EH Performance of an Hybrid Energy Harvester for Autonomous Nodes

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***Abstract* — This paper reports the Energy Harvesting (EH) performance of a hybrid energy harvester able to collect energy form different energy sources: thermal, solar and electromagnetic. The main block of the system is the quarter-wavelength patch antenna, operating in the Industrial, Scientific and Medical (ISM) frequency band 2.4-2.5 GHz. The antenna has been designed and optimized to support a Thermo-Electric Generator (TEG) and a Solar Cell on its top. Moreover, a rectifier has been designed to work with the antenna and a DC-DC converter has been used to manage the TEG output voltage.**

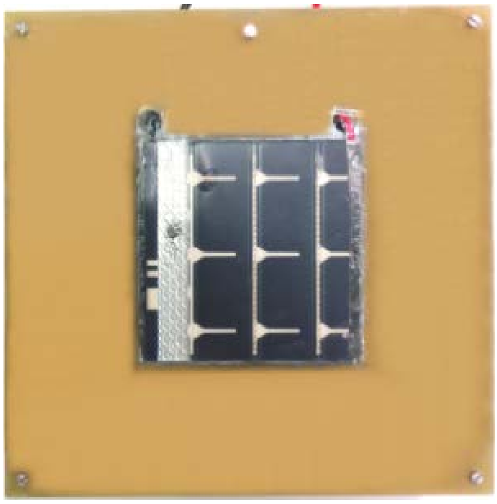
***Index Terms* — Energy harvesting, hybrid system, solar cell, thermo-electric generator, rectifier.**

I. Introduction

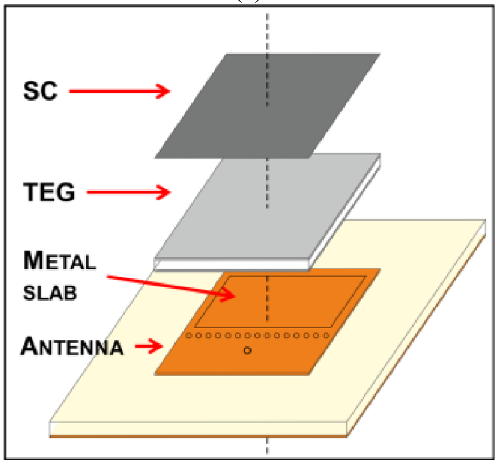
In the last decade, the Internet-of-Things (IoT) [1] and the Ubiquitous Electronics (UE) [2] paradigms are contributing to the spread of electronic devices. The need of monitoring and collecting data from environments and objects in several applications, such as logistics, manufacturing, and healthcare, are introducing new technological challenges. Energy autonomy and wireless communication capability are crucial aspects of the devices for the development of the above mentioned applications and, in this scenario, technologies like Radio Frequency IDentification (RFID) and Wireless Sensor Networks (WSNs) perfectly match the demand for electronic to satisfy those characteristics.

Autonomy is one of the key aspects for RFID tags and WSNs nodes, and Energy Harvesting (EH) [3-5] is a possible approach to supply these devices by collecting energy (EM, thermal, solar, wind, etc.) from the environment and avoiding power grid connection or batteries. Since the environment, in most of the cases, provides intermittent energy sources, the systems able to exploit only one kind of energy could be not valuable and work properly in different environments or conditions. Devices able to collect energy from several sources, such as those ones described in [6-10], can be more versatile and provide robust solutions for several sensor applications in many application fields. Example applications include autonomous and smart metering in buildings, cities, agriculture, as well as sensor networks for industrial environments.

In this paper, the EH performance of a hybrid energy harvester, able to collect energy from the EM, thermal and solar energy are reported. The EH from these kinds of energy is performed by means of a rectifier [11] connected to the antenna for the EM energy, a Thermo-Electric Generator (TEG) for the thermal one and a Solar Cell (SC) for the solar one.



