A low power bandgap reference with buffer working in the sub-threshold region for energy harvesting systems*

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Abstract: We propose a bandgap reference, which works in sub-threshold regions to the reduce power consumption in applications such as those in energy harvesting systems that stimulate the development of power management for low power consumption applications. Measurements shows that the supply current of the proposed bandgap reference is only 6.87 μA, including a voltage buffer consuming 3.6 μA of supply current, when the supply voltage is 5 V. The supply voltage can vary from 3 to 11 V and the line regulation of the proposed bandgap reference output voltage is 0.875 mV/V at room temperature. The temperature coefficiency is 88.9 ppm from 10 to 100 °C when the supply voltage is 5 V.

Key words: power management unit; intermittent mode; bandgap reference; energy harvesting

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1. Introduction

Micro energy harvesting systems have developed rapidly in the last few years, including smart medical micro systems (SMMSs) and wireless sensor network nodes (WSNNs). Generally, the node of a wireless sensor does not need a battery to provide power and it uses the harvested power from the ambient environment, including solar energy, thermal energy, mechanical energy, etc. A very special characteristic of these kinds of systems is that a function component will work at very low power in order to make full use of the small amount of harvested energy available. Therefore, a very important issue arises: how to collect and store ambient energy and how to exploit the harvested energy; this issue has attracted the interest of many researchers.

Several methods have been proposed to realize the above mentioned functions. Reference [1] uses a rechargeable battery to store harvested energy from RF energy and thermal energy. In Ref. [1], a boost DC–DC converter using inductors and capacitors is applied to convert a small amplitude input voltage into an available input power. Reference [2] presents an enhanced AC–DC converter to make full use of energy from PZT devices.

In many low power micro systems, an intermittent operation mode is an advantageous operation mode for power harvesting systems. Reference [3] shows such a system and it introduces all integrated DC–DC power harvesting and management for PZT materials used in a wireless monitoring system for orthopedic implants. This is an effective power saving method from the system point of view.

From the circuit design point of view, one important method of saving power is to reduce the power consumption of the power converter and to improve the converter efficiency. One hot topic is to recycle the gate charge of switching transistors during the converter process. References [4, 5] use an inductor to perform such a function, while References [6, 7] use a capacitor to fulfill a similar function.

Another important point for the circuit design is to reduce the power loss of the additional circuit, which is necessary to aid the functional part, such as clock generator and bandgap reference. Of all of these components, the bandgap reference is a very important part because when working in an intermittent mode[3], other components can enter a sleep mode for most of the time, while the bandgap reference must be working all the time to keep the power management alert. Therefore, a low power bandgap reference is greatly needed in such kinds of energy harvesting systems.

In this paper, a bandgap reference working in the sub-threshold region is proposed and the operation principle and design procedure are illustrated in detail.

2. Traditional bandgap reference

Many power management units work in high voltage environments[3], so a bandgap reference is really necessary for a wide input voltage range, because in the high voltage region, the same current consumption means more power consumption compared to a low voltage supply. Therefore, an ultra low supply current of the bandgap reference is preferred.

A bandgap reference not only provides a precise voltage reference, but also provides precise bias currents. The conventional bandgap reference circuit includes a CMOS op-amp, diodes, and resistors, as shown in Fig. 1[8]. In a modern CMOS process, diodes used for bandgap references are usually imple-

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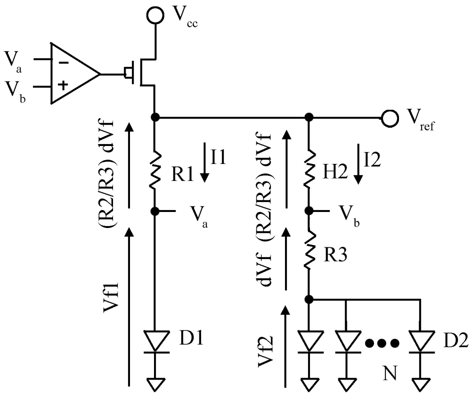

Fig. 1. Conventional bandgap reference circuit[8].

mented by parasitic PNP transistors. A general equation between diode current and the voltage across the two terminals is expressed as

$$I = I_S\left(\exp\frac{qV_D}{kT} - 1\right) \cong I_S\exp\frac{qV_D}{kT},\ \text{when } V_D \gg \frac{kT}{q}, \quad (1)$$

where k is Boltzmann′s constant (1.38×10^{-23} J/K) and q is the electronic charge (1.6×10^{-19} C).

