A STANDALONE PYROELECTRIC HARVESTER FOR THERMAL ENERGY HARVESTING

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Abstract: Micro heat engines incorporating pyroelectric generators provide an alternative to thermoelectric generators, to harvest electrical energy from ambient thermal gradients. In this paper we present the design, simulation and validation of such a harvester. Additionally, an electrical network model of the device has been developed, validated and used to predict the important operational characteristics like frequency, thermal power transferred, thermal profiles and others. The generator is fabricated in a cost-effective way out of a bimetallic strip and two pyroelectric generators. It is working in a complete stand-alone mode without the need of auxiliary circuitry and generates 15.7 µW from a temperature difference of 85 K.

Keywords: Micro heat engine, pyroelectric generator, bimetal, thermal gradient, energy scavenging

INTRODUCTION

Presently thermal energy is harvested using thermoelectric generators (TEGs). However, the efficiency of such devices is quite low. Moreover, miniaturized TEGs operating above 200 °C are rarely available. Although not regarded with too much attention, pyroelectric harvesters form another class of materials capable of harvesting thermal energy. Such materials are stated to have conversion efficiency as high as 50 % of the Carnot's efficiency [1]. However, pyroelectric generators respond only to thermal transients [1], which unfortunately are rare whereas spatial thermal gradients are abundant in nature. This problem can be solved by the use of heat engines as devices transporting heat intermittently between a heat source and a heat sink. Hence, a heat engine is capable of generating thermal transients from an available spatial thermal gradient. We have previously presented a harvester consisting of a PEG integrated into a micro heat engine to generate 3.03 µW of electrical energy from a temperature difference of 79.5 K [2]. The device in [2] makes use of an expensive silicon micro machined heat engine. We recently presented an inexpensive micro heat engine fabricated out of a simple bimetallic strip [3]. In this paper we present a standalone device consisting of this micro heat engine and two PEGs, to generate electrical power from a spatial thermal gradient.

THEORY

Bimetallic strips are beams consisting of two layers of materials with different rates of thermal expansion [4]. Heating or cooling of such a beam leads, aside from thermal elongation or shrinkage, to a predominant bending due to a thermally induced bending moment. Hence, huge lateral deflections can occur under thermal stress. In contrary to that, a beam made of a single material will only show elongation or shrinkage. Lateral deflections will only occur when the beam is forced into thermal buckling, e.g. by mounting it with a double-side clamping. In this set-up, a uniform beam buckles into a convex or concave shape in an unpredictable way and under a rise of temperature only. When a bimetallic beam is forced into buckling in the same set-up, it takes a predictable concave or convex deflection [4] for a rise and fall of temperature. Using these benefits we have already demonstrated a micro heat engine using a bimetallic beam in buckling mode, sandwiched between a heat source and heat sink [3]. To generate electrical power, two PEGs are attached to the micro heat engine, as shown in Figure 1. When in contact with the heat source, the PEGs and the beam are heated up. Bending moments are generated inside the beam, as indicated in Figure 1a. Once these moments exceed a threshold, the beam flips upward along with the attached PEGs and comes in contact with the heat sink (Figure 1b). Subsequently the PEGs and the beam are cooling down. When the thermal moments inside the beam exceed a threshold in the opposite direction, the beam and PEGs flip back to their initial position. The whole process continues and provides thermal transients for the PEGs. Each PEG converts these thermal oscillations into electrical power P [1]:

$$P = \left[\frac{p^2}{\varepsilon_r}\right]\frac{Ad}{\varepsilon_0}(\Delta T_p)^2 f, \tag{1}$$

where p is the pyroelectric coefficient, A is the area of cross section, d is the thickness and ε_r is the dielectric constant of the PEG, ΔT_p is the net change in temperature experienced by the PEG and f is the operational frequency of the harvester.

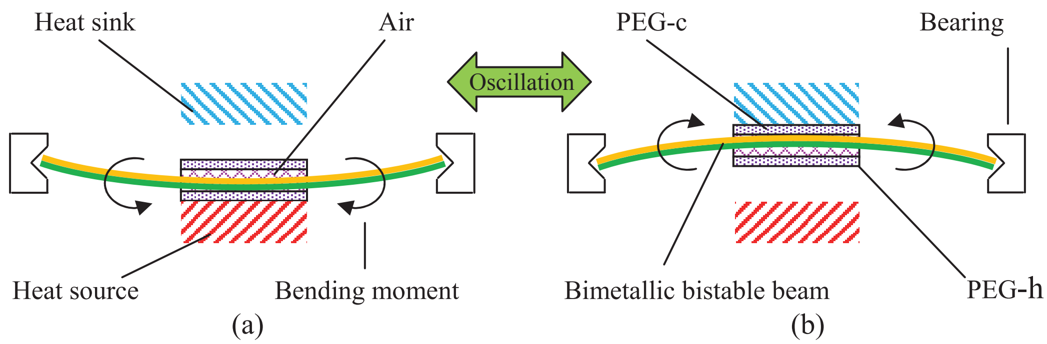

Figure 1: Schematic of the operation principle of the pyroelectric harvester, showing the PEGs and beam in contact with the (a) heat source and (b) sink . PEG-c and PEG-h indicate the PEG near to the cold and hot sides respectively.

