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A novel self-powered wireless temperature sensor based on thermoelectric generators

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ABSTRACT

A novel self-powered wireless temperature sensor has been designed and presented for solving the power supply problem of temperature sensors. This sensor can autonomously measure temperature under positive temperature fluctuation situations. The self-powered characteristic, realized by using four thermoelectric generators, enables the sensor to operate without any batteries or other power sources. In order to obtain these features, attentions are not only focused on the method to combine signal sensing and power generating together, but also on the method to improve measurement accuracy. Experimental results confirm that this novel sensor has excellent measurement accuracy. The measured performance is consistent with the calculated characteristics. For typical application, this self-powered temperature sensor can detect fire before it develops to flashover state. And the maximum detection distance grows with the growth of burning rate. All the results indicate this innovative sensor is a promising self-powered device which can be used to measure temperature value in positive temperature fluctuation situations.

1. Introduction

As the demand for sustainable and maintenance-free sensor networks is soaring, the energy supply problem of sensors is attracting more and more attentions [1,2]. However, commercially available temperature sensors commonly require batteries as its power source although replacing batteries is a tedious and costly job [3]. Therefore, it is of high priority to develop a self-powered temperature sensor which can operate without any batteries.

Generally speaking, there are two methods to realize a sensor operating without batteries. One is the energy conversion system which can convert other kinds of energy into electrical energy [4,5], such as pressures [6], vibrations [7], winds [8], electromagnetic waves [9], ultraviolet rays [10], and heats [11,12]. The other is passive sensors which are mainly based on the surface acoustic wave (SAW) technique [13–15].

Unfortunately, each of these techniques has its own limitations and challenges. The energy conversion system needs to add an extra energy conversion module to the existing sensor system, which is against the mobility and miniaturization requirements. The SAW sensor sends a low frequency signal with low power which makes its practical propagation distance restricted to several meters [16]. And this distance is not comparable with the transmitting distance of wireless temperature sensors which are powered by batteries.

In recent years, there are some cases of thermoelectric (TE) modules used for harnessing energy for wireless sensors [17,18]. The TE modules in those studies are used as power module rather than sense module. And there has been no report that TE modules are used as both the power module and sense module in a self-powered wireless temperature sensor. The object of this study is to present the design consideration and result analysis of a novel self-powered temperature sensor based on TE modules. The TE modules, adopted in this study, are used as not only the power module but also the sense module. The final device can simultaneously perform temperature measuring and self-powering supplying functions under the positive temperature fluctuation.

2. Principle and implementation

2.1. Principle of TE generators

The principle of TE generators (TEG) can be explained by Fig. 1. An electromotive current will be generated when two dissimilar conductors are connected at two points and a temperature difference is applied on these points (Fig. 1a). This phenomenon is called Seebeck effect, and the voltage is called thermal voltage. The two connected dissimilar conductors constitute a pair of TE legs. If

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Nomenclature

U_{op}	open-circuit voltage (V)
U_o	output voltage (V)
V'	negative electrode potential (V)
I	minimum current for starting (A)
R_L	load resistance (Ω)
R_m	resistance of a TE module (Ω)
P_{max}	calculated maximum output power (W)
T	temperature need to be measured (K)
ΔT	temperature difference (K)
T_0	cold-side temperature (K)
T_1	temperature of hot side (K)
Q_{min}	minimum heat power for starting (W)
q_{min}	minimum thermal flux for starting (W/m^2)
Q	thermal radiation power (W)
P	effective thermal radiation power (W)
E_b	black-body radiation (W/m^2)
S	effective area of the hot side (m^2)
A	cross sectional area of a TE leg (m^2)
l	length of a TE leg (m)
R	distance (m)
R_{dmax}	maximum detection distance (m)
$\dot{m}$	burning rate (g/s)
h_c	calorific value (J/g)
α	Seebeck coefficient of a TE device (V/K)
κ	thermal conductance (W/K)
λ	thermal conductivity of a TE leg (W/m K)
α_r	absorptance of heat absorption coating
ε	emissivity of heat absorption coating
χ_r	efficiency of thermal radiation

many pairs of TE legs connect in series, as shown in Fig. 1b, more voltage will be generated when the temperature difference is applied on the hot and cold contacts of the device. The output thermoelectric voltage under open-circuit condition can be expressed as:

$$U_{op} = \alpha \Delta T, \tag{1a}$$

where U_{op} is the open-circuit voltage of TEG, α is the total Seebeck coefficient of a TE device. The parameter ΔT is the temperature difference across the hot and cold connects of the device.