(a)



(b)

Fig. 1. Prototype of the multi-harvester system (a) and its structure (b). The patch, the TEG and the SC dimensions are 35x35 mm^2; the substrate dimensions are 80x80 mm^2.

II. System Description

The multi-harvesting system, the basic structure and the EM antenna performance of which have been already documented in [9], is shown in Fig. 1. A similar structure, without the SC, and its operating principle are documented in [7, 8]. In the present case, the antenna has been slightly modified, without affecting the EM performance, to improve the thermal one.

The structure consists of a stack of a quarter-wave patch antenna that acts as a physical support for the TEG [12] and the SC [13]. This allows for a compact and highly integrated solution. Moreover, the structure has been optimized in agreement with the constraints introduced by the TEG and the SC in order to optimize their EH performance. In particular, assuming the heat/solar source located over the multi harvester, the SC is positioned on top of the structure in order to be directly exposed to the light. For the same reason, the hot side of the TEG is in direct contact with the SC and its cold side with the patch antenna and, then, with the ground plane with an heat-sink.

In the previous work, due to the high thermal resistance of the vias array in the substrate between the heat-sink and the cold side of the TEG, a low output voltage was obtained [9]. In this work an improved prototype is presented where a slit is formed in the FR4 substrate in order to accommodate a metal slab able to maintain high thermal conductivity between the heat-sink and the cold side of the TEG.

III. System Performance

In this section, the EM, thermal and solar EH performance of the entire system are reported and analyzed. Several measurements campaigns have been performed. The EM EH has been evaluated by means of signal generator and multi-meter. The voltage and temperature measurements of the TEG and the SC have been performed by using the Analog-to-Digital Converters (ADCs) of an Arduino UNO board [14] and the LM35 sensors [15], respectively, as described in [8].

A. Antenna with rectifier

The rectifier is a single stage voltage multiplier [11] and its performance have been analyzed by measuring the output DC signal in two cases: connected directly to a 50 Ω signal generator; and connected to the harvester patch antenna and illuminated by another antenna at the output of the signal generator. Fig. 2 shows the output voltage across the 4 kΩ load resistor as a function of the RF input power available at the rectifier (checked with the spectrum analyzer) obtained in the two cases: at 0 dBm we have an output power of about 0.56 mW an efficiency of about 56 %, an output voltage of about 1.5 V.

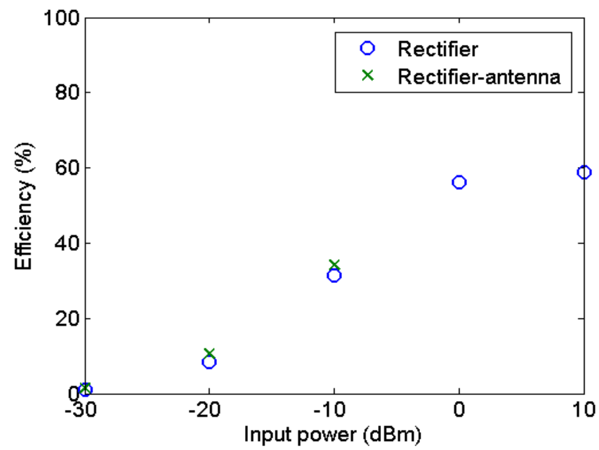


Fig. 2. DC output voltage generated by the rectifier vs. the RF input power.

B. TEG

The TEG performance has been analyzed by measuring the generated voltage as a function of the temperature gradient. An heat source has been The results plotted in Fig. 3 have been computed by averaging a sequence of voltage samples measured across a load resistor of 100 kΩ during the steady-state of each temperature gradient value. The voltage shows a quite linear behavior.

