supply rejection ratio (PSRR) bandgap voltage reference (BGR) which is used in the signal processing circuit of energy harvesters is presented in this paper. The PSRR of the BGR is improved by adding a pre-regulating circuit and a low pass filter. The pre-regulating circuit mainly improves the BGR PSRR at low frequency and the low pass filter mainly improves the BGR PSRR at high frequency. The BGR is verified by SMIC 0.18 μm 1P6M process. The supply voltage is 2.5 V and the BGR provides a reference voltage of 1.19 V. The simulation results show that the PSRR at 1MHz is about -40 dB and the PSRR at DC region is about -125 dB. Besides, this circuit enhances the line regulation performance. When the supply voltage varies from 2.5 V to 6 V, a stable output voltage can be obtained. The overall current consumption of this design is less than 50 μA under 2.5 V.

Key Words: MEMS, Energy Harvester, The Voltage Reference, The High PSRR, The High Line Regulation Rate

1. Introduction

Voltage references are widely used in analog and mixed-signal applications, such as switch-mode voltage regulators, high performance analog-to-digital converters (A/D), and energy harvesters. Bandgap voltage references have been the most popular solution since they have been first introduced. The references should be little affected by process, supply voltage and temperature variations. In consideration of modern system on chip (SOC) design, there is a growing trend of designing high PSRR voltage references even at high frequency. Bandgap reference design can be found in many papers [1–4]. In such cases regulated supply voltage is often used to achieve a high PSRR.

The output signal of MEMS energy harvesters [5,6] are relative low because of its microscale and brings a great many challenges for the power management circuit design. In order to meet the goals of low voltage supply and low power dissipation for MEMS harvester, it is necessary to choose a structure to achieve high PSRR, over a broad frequency range to reject noise coupled from high-speed digital circuit on the chip. The supply noise injected to the output of BGR circuit is the most significant noise, comparing to other sources [3]. Thus a high PSRR BGR is desired to achieve a high performance analog and digital system, particularly in wireless communications. Some techniques to improve the PSRR of the BGR are mentioned in [7–9]. In order to achieve a high PSRR bandgap reference, a structure is presented in this paper. It is implemented by adding a pre-regulating circuit to improve the low frequency PSRR and a low pass filter to improve the high frequency PSRR [10]. Besides, the line regulation performance is ameliorated.

This paper is organized as follows: section 2 discusses the fundamental principles of the BGR and the existing circuit techniques for high PSRR design. The proposed bandgap reference circuit is presented in section 3. The simulation results are described and discussed in section 4.

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2. Fundamental Principles of Bandgap References

In a bandgap reference circuit, the reference voltage is obtained by compensating the negative temperature coefficient of the base-emitter voltage V_{BE} with the positive one of ΔV_{BE}, which is the difference of two base-emitter voltages. In order to comply with the standard CMOS process, the base-emitter voltage is often implemented by the PNP bipolar transistor and its collector should be connected to the lowest potential (GND in this paper). The conventional BGR structure [11,12] is shown as Figure 1. Inside this circuit, the currents in M_1, M_2 and M_3 are set to be equal ($I_1 = I_2 = I_3$). The reference voltage V_{ref} of the bandgap reference circuit can be calculated by

$$\begin{aligned} V_{ref} &= I_3 R_2 + V_{EB3} = \frac{(V_{EB1} - V_{EB2})}{R_1} R_2 + V_{EB3} \\ &= V_T \ln N \frac{R_2}{R_1} + V_{EB3} \end{aligned} \tag{1}$$

where I_3 is the proportional to absolute temperature (PTAT) current and V_T is the thermal voltage. Besides, N is the area ratio of Q_2 to Q_1 and V_{EB1}, V_{EB2}, and V_{EB3} are the junction voltage of Q_1, Q_2, and Q_3, respectively. The reference voltage is obtained through the I_3. V_{EB3} provides the negative temperature coefficient voltage and the I_3R_2 provides the positive temperature coefficient voltage. Normally, the temperature performance is adjusted by changing the ratio of R_2 and R_1.

