Electrical Power and Energy Systems 67 (2015) 417–422

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Significant performance improvement for micro-thermoelectric energy generator based on system analysis

Xiao Yu, Dehui Xu, Yanxiang Liu, Hong Zhou, Yi Wang, Xiuli Gao, Fei Feng, Yuelin Wang, Tie Li *

Science and Technology on Micro-system Laboratory, Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, Shanghai 200050, China

ARTICLE INFO

Article history:
Received 3 January 2014
Received in revised form 17 November 2014
Accepted 5 December 2014

Keywords:
Thermoelectric
System model
Optimization
Thermal match

ABSTRACT

This study presents a high-performance micro-thermoelectric generator (μ-TEG) optimized based on a system analysis. The system analysis indicates the thermal matching requirement for thermocouples dimension and array density to maximize the output power. With the measured performance of a reference device, the complicated thermal properties of various application environments can be easily derived, which are necessary parameters for thermal matching. The effect has been further proved by a CMOS-MEMS fabricated μ-TEG module for different applications. The wristwatch-TEG application produces 0.32 μW output power, realizing an improvement of three orders of magnitudes for the reported wristwatch-TEG device of the similar materials.

Introduction

Energy autonomy has been a long-standing challenge to wearable electric devices and wireless autonomous transducers which are, for example, inconvenient for battery recharging. With the decrease of power consumption in state-of-art electric devices, it becomes possible to employ the miniaturized energy harvester as the power supplier. For one of the miniaturized energy harvester, micro-thermoelectric energy generator [1] (μ-TEG) converts thermal gradient into voltage by Seebeck effect, and fabricated by microfabrication technology. Advantages including environment friendly, high energy density, static working mode and long working life, make it to be a very attractive energy havester.

The design of μ-TEG chip usually starts from the basic element of thermopile, namely thermocouple, to suppress the heat loss in heat dissipation path [2,3]. Such efforts can be analyzed via either thermal simulation [4] or experimental results [5], in terms of temperature difference across the thermocouple to that across the whole chip ratio. The optimized thermocouples are then arrayed (namely thermopile) and produce a multiplied open-circuit voltage when applyed an external temperature gradient. The output performances of fabricated μ-TEG device are mostly evaluated by the power factor PF, defined by the output power normalized to the area and temperature difference squared [6]. In this regard, it is obvious that, for a given thermocouple element, a dense array always achieves a higher PF than a sparse array does. In practical applications, however, thermal resistances usually exist at the hot and/or cold sides of the devices. Therefore, the temperature gradient dropped on the device will be decreased when the density of thermocouples is increased, since their parallel thermal resistance is also decreased. A trade-off between temperature gradient and array density then rises. As a result, a TEG device with a high PF usually turns out a low output power in cruel environment [7]. An adoptable solution to this problem is to work out the interrelation between the optimal structure dimension of TEG device and environment properties by building a system-level model [8]. In various practical cases with different external thermal resistances, it becomes challenging to build analytical models for each of them to extract the thermal properties. For instance, human body can work as a rich energy source to supply with body warmth, blood pressure and body motions to name a few [9]. Although thermoelectric generators could be one of the most promising energy harvesting method for human body network, the complicate thermal conditions of body also hinder people from optimizing the TEG device by precisely modeling the thermoelectric system. It is also difficult to predict the thermal contact conditions due to the complicate interfaces [10]. As a result, the experimental results can hardly consist with simulations.

To overcome problems of traditional optimization method, this study introduces an applicable optimization method for μ-TEG device used in various environments. With a system-level analysis, we design a μ-TEG structure with long thermocouples and low heat loss. By using a reference μ-TEG device, the optimal thermo-

* Corresponding author. Tel: +86 21 62511070 5471; fax: +86 21 62131744.
E-mail address: tli@mail.sim.ac.cn (T. Li).

http://dx.doi.org/10.1016/j.ijepes.2014.12.039
0142-0615/

couple density can be derived to reach the maximum output power for a target application environment. Practical performances are further verified by a μ-TEG module embedded with thin-film-based μ-TEG elements [11] in different application environments. Detailed analysis and optimization procedure are described as below.

System analysis

μ-TEG system model

A typical thermoelectric energy harvesting system is mainly composed with heat source, heat sink, and the μ-TEG device which consists of TEG chip(s) and the packaging frame. In practice, thermal resistors exist in each component and thermal contact interface as shown in Fig. 1. Here we use K_{source}, K_{sink}, K_m, and K_g to denote the thermal resistance of the heat source, heat sink, frame of packaging module and thermopile, respectively, K_{cm_h}, and K_{cm_c} to denote the thermal contact resistance at the hot and cold side of packaging module respectively, and K_{ct_h}, and K_{ct_c} to denote the thermal contact resistance at the hot and cold side of μ-TEG chip, respectively.

To simplify the analysis, it is reasonable to assume: (1) the heat contributions by Peltier effect, Joule heating, and Thomson effect can be neglected; (2) the dimension of the packaged μ-TEG module is much larger than that of the μ-TEG chip (as seen in most applications).