In this circuit, V_a and V_b are set to be the same if the op-amp works. dV_f is the forward voltage difference between one diode D1 and N diodes D2.

$$dV_f = V_{f1} - V_{f2} = \frac{kT}{q}\ln\frac{NR_2}{R_1} = \phi_t\ln\frac{NR_2}{R_1}. \quad (2)$$

So, the bandgap reference output voltage becomes

$$V_{ref} = V_{f1} + \frac{R_2}{R_3}dV_f, \quad (3)$$

where V_{f1} is the built-in voltage of the diode and dV_f is proportional to the thermal voltage ϕ_t. Here, V_{f1}has a negative temperature coefficient, whereas ϕ_t has a positive temperature coefficient, so that V_{ref} is determined by the resistance ratio between R_1, R_2, R_3, being only slightly influenced by the absolute value of these resistances.

The drawback of this traditional bandgap reference is that the circuit cannot work on a low supply voltage and may consume too much power because there are so many parallel diodes. But as far as a concrete application is concerned, this structure is suitable for such an application background. There are two reasons for this. First, being not good at working on a low power supply voltage can be a good aspect for a wide supply voltage. In a low voltage operation, the current mode is used to keep the output voltage stable when the supply changes. While large supply ranges are concerned, a voltage operational amplifier is a good choice. Second, the problem of too much power dissipation can be solved by using transistors working in the sub-threshold, which will be explained in detail in the next section.

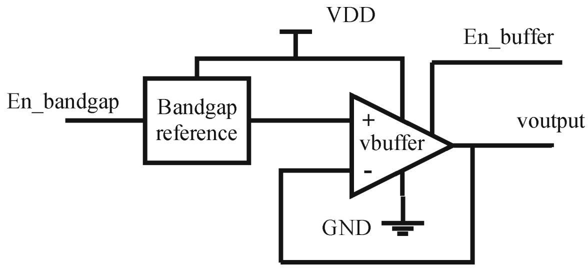

Fig. 2. System diagram of the proposed bandgap reference.

3. The proposed bandgap reference working in the sub-threshold regions and its voltage buffer

Figure 2 shows the system diagram of the proposed bandgap reference. In order to reduce the power dissipation of the bandgap reference, transistors working in subthreshold regions are used to reduce the supply current. Transistors working in moderate regions can also be biased by a smaller current. But larger V_G–V_T will lead to a larger voltage DC offset, which will greatly affect the performance of an operational amplifier in the bandgap reference. Other than reducing power dissipation, several high performance parameters of a bandgap reference must be kept under different conditions, such as supply voltage variations, temperature variations, and different technology corners. The proposed bandgap reference with transistors working in sub-threshold regions has a weak current drive capability. In order to make sure that the load current of a bandgap reference can reach 1 μA, a voltage buffer is integrated to increase the drive capability of the bandgap reference. Although this voltage buffer will increase the power dissipation, it can reduce measurement errors caused by a resistance load. In given application systems, the signal En_buffer can be disabled to reduce the power dissipation of the voltage buffer when the whole system is in the idle state.

