Flexible and Robust Multilayer Micro-Vibrational Harvesters for High Acceleration Environments

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Abstract. This paper presents the fabrication and characterization of multilayer PVDF resonant micro-vibrational energy harvesters designed to withstand environments in which high levels of acceleration are present. The multilayer cantilevers are fabricated by combining two folded PVDF stacks into a multilayered, bimorph structure. This acts to increase the overall capacitance of the harvester, a problem that plagues PVDF cantilevers as a result of its low dielectric constant. Moderate powers (7 µW) are produced from the cantilevers even at high acceleration levels (20 g) due to the limited piezoelectric coefficient of PVDF; however, as a result of the high tensile strength and low elastic modulus of PVDF, the cantilevers are able to survive extremely high accelerations (> 4000 g) without breakage – a critical problem for harvesters based on brittle piezoelectric materials and substrates.

1. Introduction

Our increasing desire to measure the world around us has pushed the development of autonomous wireless sensor nodes establishing a need for self-sufficient power sources. At the same time, advances in ultra-low power communication strategies, such as the ultra-wideband radio technology (UWB), continue to reduce the energy requirements of such nodes [1]. Thus, in many environments, piezoelectric harvesters are more than capable of fulfilling the power requirements of sensor nodes; however, designing an inertial harvester to survive conditions in which low-frequency, high amplitude vibrations (or shocks) are present (i.e. transportation applications, industrial machinery, etc.) remains a challenge [2, 3]. Inertial energy harvesters based on rigid, brittle piezoelectric materials such as PZT, PMN-PT, AIN, etc. and relatively stiff, fragile substrates such as silicon require large structures, and carefully designed stops to limit cantilever displacement, achieving only minor gains in terms of reliability [4].

Polyvinylidene fluoride (PVDF), a flexible polymeric piezoelectric material, is often overlooked in the design of inertial harvesters due to its relatively low piezoelectric coefficient (23 pC/N), and its low dielectric constant ($\varepsilon_r=10$) causing it to generate low currents, and comparatively high voltages. However, PVDF offers a compliant solution enabling small, low frequency structures which are able to withstand high deformations without failure.

Thus, here we present fully packaged multilayer cantilevers fabricated by combining two folded PVDF stacks into a bimorph structure and encapsulated in a PMMA encasing. The harvesters are...
characterized at continuously varying moderate accelerations (20 g) and subjected to high-amplitude impacts in order to evaluate their performance and durability.

2. Design and Fabrication

The low dielectric constant of PVDF presents a concern, especially for low-frequency inertial harvesters, since the optimum load is inversely proportional to $\omega C$, where $\omega$ is the angular frequency and $C$ is the capacitance of the harvester. The optimum load of PVDF harvesters can often be tens of megaohms – signifying high voltages but very little current passing into the power management circuitry [5, 6]. The capacitance of the structure is proportional to the number of layers which make up the device; therefore, combining several layers in parallel lowers the optimum load of the harvester, allowing increased current to flow [7, 8]. Thus, the design of the PVDF harvesters incorporates multiple thin layers of piezoelectric material connected in parallel (as opposed to a single thick layer) in order to augment the capacitance of the device. 4-layer harvesters achieve a capacitance of 850 pF, while 2-layer devices have a capacitance of approximately 420 pF.

Piezoelectric harvesters occupying a volume of $64 \text{ mm}^3$ ($4 \times 4 \times 4 \text{ mm}^3$ - including displacement) were fabricated by combining two folded PVDF stacks into a multilayered, bimorph structure as illustrated in figure 1. The PVDF used in these harvesters was supplied by Measurement Specialties. Their thinnest piezoelectric films were selected - 28 µm thick with Cu/Ni (70/10 nm) pre-sputtered electrodes on either side of the film. A compliant and easily applicable dry adhesive layer (ARClear) with a thickness of 50 µm was added between successive layers of PVDF to bind the structure together. Both materials, the PVDF and the dry adhesive, were patterned by laser ablation (Trotec Speedy 300).