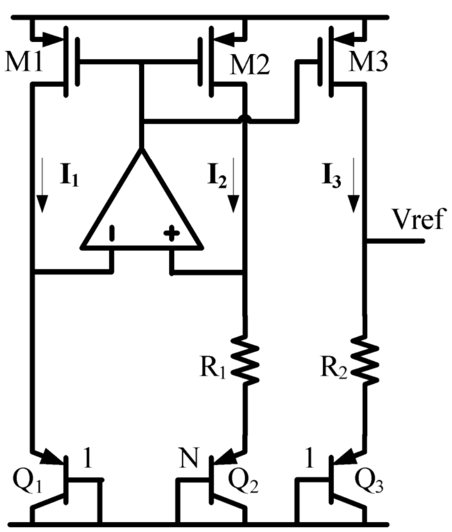

Figure 1. Structure of the conventional BGR.

The power supply rejection ratio can be improved by regulating the supply voltage of the bandgap core circuit in many cases. In [2], an operational amplifier is configured as a regulator to generate a local supply and this greatly improves the low frequency PSRR. Besides, a bandgap reference, whose internal regulated supply is generated by using a high gain feedback loop, is described in [3]. Also, the supply voltage of the bandgap core is regulated by a low dropout voltage regulator in [7]. In the design, the added regulator only improves the PSRR by about 10 dB at DC region. It is because of the bias current of the low dropout voltage regulator that is generated by a general resistor-MOS transistor reference circuit.

3. Bandgap Reference Circuit Implementation

The proposed bandgap reference in this paper uses a low dropout voltage regulator where the bias current is obtained from the bandgap core circuit. The conceptual diagram of this design is illustrated in Figure 2. The pre-regulator basically provides a first order voltage-mode bandgap reference. A PNP bipolar transistor and a PTAT current generated by the bandgap provide a relatively steady voltage V_{EB4}. Then the pre-regulated voltage Vpre_reg can be calculated by

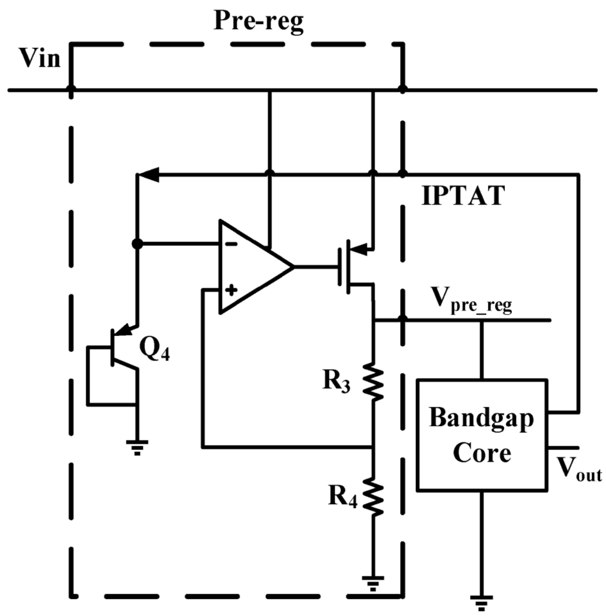

Figure 2. Conceptual diagram of the BGR in this design.

$$V_{\text{pre}\_ref} = V_{EB4}(1+\frac{R_3}{R_4}) \quad (2)$$

where V_{EB4} is the junction voltage of Q_4. Besides, the pre-regulator does not need to be well temperature compensated. The current mirrors in the bandgap will have high enough output impedance to effectively reject small voltage fluctuation experienced by the pre-regulated supply voltage ($V_{\text{pre\_reg}}$). The bandgap core provides a current for the pre-regulator and the pre-regulator provides a supply voltage for the bandgap core. Consequently, the bandgap reference voltage Vout is generated by a loop which is made up of the pre-regulator and the bandgap core.

In this circuit, the PSRR mostly depends on the product of the gain of the two amplifiers in pre-regulator and bandgap core. As a result, the PSRR is improved by such gain of the pre-regulator's amplifier.

The straight forward implementation of the current-mode bandgap relies on the high and finite impedance of the current mirrors. Consequently, the output voltage varies as the input voltage changes because of the finite output impedance of the transistors sourcing the currents. One way to increase the output impedance is by actively cascading the mirrors. However, pre-regulating the supply voltage of the bandgap core as illustrated in Figure 2 in this paper is a more effective method. As a result, line regulation performance is ameliorated. The pre-regulator basically provides a first order voltage-mode bandgap reference.

The conventional BGR structure illustrated in Figure 1 is chosen as the structure of the bandgap core in this paper. The specific circuit is shown as Figure 3. The amplifier in Figure 1 is replaced by the transistors from M_{a1} to M_{a9} which compose a symmetrical amplifier structure. The transistor M_9 is the current source. Also, the pre-regulated supply voltage ($V_{\text{pre\_reg}}$) is obtained through M_4 and Q_4.