3.1. Current performance of transistors working in the sub-threshold regions

MOS transistors’ drain–source current working in the sub-threshold region can be expressed as

$$I_D = I_0\frac{W}{L}\exp\frac{V_G - V_T}{n\phi_t}\left[1 - \exp\left(-\frac{V_{DS}}{\phi_t}\right)\right], \quad (4)$$

where I_0 is a constant dependent on technology parameters, W and L are the width and length of MOS transistors, respectively. V_T represents the threshold voltage. n is a technology parameter depending on the process and ϕ_t is the thermal voltage, which is about 26 mV at room temperature, i.e., 27 °C. Equation (4) is suitable for general analysis when $V_G \ll V_T$. It is obvious that the drain source sub-threshold current depends exponentially on $V_G - V_T$. Therefore, the sub-threshold current is sensitive to the variation in V_T.

And the transconductance of MOS transistors working in the sub-threshold region can be expressed as

$$g_m = \frac{I_D}{n\phi_t}, \quad (5)$$

which shows the relation between g_m and I_D in the sub-threshold region.

3.2. Selection of width and length of transistors working in the sub-threshold region in the bandgap reference

Determining transistor' size is the key point in the circuit design process. During this process, g_m/I_D is a very important design parameter and it represents the ratio of the transconductance g_m to the drain current I_D. In order to get a high ratio of g_m/I_D, in order to reduce the power consumption[9, 10], many people have already done a lot of work. In Ref. [11], Enz and Vittoz presented an EKV model for MOS transistors and this model can represent the MOS characteristics in different working regions using one equation, whichever possible region the MOS transistors may work in. In Ref. [12], researchers proposed another MOSFET model, which has a common property that tries to use a unified model for MOS transistors in all regions, and the corresponding design methods. According to all of these papers, there are several equations available to design low power circuits.

$$I_D = 2\pi \mathrm{GBW} C_L n\phi_t \left(\frac{1+\sqrt{1+i_f}}{2}\right), \tag{6}$$

$$\frac{W}{L} = \frac{2\pi \mathrm{GBW} C_L}{\mu C_{ox}\phi_t}\left(\frac{1}{\sqrt{1+i_f}-1}\right), \tag{7}$$

$$V_{DS(sat)} \cong \left(\left(\sqrt{1+i_f}-1\right)+4\right)\phi_t, \tag{8}$$

$$f_t \cong \frac{\mu\phi_t}{\pi L^2}\left(\sqrt{1+i_f}-1\right), \tag{9}$$

where I_D is the current of a MOS transistor from the drain to the source, GBW is the unity-gain bandwidth, C_L is the load capacitance, n is the slope factor, ϕ_t is the thermal voltage, i_f is the inversion level, C_{ox} is the oxide capacitance per area, f_t is the cut-off frequency of a MOS transistor, W is the width of a MOS transistor, L is the length of a MOS transistor, μ is the mobility of electrons or holes, and V_{DS} is the drain to source voltage of a MOS transistor.

Figure 3 shows a circuit for the bandgap reference. M1–M5 consist of an op-amp to keep the same voltage value of V_a and V_b. M6 and M7 provide the bias current for the op-amp. The output of an op-amp is connected to the gate of M8 and M9. In order to reduce the power consumption, all of these transistors are biased in or near the sub-threshold regions to lower the current consumption. Start-up circuits are not drawn in Fig. 3.

A low current was assigned to every branch in Fig. 3. Every branch of the op-amp is less than 70 nA and the bias current should be less than 140 nA at 125 °C, while the current through the resistors is less than 1.5 μA. Because this system is not very stringent on circuit speed, its GBW is set to be 2.5 kHz. By far, the i_f parameter of transistor M1 and M2 can be obtained according to Eq. (6). Consequently, the W/L of transistors are obtained according to Eq. (7). At the same time, checking f_t parameters of the transistors is necessary. If the

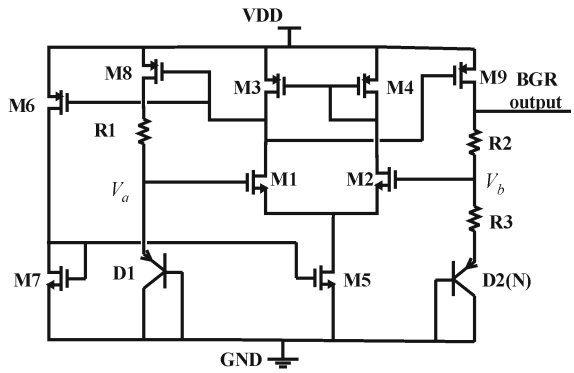

Fig. 3. Circuit of the proposed bandgap reference.