![Figure 1: 3D schematic of a folded multistack PVDF harvester.](image)

As demonstrated in figure 1, vias patterned into successive layers of PVDF and dry adhesive allow electrical connections to be made between the layers. The layers are connected in parallel; therefore, the PVDF is polarized in the same direction on either side of the neutral plane of the cantilever. For a simple 2-layer bimorph structure, the layers are electrically connected in the center plane. For multistack structures, the PVDF layers are again electrically connected in the center plane, but vias are also patterned to connect the inner electrodes of the folded PVDF stacks. An additional via is also required to make the external connections as shown in figure 1.
Tungsten proof masses (2 x 4 x 0.5 mm\(^3\)), extending to half the length of the cantilever, were also patterned by laser machining and fixed to the end of the cantilevers with a layer of dry adhesive. A single proof mass was added in the case of the 2-layer structure in order to tune the resonance frequency to 100 Hz, while two masses were used in the case of the 4-layer structures to reduce the frequency to 350 Hz.

The harvesters were then placed in a PMMA package (1 x 1 x 0.5 cm) with a 4 mm gap between the ceiling and the floor of the cavity to limit the displacement of the mass at high accelerations (figure 2)

![Figure 2: A packaged multilayer (4 layer) PVDF harvester on a 1SFr. coin (1 x 1 x 0.5 cm).](image)

3. Characterization

Electromechanical testing of the cantilevers using a continuous sinusoidal acceleration of 20 g with and without the PMMA packaging reveals a slight degradation in the harvester performance as a result of increased damping within the package. The maximum power output is achieved by the simple bimorph structure which generates 7 µW at 100 Hz for an input acceleration of 20 g (figure 3). The quality factor of the structure (Q = 4) is very low in comparison to most resonant energy harvesters evident by the large observable bandwidth (FWHM = 25 Hz). A portion of the damping can be attributed to the packaging; however, as stated previously damping of the structure is comparable even when unpackaged. The main contributor is the PVDF which has a lower Q than ceramic piezoelectric materials. In addition, the dry adhesive also contributes to the increased damping of the structure.

![Figure 3: Generated power as a function of frequency and acceleration from a packaged bimorph PVDF cantilever excited at 20 g.](image)
4. High Acceleration Testing

Shock tests performed by inflicting impact accelerations up to 4000 g show that the cantilevers are able to survive high acceleration environments. The harvesters were placed on a large mass (as illustrated in figure 4a) equipped with an accelerometer and dropped from 40 cm onto a cement floor. The voltage generated by the oscillating harvester was recorded and is presented along with the acceleration profile in figure 4b. After repeated high acceleration shock tests, the harvesters were retested with a continuous sinusoidal acceleration of 20 g. These tests which show equivalent performance before and after the shock tests demonstrate that harvesters are not damaged by the high acceleration impacts.

![Shock test setup](image)

Figure 4: a) Shock test setup to measure the effects of high acceleration impacts on vibrational energy harvesters. b) Shock impulse and the voltage signal output from the harvester.

Lifetime tests were also performed on the harvesters by providing a sinusoidal input excitation at the resonance frequency of the cantilevers over an extended period (18 hrs. at 20 g). In these tests, the harvesters undergo 6.5 million cycles. The RMS voltage generated by the harvesters was recorded periodically throughout these tests. Figure 3 shows a gradual reduction of the measured power by 50% after several hours of operation; however, upon successive testing after a period of rest the original power was recovered. The reduction observed in the output power the harvester over time is mainly due to a shift in its resonance frequency as evidenced by the increase in output power observed when the frequency of the input vibrations is adjusted after 18 hours of operation as shown in figure 5.
Figure 5: Accelerated lifetime tests driving the harvesters through 6.5 million cycles at an acceleration of 20 g. The power decay over time is mainly due to a shift in the resonance frequency.

5. Conclusions
The cantilevers produced in this study are small, yet flexible allowing low vibrational frequencies to be targeted while remaining robust enough to survive high acceleration environments. Optimization to improve the modest output power is currently ongoing.

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