The whole circuit of the bandgap designed in this paper is illustrated in Figure 4. It is made up of four parts: start-up circuit, pre-regulator circuit, bandgap core circuit, and a low pass filter. The structure of the error amplifier used in pre-regulator is the same as the one in bandgap core. The lowest input voltage is 2.5 V and the voltage drop is about 0.2 V. The feedback capacitor C_c in the pre-regulator is used to compensate the amplifier. As a result, the dominant pole is produced at node A. The resistor R_f, in series with C_c, is to abolish the positive zero.

The start-up circuit is shown in the left of Figure 4. It is controlled by the output voltage (V_{ref}) and the pull-down nodes A and B is chosen seriously. If V_{ref} is zero, node A and node B will be zero. Consequently, $V_{\text{pre\_reg}}$ will be equal to V_{in} and V_{ref} will be equal to $V_{\text{pre\_reg}}$. When Vref reaches the normal voltage, the transistors M_{s1} and M_{s2} will be closed. The transistor M_4 and the resistor R_3 form a low pass filter. Here, the transistor M_4 is used for a capacitor to reduce the area.

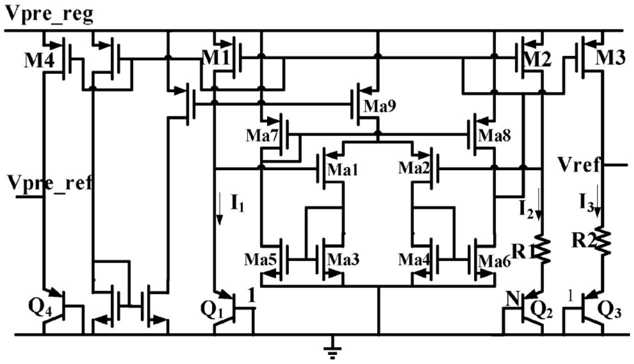

Figure 3. Structure of the bandgap core.

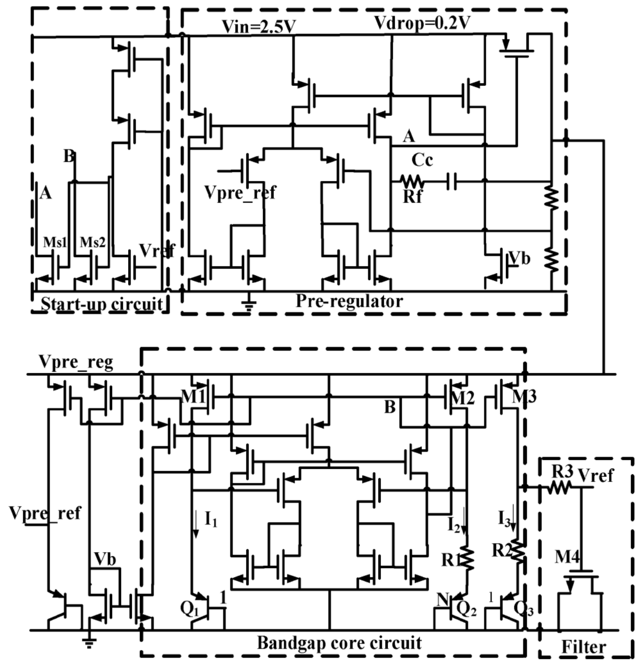

Figure 4. Specific circuit of the high PSRR BGR.

4. Simulation and Analysis

The proposed bandgap voltage reference shown in Figure 4 has been simulated in SPECTRE with SMIC 0.18 μm 1P6M process. The PSRR of the BGR simulation results with and without the pre-regulator circuit are shown in Figure 5.

The PSRR with the pre-regulator is -125 dB at DC region and it is improved by about 60 dB. In addition, a low pass filter, which is implemented by R_3 and M_4, is added to the BGR to improve the PSRR at high frequency region. The comparison results are shown in Figure 6.

The worst PSRR of the bandgap with low pass filter can still reach to -40 dB. The simulation results in Figures 5 and 6 imply that the pre-regulator circuit improves the low frequency PSRR and the low pass filter improves the high frequency PSRR.

The effects of the pre-regulator on line regulation performance are illustrated in Figure 7. With the input supply voltage changing from 1.5 V to 6 V, the output reference voltage without pre-regulator varies from 1.190 V to 1.255 V. However, the output voltage with pre-regulator varies from 1.190 V to 1.194 V. In addition, the output reference voltage with pre-regulator remains to be 1.194 V when the input voltage varies from 1.84 V to 6 V. The simulation results in Figure 7 imply that the pre-regulator circuit greatly improves the line regulation rate.