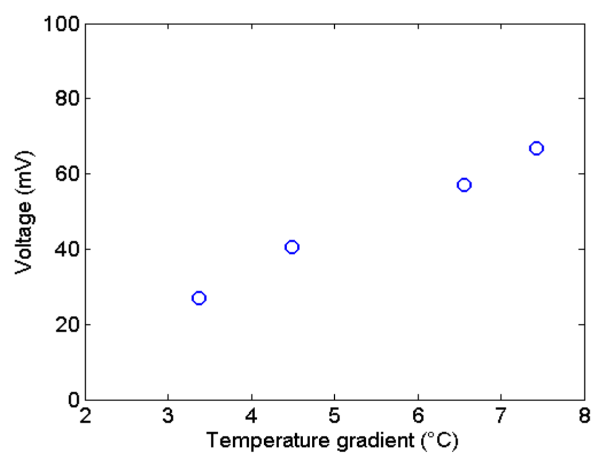


Fig. 3. DC voltage generated by the TEG vs. temperature gradient.

The voltage generated by the TEG in the analyzed conditions is in the order of a few tens of millivolts (Fig. 3) and it can be used to improve the performance of a rectifier, as demonstrated in [8] or, alternatively, it can be increased by means of a DC-DC converter connected to the TEG as described in the following subsection.

C. TEG with DC-DC converter

In order to improve the voltage collected from the TEG and make it useful to power up the electronic device, an integrated DC-DC converter, the LTC3108 [16], has been connected to the TEG's terminals.

The voltage generated by the DC-DC converter across a 100 kΩ has been measured by varying the temperature gradients. Then, the delivered power has been computed and plotted in Fig. 4. Such as in the previous case, the power has been evaluated by averaging a sequence of samples measured during the steady-state of each temperature gradient value. It must be noticed that this is the power provided by the nominal 5V storage output to the load: this means that, it can be used to charge a capacitor and then to supply, on request, the electronic circuitry.

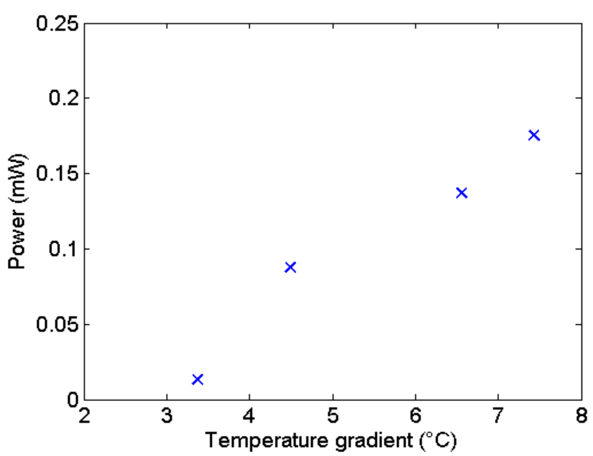


Fig. 4. Power provided by the DC-DC converter vs. temperature gradient.

The generated power differs from the datasheet values because the measured temperature gradient is between the TEG hot side and the antenna ground plane with the heatsink, not the cold side of the TEG, buried in the structure.

D. Solar cell

The SC, on the top of the structure, is able to collect energy from the solar rays or any other light source. In full sun condition the module is able to produce 2.8 mW/cm^2 [12]. In the present case the solar cell, the dimensions of which are 3.5x3.5 cm^2 is able to produce up to 34.3 mW in ideal conditions. The maximum voltage measured in real conditions across a load of 100 kΩ, is 1.7 V, that corresponds to the maximum voltage reachable with this SC.

E. Outdoor performance

An outdoor measurements campaign has been performed. The weather conditions were: a sunny day with a temperature of 34 °C and a wind of about 8 km/h. In this conditions the SC has been able to generate constantly 1.7 V across a load of 100 kΩ. The TEG generated a maximum output voltage of about 2.5V across a load of 100 kΩ which power of 0.06 mW; the mean voltage was 1.5 V and the mean power 0.025 mW.

IV. Conclusion

In this work, the EH performance of a versatile and robust hybrid harvester are reported. The system can be used in several applications and environments, and is able to harvest EM, solar and thermal energy improving the nodes autonomy. The harvested power depends on the environments conditions and the transducers performance. The measured powers reach values up to some mW useful to store energy and to supply electronic devices such as low power sensors nodes.

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