Polymer energy harvester for powering wireless communication systems

F.-A. Costache*, C. Schirrmann*, R. Seifert*, K. Bornhorst*, B. Pawlik*, H.-G. Despang*, A. Heinig*

*Fraunhofer Institute for Photonic Microsystems, Maria-Reiche Str. 2, Dresden 01109, Germany

Abstract

Energy was generated from harvester structures based on various electroactive polymer thin films of different electro-mechanical properties under applied pressure and frequency characteristics specific to human motion. A self-priming energy harvesting circuit was designed and optimized to collect and store this energy. The circuit enables a gradual increase in voltage each time pressure is applied on the harvester and more energy to be stored with each generation cycle. Thus stored energy of up to 10 μW/cm² at 10 Hz was successfully used to power a wireless transmitter. The results revealed that, with increasing number of layers in a fluoropolymer harvester system, the time between signal transmissions could be shortened more and more.

Keywords: Energy harvesting; Electroactive polymers; Self-priming circuit; Wireless transmission.

1. Introduction

Harvesting energy from the surrounding environment and converting it into usable electrical energy has become an attractive approach to producing sustainable power sources for wireless sensors and low-power electronics. In particular, emergent polymer materials are of great interest for electrostatic energy converters due to their large relative permittivity and simple processing [1, 2]. Polymers are usually employed in capacitive designs, which are passive structures that require an energy cycle for the mechanical-to-electrical energy conversion [3]. The easiest to implement energy conversion cycle to a polymer capacitor includes four steps: 1. mechanical compression for...
maximizing the initial capacity; 2. electrical charging with an external polarization source; 3. mechanical relaxation
to a minimum capacity; 4. charge collection. Energy conversion at each cycle arises hence from the total change in
capacity. For such harvesting concepts, however, charge losses due to leakage in the harvesting circuit pose a
serious challenge.

In this paper, the energy necessary to power a wireless transmitter could be harvested by means of a self-priming
circuit from polymer stacks subjected to mechanical deformation.

2. Electrostatic polymer energy harvester

2.1. Energy harvester structure and self-priming circuit

The harvester samples consisted of stacks of polymer thin films sandwiched between electrodes and electrically
contacted as in a parallel connection of plane capacitors. Namely, several commercially available polymers of
relatively large permittivity $\varepsilon_r$, i.e. polyamide (PA 6.6, Goodfellow), poly(vinylidene fluoride-trifluoroethylene-1,1-
chlorofluoroethylene) (P(VDF-TrFE-CFE), Piezotech) with a mole ratio of 61.7/29.8/8.5 mol% (PTC 8.5) and
thermoplastic polyurethane elastomer (PU 85, BASF Elastollan) were used as dielectrics (Fig. 1a). Polymer thin
films about 25 $\mu$m thick were obtained by spin coating on a glass substrate and square-shaped copper electrodes of
20 × 20 mm² area and 100 $\mu$m thickness were glued on both sides of the polymer film (Fig. 1b). The results
indicated that with this method, additionally to the polymer layer, an air gap about 5 $\mu$m thick is formed.

To simulate the vibration specific to human motion, the polymer stacks were subjected to dynamic deformation
by means of a self-developed pneumatic piston setup of low but variable frequency and pressure characteristics. As
shown in Fig. 1c, the piston impacts upon the harvester stack causing a mechanical deformation which, translated
into the electrical capacity change, can be processed by the self-priming circuit.

Fig. 1. (a) Permittivity $\varepsilon_r$ of the polymers studied in this work and resistance R of polymer film stacks. The latter was measured in the developed
set-up at 4 Hz and 1 bar. (b) Principle sketch of a 20×20×0.2 mm³ polymer harvester with an air gap. (c) Image of the harvester test set-up
including (I) pneumatic piston setup; (II) polymer harvester and (III) harvesting circuit.

| Material   | $\varepsilon_r$ @ 100 Hz | R [MΩ] – this work |
|------------|-------------------------|--------------------|
| PTC 8.5    | 45[^1, 2]               | 27                 |
| PU 85      | 7.0[^3]                 | 95                 |
| PA 6.6     | 3.8[^3]                 | 54                 |