Figure 8 shows the simulated output reference volt-

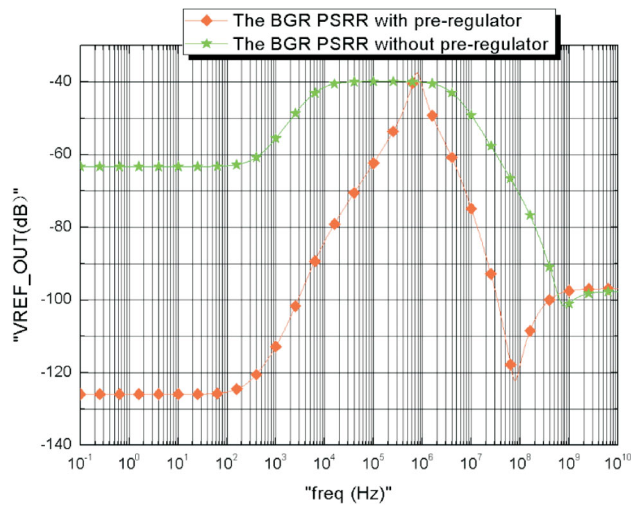

Figure 5. BGR PSRR with and without pre-regulator.

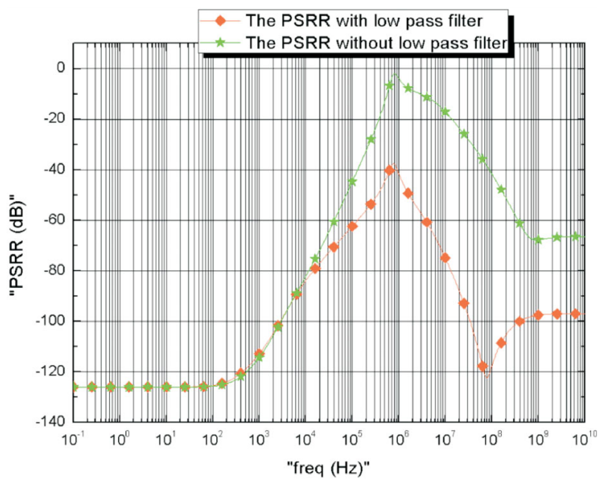

Figure 6. PSRR with and without low pass filter.

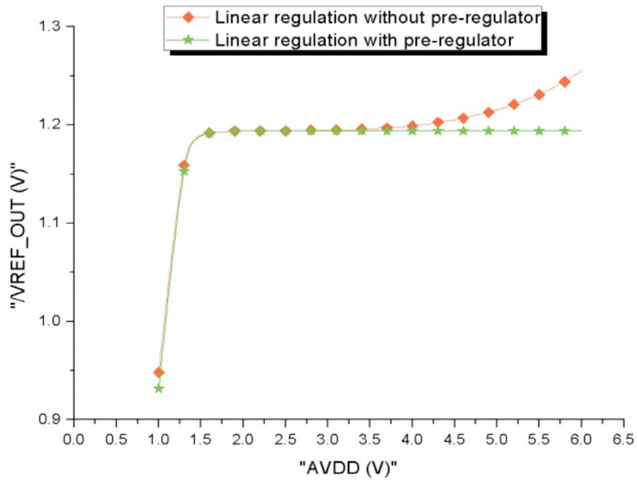

Figure 7. Line regulation of the BGR with and without the pre-regulator.

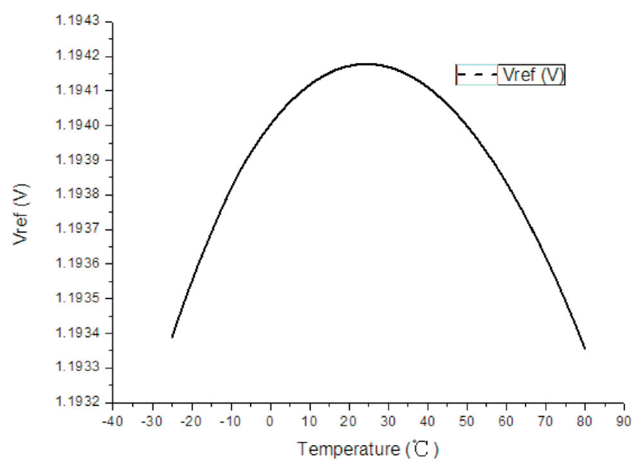

Figure 8. Reference voltage versus temperature.

age of the proposed bandgap reference as a function of temperature over the range -25 °C to 80 °C. The curve exhibit a variation of about 810 μV. The corresponding temperature coefficient is 6.51 ppm/°C.