MODELING

An electrical network model of the harvester has been developed to obtain the relevant operational parameters like the operation frequency, thermal profiles of the PEGs, thermal energy transported through the heat engine etc [3,5]. To setup the model, the harvester is divided into small slices normal to the beam axis. The network elements for a single slice are shown in Figure 2, for simplicity and clarity. Furthermore, each node shown (red dot) is connected to the corresponding node in the adjacent slices via thermal resistances. The switches simulate the switching/oscillating behavior of the harvester. For example, when the beam and PEGs are getting heated up and the temperature at the sensing node exceeds a set value, the switches flip their positions. The circuit now simulates the harvester wherein the beam and PEGs are in contact with the cold side. Subsequently the beam and PEGs are cooling down. When the temperature at the sensing node falls below another set value, the switches flip back to their initial position. The whole process continues simulating the oscillation of the beam and PEGs between the hot and cold sides. The entire electrical equivalent circuit is simulated in *PSpice 16.0*.

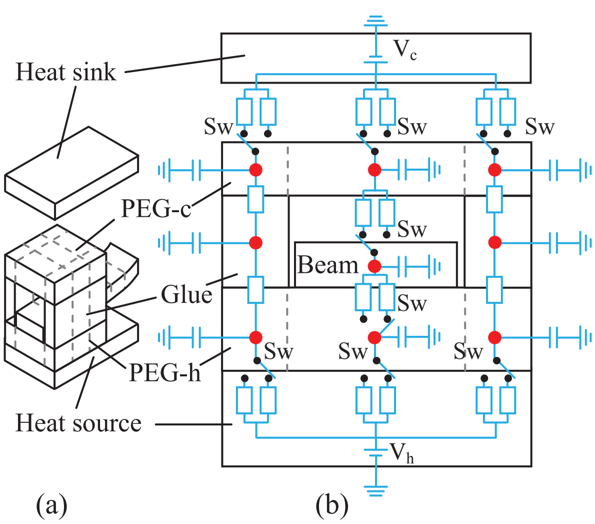

Figure 2: Electrical network elements of the PEGs with inserted bimetallic beam, with thermal resistances, capacitances and switches representing the operation and thermal characteristics of the harvester.

FABRICATION

Figure 3 explains the attachment of the PEGs to the micro heat engine. The 40×6 mm^2 area-sized micro heat engine is fabricated from a 280 µm thick sheet of bimetal (type *MS, Rau GmbH*) by laser micromachining (*ACI Laser Components DPL Magic Maker Nd:YAG*). The 10×10 mm^2 sized PEGs, each with an additional 2×2 mm^2 protruded section, are cut from a 270 µm thick sheet of *Vibrit 1100* (*Johnson Matthey Piezoproducts*) using the same laser. 100 µm diameter copper wires are soldered onto the protruding regions to create flexible electrical contacts. The heat sink and source are fabricated out of copper blocks. The bearings, which also act as the thermally insulating spacers between the source and sink, are fabricated out of PEEK. These bearings have a wedge-shaped profile supporting the beam. This emulates the behavior of a hinge and ensures that the harvester oscillates from small thermal gradients. One bearing is fixed, whereas the other one is movable along the beam axis. A tuning screw attached to the latter helps to adjust the axial pre-stress and thereby the buckling temperatures. The assembly is held together by two screws and is 7.6×10×59 mm^3 in size.

VALIDATION

The schematic of the test setup used to evaluate the harvester and a close-up photograph of the harvester in the test set-up are shown in Figure 4. It consists of two computer-controlled thermal chucks mounted on XYZ- and Z- stages. The upper chuck is moved away to place the harvester on the lower chuck. Thereafter,

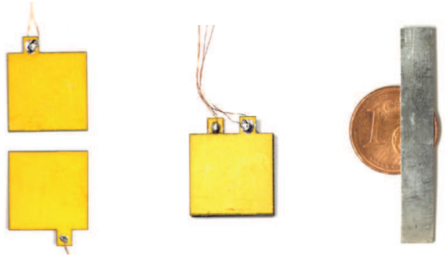

Figure 3: a) Fabricated PEGs with soldered wires b) PEG assembly and c) bimetallic strip. The PEGs are kept one over another, with a 300 µm spacer in-between. Thereafter, glue is applied to the top and bottom edges. The spacer is removed once the glue has set. Subsequently, the beam is inserted into the gap between the PEGs.

the stages are adjusted such that the harvester is held tightly in its position. A thin film of thermal paste is applied at the interfaces between the harvesters and chucks to minimize the thermal contact resistances. The temperatures of the chucks are set and monitored to the desired value using a *Labview 8.2*-based user interface.