Fig. 2. (a) Energy harvesting circuit diagram comprising the following modules: 1 – initial load circuit, 2 – self-priming circuit, 3 – variable
polymer capacitor (harvester), 4 – self-controlled storage switch, 5 – storage capacitor, 6 – self-controlled out-coupling switch, 7 – out-
coupling connection. (b) LTSpice simulation of several circuit modules from (a), i.e. simulated voltage vs. time, corresponding to a polymer
harvester deformation at 4 Hz and 1 bar, at: (2) the self-priming circuit and energy harvester, (5) the storage capacitor and (7) the out-
coupling of the harvesting circuit.
A self-priming energy harvesting circuit for electrostatic energy harvesting based on [5] was improved for system losses and used to collect and store the generated energy. The circuit included several modules, for instance an initial load module, a self-priming module for the polymer harvester and an energy storage module (Fig. 2a). An initial load of 5-10 V was used in this circuit. The self-priming circuit enables recovering the charge lost in the system per cycle, i.e. harvester stack compression and relaxation, and a gradual increase in voltage with each generation cycle (Fig. 2b). Although with this concept the voltage could potentially be increased to much higher values, the maximum voltage was limited by the storage switch to $U_{\text{max}} = 100$ V to avoid the usage of high voltage components. Fig. 2b shows the simulated output coupling signal of the harvesting circuit. This was in good agreement with the signal measured upon harvester compression (see Section 3).

2.2. Energy harvester characterization

Measurements of the change in capacity with the applied pressure, which provides the harvested energy, were carried out for the samples described above by means of an LCR meter (HP 4284A) directly at the sample (Fig 2a, module 3). These measurements revealed that the largest capacity change of about 3 nF was obtained for the PTC 8.5 terpolymer and the lowest for PA 6.6 of about 0.3 nF (Fig. 3a). Furthermore, the corresponding harvested power obtained from all polymer harvesters investigated increased with the applied vibration frequency (Fig. 3b). The highest harvested power of $10 \mu W/cm^2$ at 10 Hz was obtained again from the PTC 8.5 samples (Fig. 3b).

![Fig. 3. (a) Change in capacitance vs. applied pressure for various polymer harvesters. Measurements were performed with an LCR meter directly at the harvester (PTC: P(VDF-TrFE-CFE), PU: polyurethane, PA: polyamide). (b) Harvested power as a function of frequency for various polymer harvesters (measurement at $U_{\text{max}} = 100$ V).](image)

The obtained results indicate that for the design proposed, the permittivity $\varepsilon_r$ of the films and resistance $R$ of the harvester stacks (Fig. 1a) play an important role in the amount of harvested energy, namely $\varepsilon_r$ is responsible for the initial capacity and $R$ for additional losses in the system. The data obtained in Fig. 3b are comparable to some extent and this could be explained by extra system losses due to the fact that the PTC 8.5 harvester has low resistance while the PU 85 and PA 6.6 harvesters exhibit high resistance.

3. Application for powering wireless transmitters

3.1. Telegram transmission

Both the polymer harvester and the harvester circuit were optimized for powering a wireless transmitter (RF module, EnOcean PTM 230). By means of the developed harvester circuit, charge was stored at each cycle in the storage capacitor until the energy necessary for powering the wireless transmitter was reached. For the purpose of using the polymer harvester as a power supply and thus be able to send telegrams, the circuit of the transmitter was adapted to receive the power generated by the harvester and stored in the storage capacitor. The measurements indicated that 0.25 mJ energy (current 0.2 $\mu A$) was sufficient to transmit one telegram with the EnOcean transmitter.
As above stated the harvested power at the storage capacitor increases with the vibration frequency. Fig. 4a presents, the power generated by terpolymer harvester samples with increasing number of layers. These measurements reveal that the harvested power also increases with the number of layers.

![Graphs showing harvested power and time between transmissions](image)

Fig. 4. (a) Harvested power as a function of frequency for harvesters based on multi-layers of PTC 8.5 polymer. N denotes the number of layers. (measurement at $V_{\text{max}} = 100$ V). (b) Time between telegram transmissions with the energy supplied by a polymer harvester with increasing number of layers and the corresponding current (measurements at 4 Hz and 1 bar).

Such multi-layered harvesters were used to power the wireless transmitter. The results in Fig. 4b indicate that these harvesters could deliver sufficient energy to transmit telegrams, the time between transmissions being shorter and the obtained current larger with increasing number of layers in the polymer harvester.

The optimization of the polymer stack design and of the components in the harvesting circuit (i.e. the storage capacitor) could provide means for further improving the generated energy and reducing the time needed to send RF signals. Upon such improvements the time between two telegram transmissions could potentially be reduced to seconds. Measurements revealed that, after an initial loading, the system could work completely autonomously until the storage capacitor was fully depleted.

4. Conclusions

In this paper, energy was generated by subjecting thin films of selected electroactive polymers to a quasi-static mechanical deformation. The mechanical work could be converted into electrical energy by varying the capacitance of various polymer stacks. This energy could be stored and used to power a wireless transmitter. The time between telegram transmissions could be shortened by further optimizing the harvester design and the circuit. In a next step, such harvesters will be integrated in footwear.

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