Figure 9 shows the layout of the bandgap reference and packaged IC chip designed in this paper. The capacitor is used to compensate the stability of the bandgap. During the layout, more attention should be paid to the match of resistor and bipolar.

Figure 10 displays the differences of PSRR between pre-simulation and post-simulation. The post-simulation result is worse than pre-simulation result due to the mismatch and parasitic parameters.

5. Conclusions

A bandgap voltage reference with high PSRR and high line regulation rate which is used in the processing circuit of energy harvesters is presented in this paper. This BGR is implemented in SMIC 0.18 μm process. The difference from conventional BGR is that a pre-regulator circuit and a low pass filter are added. The pre-regulator improves the low frequency PSRR and the line regulation rate. The low frequency PSRR is about -125 dB and the output voltage remains to be 1.194 V when the input voltage varies from 1.84 V to 6 V. Besides, the low pass filter improves the high frequency PSRR. The PSRR at 1 MHz is about -40 dB.

Acknowledgments

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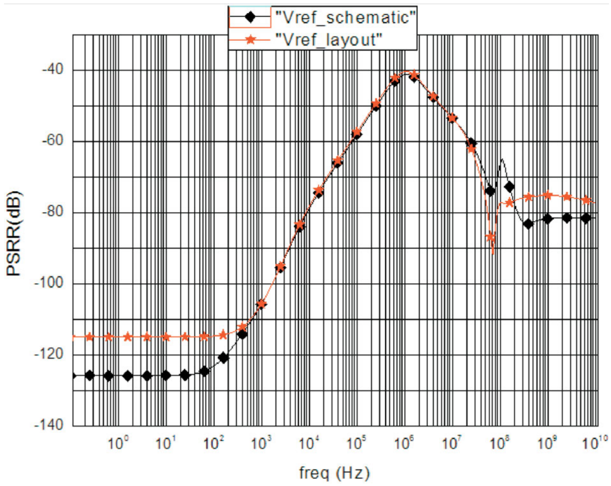

Figure 10. The PSRR between post-sim and pre-sim.

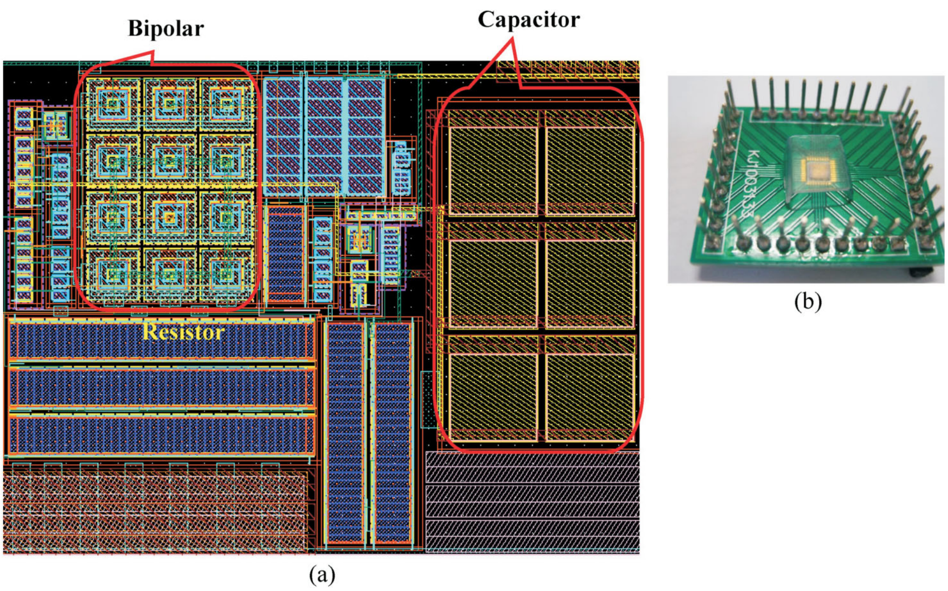

Figure 9. Layout of the proposed bandgap reference (a) and packaged IC chip (b).

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