The temperature of the hot chuck is set to 108 °C. Thereafter the temperature of the cold chuck is adjusted such that the engine is running with equal heating and cooling time. The voltage across each PEG is measured, one at a time, using a *Keithley 6514* electrometer coupled to a *Tektronix TDS2014* oscilloscope. A typical voltage waveform across one of the PEGs is shown in Figure 5. From the measured peak-to-peak voltage and frequency, the electrical power generated in each PEG is calculated as [2]:

$$P = C\Delta V_p^2 f \tag{2}$$

where C is the capacitance of the PEG and ΔV_p is the net change in the open circuit voltage across it.

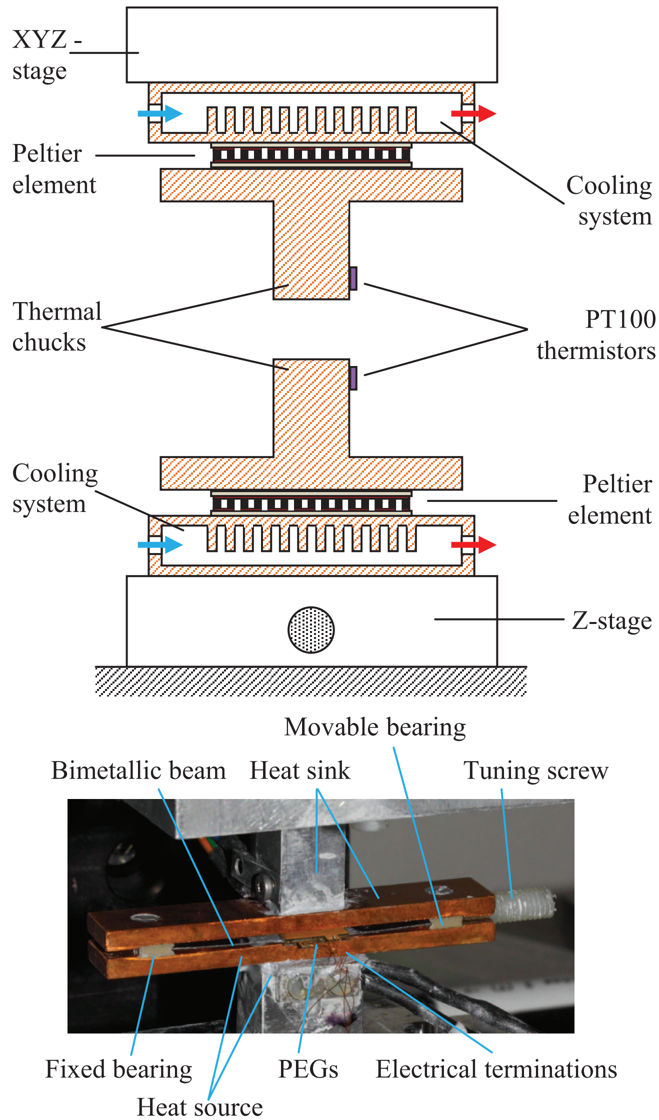

Figure 4: Schematic drawing of the test setup used to characterize the harvester (top) and photograph of a pyroelectric harvester in the test setup. Both the thermal chucks are capable of functioning as either a heat source (hot side) or sink (cold side). In this work the upper chuck is used as the hot side and the lower one as the cold side. This reduces the influence of convection to a great extent.

RESULTS AND DISCUSSION

In a series of experiments the temperatures of the hot and cold chucks were varied from 108 to 88 and 23 to 43 °C respectively, in steps of 2 °C. The variation of the operational frequency of the harvester with the temperature difference between the hot and cold chucks (ΔT_{hc}) is shown in Figure 6. The simulated values represent the best fit possible with the previously mentioned electrical network model. As a result, the frequency increases in a nearly linear fashion with ΔT_{hc}. The operational frequency is reduced significantly compared to data obtained from an engine without PEGs [3]. For example, the operational frequency of the present device is only 0.11 Hz compared to 0.88 Hz in [3], from a ΔT_{hc} of 71 K. This is attributed to the increased number of thermal interfaces and newly integrated PEGs of relatively high bulk thermal resistances. The dependency of the power generated independently by the two generators as well as their sum total on ΔT_{hc} is shown in Figure 7. The simulated values of power are calculated using equation (1), based on the data obtained from the electrical network model. The harvester generates an electrical power of 15.7 µW in total from a temperature difference of 85 K. The linear increase of output power vs. the temperature difference also reflects the linear increase of the