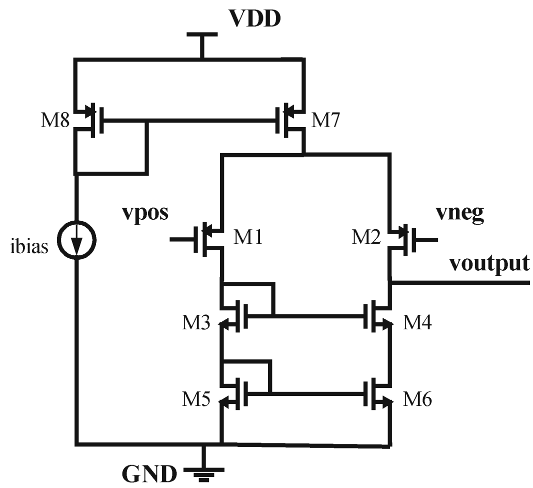

Fig. 4. Concrete circuit for the voltage buffer of the bandgap reference.

MOS transistor parameters satisfy the requirement that the unity gain frequency is greater than at least three times the GBW, the design space will avoid parasitic diffusion and the overlap capacitance to be of the same order as the load capacitance.

3.3. Voltage buffer of the bandgap reference

Figure 4 shows the concrete circuit of the voltage buffer of the proposed bandgap reference. A traditional single stage amplifier is used as a voltage buffer to increase the drive capacity of the proposed bandgap reference. M1 and M2 are PMOS transistors used as input transistors. M3–M6 are used as current sources to form the active load of the input pair. ibias provides a current reference for the amplifier. All the transistors in Fig. 4 are working in the saturation region. The current through the transistor M7 is about 3.2 μA according to the simulation results.

4. Verification

The proposed bandgap reference was fabricated on chartered 0.35-μm CMOS EEPROM technology. Figure 5 shows a die photo of the proposed bandgap reference. The active area of the die is 370 × 454 μm^2, including the voltage buffer.

Figure 6 shows a test image of the proposed bandgap reference when its supply voltage is 5 V. In this typical working condition, the whole supply current is 6.87 μA, including the voltage buffer, whose current is 3.6 μA.

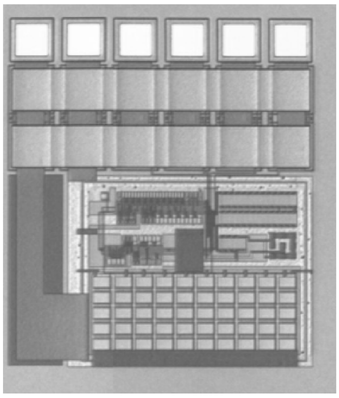

Fig. 5. Die photo of the proposed bandgap reference.

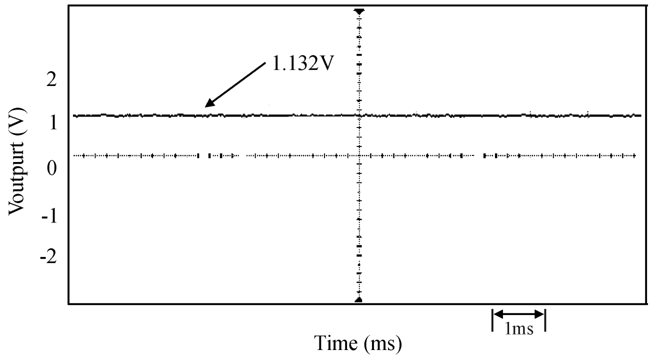

Fig. 6. Test image of the proposed bandgap reference.