In reality, there must be a load connected to the TEG, and the actual output thermoelectric voltage U_o can be expressed as following equation [19]:

$$U_o = U_{op}\frac{R_L}{R_L + R_m}, \tag{1b}$$

The parameter R_L is the load resistance. The parameter R_m is the resistance of a TE module. When R_L is much higher than R_m, Eq. (1b) can be simplified to Eq. (1c).

$$U_o \approx U_{op} = \alpha \Delta T \tag{1c}$$

As shown in Eq. (1c), the output voltage can be approximated as the open-circuit voltage when the load resistance is much times higher than the internal resistance of TEG. In practical applications, if the parameter R_L is high but difficult to measure, the thermoelectric voltage U_{op} can be obtained by measuring U_o. And the temperature difference ΔT can also be obtained by measuring U_o.

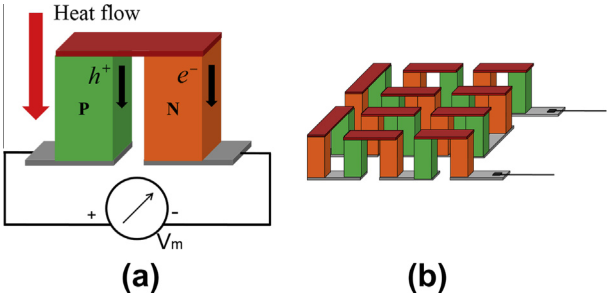

Fig. 1. The principle of Seebeck effect (a) and the principle of thermoelectric module (b).

2.2. Principle of self-powered wireless temperature sensor

The simple principle of the self-powered wireless temperature sensor (SPWTS) can be explained by Fig. 2.

A TEG and a temperature compensation component (TCC) compose a self-powered temperature probe (SPTP). The function of the TEG is to measure the temperature difference between its two sides and to convert the temperature gradient into electric power. Meanwhile the function of the TCC is to provide a temperature reference which is just like the cold end compensation for thermocouple thermometers. To ensure the accuracy, the TCC is a digital temperature sensor as usual. When the TEG is exposed to a temperature difference, it will generate a thermal voltage which is mathematically related to the temperature difference. This thermal voltage, an analog signal, is transmitted to the microprocessor by an A/D converter module. And based on Eq. (1c), the thermal voltage can be approximated as the open-circuit voltage, because the input resistance of an A/D converter is usually much times higher than the internal resistance of TEG. This thermal voltage is also supplied to other modules as power supply through a power management module. And the power management module also provides a reference voltage for the A/D converter. The cold-side temperature of the TEG is detected by the TCC. Then the cold-side temperature value is directly transmitted to the microprocessor in digital signals. To calculate the temperature, these two signals are processed by the microprocessor according to the following equation:

$$T = \frac{U_o}{\alpha} + T_0, \tag{2}$$

where T is the temperature value which needs to be measured, and U_o is the output voltage which is generated by the TEG. The parameter α is the total Seebeck coefficient of the TEG, and T_0 is the cold-side temperature. As the cold-side temperature T_0 is relatively low, the maximum measurement temperature mainly depends on the TE module whose maximum operating temperature is usually at 200 °C or higher [20,21]. However, if only using a digital sensor to measure the temperature, the maximum measurement temperature of this device will be decreased. The operating temperature of digital temperature sensors is equal to that of standard IC technology, which is below 150 °C [22]. Therefore, based on the temperature compensation principle, the maximum measurement temperature of this device will be higher than the situation that only a digital sensor is used to measure the temperature.