Denoted by K_{tp}, the average thermal resistance of each thermocouple, which is defined by:

$$K_{tp} = n \cdot K_g, \tag{1}$$

where n is the quantity of the thermocouples. Denote by K_c the average thermal contact resistance at the hot and cold side of each thermocouple, which can be defined by:

$$K_c = n \cdot (K_{ct\_h} + K_{ct\_c}). \tag{2}$$

For each thermocouple, the thermal resistors K_{tp} and K_c are connected in series forming one of the parallel branches of the whole thermopile. If the environment property and dimension of the packaging module are constants, K_{source}, K_{sink}, K_{cm_h}, K_{cm_c}, and K_m are then independent of the quantity of thermocouples. For convenience, those series thermal resistance can be substituted by K_{ex} defined as:

$$K_{ex} = K_{source} + K_{\sin k} + K_{cm\_h} + K_{cm\_c} + K_m \tag{3}$$

Considering the heat flow behavior is similar to current flow in closed circuit, the equivalent thermal circuit can be then illustrated as in Fig. 2. Here ΔT represents the temperature difference between the heat source and heat sink, ΔT_c the temperature difference between the hot and cold side of the μ-TEG chip, and ΔT_{tp} the temperature difference between the hot and cold junctions of the thermocouple. Taking the temperature gradients as the voltages, and the thermal resistances as the electrical resistance, it can be derived:

$$\Delta T_{tp} = \frac{K_{tp}}{K_{tp} + K_c + n \cdot K_{ex}} \cdot \Delta T \tag{4}$$

and

$$\Delta T_{tp} = \frac{K_{tp}}{K_{tp} + K_c} \cdot \Delta T_c. \tag{5}$$

According to the Seebeck effect, the generated voltage of μ-TEG device can be calculated as:

$$V = n \cdot \alpha \cdot \Delta T \cdot \frac{K_{tp}}{K_{tp} + K_c + n \cdot K_{ex}}, \tag{6}$$

where α is the Seebeck coefficient of the thermoelectric material. Setting the average electrical resistance of each thermocouple as R_{tp}, the series resistance of n pairs of thermocouples R_g is

$$R_g = n \cdot R_{tp}. \tag{7}$$

Hence the output power of the μ-TEG device under the matched load can be derived as

$$P_{out} = \frac{n \cdot \alpha^2 \cdot \Delta T^2}{4R_{tp}} \cdot \left(\frac{K_{tp}}{K_{tp} + K_c + n \cdot K_{ex}}\right)^2. \tag{8}$$

Assuming that the parasitic thermal resistance of embedded air and supporting films in the chip can be neglected, and the electric contact resistance between the metal electrodes and thermal legs (one branch of a thermocouple) is small enough, the K_{tp}, R_{tp} can be then represented by the shape dimension of the thermal leg respectively as

$$R_{tp} = \frac{l}{S_{tp} \cdot \sigma_m} \tag{9}$$

and

$$K_{tp} = \frac{l}{S_{tp} \cdot \lambda_m}, \tag{10}$$

where S_{tp} and l are the cross-section and length of thermal legs respectively (assuming the n leg and p leg with the same dimension). Here σ_m is defined by

$$\sigma_m = \frac{1}{\frac{1}{\sigma_p} + \frac{1}{\sigma_n}}, \tag{11}$$

where σ_p is the electric conductivity of p type thermal leg, and σ_n is the electric conductivity of n type thermal leg, and λ_m is defined by

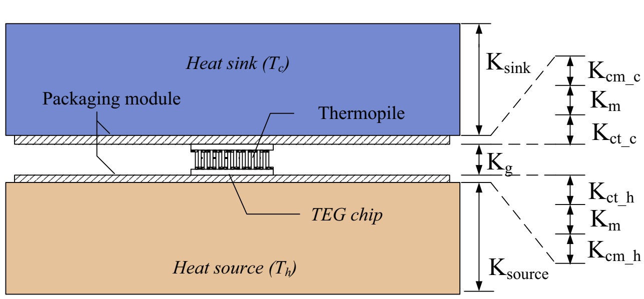

Fig. 1. Thermal structure of a thermoelectric converting system.

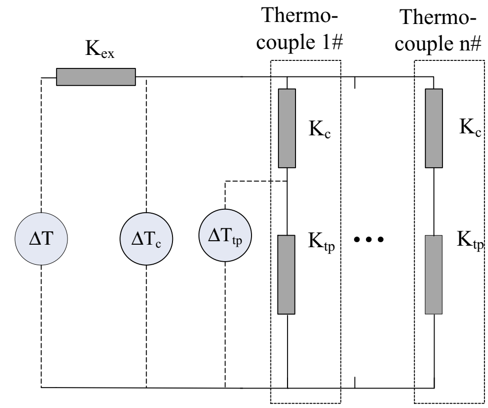

Fig. 2. Equivalent thermal circuit.