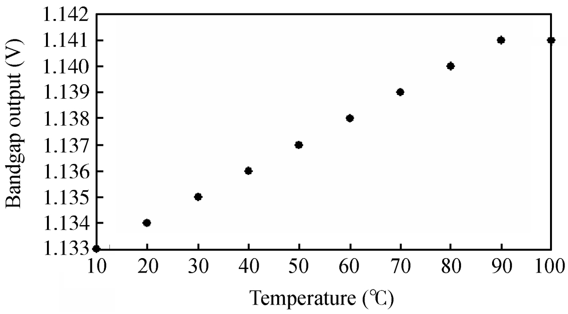

Fig. 7. Output voltage of the proposed bandgap versus temperature.

Figure 7 shows the output voltage characteristics of the proposed bandgap reference at different temperatures. The measurement result shows that the temperature coefficient is about 88.9 ppm/°C in the range from 10 to 100 °C. In energy harvesting systems, chips must operate while only consuming ultra low power. Therefore, their working temperatures are very close to ambient temperature, which means that the proposed bandgap reference can work in a wide ambient temperature range from 10 to 100 °C.

Figure 8 shows the output voltage characteristics of the proposed bandgap reference under different power supply voltages. When the supply voltage changes from 3 to 11 V, the output voltage of the bandgap reference circuit varies by about 0.875 mV/V.

In an energy harvesting system, the most important specification is the power consumption. All the power consumption values listed below include the power consumption of the voltage buffer. Table 1 shows the current consumption of the proposed bandgap reference at different temperatures. As the

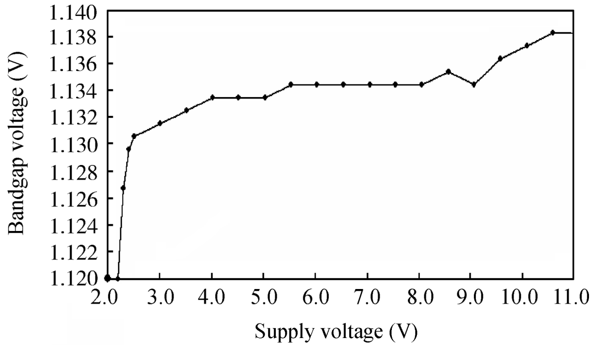

Fig. 8. Output voltage of the proposed bandgap versus supply voltage.

Table 1. Current consumption of the proposed bandgap reference at different temperatures.

Temperature (°C)	10	20	30	40	50
Supply current (μA)	6.81	6.87	6.95	7.12	7.37
Temperature (°C)	60	70	80	90	100
Supply current (μA)	7.62	7.96	8.33	8.71	9.12

Table 2. Current consumption of the proposed bandgap reference at different input supply voltages.

Supply voltage (V)	3	4	5	6	7
Supply current (μA)	6.54	6.71	6.87	7.04	7.26
Supply voltage (V)	8	9	10	11	
Supply current (μA)	7.62	8.14	8.79	10.56	

temperature increased, the power supply consumption of the bandgap increased. Table 2 shows the current consumption of the proposed bandgap reference at different supply voltages. When increasing the supply voltage, the proposed circuit consumes more supply current. The leakage current caused by the PAD has been added to the total current consumption.

5. Conclusion

A bandgap reference working in the sub-threshold region is proposed and measurement results have been shown in this paper. A voltage buffer working in the saturation region has been added to increase the drive capacity of the proposed bandgap reference. When the supply voltage is 5 V and at room temperature, the supply current is 6.87 μA, including a voltage buffer whose current consumption is 3.6 μA. The temperature coefficiency can reach 88.9 ppm/°C in the range from 10 to 100 °C when the supply voltage is 5 V, and the line regulation can reach 0.875 mV/V when the supply voltage varies from 3 to 11 V at room temperature. This design can be used widely in power management units in energy harvesting systems working in an intermittent mode.

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