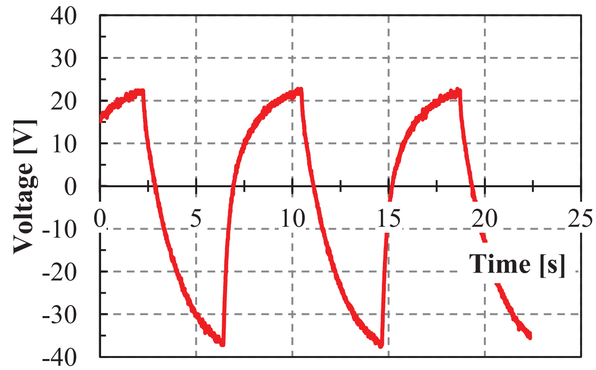

Figure 5: Recorded open circuit voltage waveform across PEG-c for temperatures of 108 °C and 23 °C at the hot and cold side, respectively.

operation frequency with ΔT_{hc}. The small difference in the power generated by the two PEGs is attributed to the unequal thermal contact resistances with the source/sink. Again, the electrical network model is capable to predict the trend and the values of the output power quite well. The small deviation of the measured power from the power estimated using the electrical network model is due to the increase in thermal contact resistance for a small period of time, before each state transition.

CONCLUSION

A standalone pyroelectric harvester has been fabricated by simple laser micromachining and conventional milling process. For a temperature difference of 85 K the harvester generates an electrical power of 15.7 µW. Additionally, the harvester is capable of operating with the cold side kept above room temperature. This favors the cooling of the cold side via a heat sink and natural convection only. Moreover, the harvester is capable of operating from a temperature difference as small as 45 K, still generating 3.3 µW of electrical power. This minimum

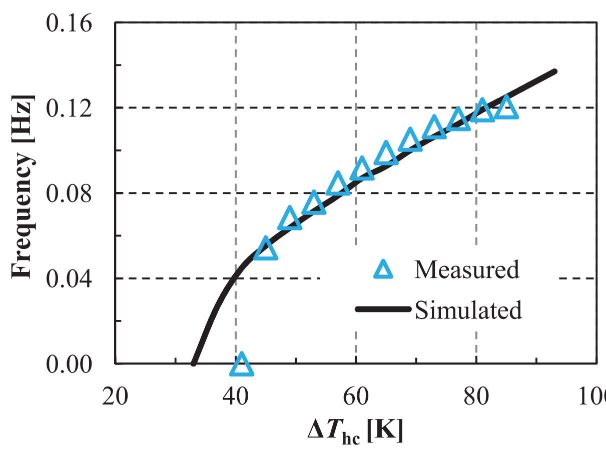

Figure 6: Variation of the operational frequency f with the temperature difference between the heat source and sink (ΔT_{hc}).

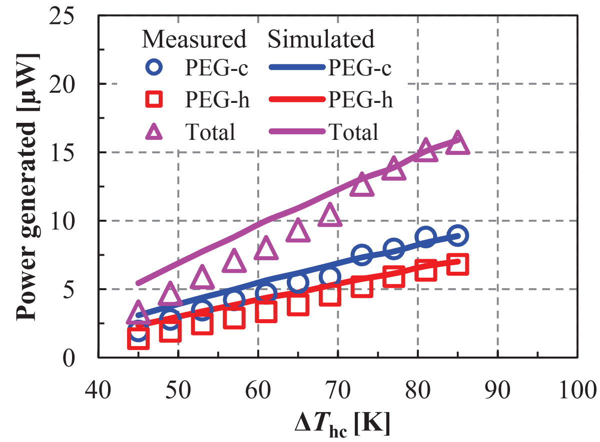

Figure 7: Dependency of the power generated by each PEG and of the total power on ΔT_{hc}.

generated power is comparable to that obtained using the harvester in [3], though only from a much higher temperature difference of 79.5 K. A transparent electrical network model of the harvester has been developed and validated, with a good match of model and experimental data. This is an important finding, as a full dynamic FEM model of the micro heat engine with attached PEGs would require a considerably higher computing power with only a limited insight into the influence of relevant material and design parameters onto the performance of the harvester. Further research on this energy harvesting concept will focus on an increase of the operational frequency utilizing liquid metal droplet arrays at the thermal interfaces [6] and implementation of SSHI circuits [1].

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