Highly Efficient Low-frequency Energy Harvester Using Bulk Piezoelectric Ceramics

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Abstract. This paper describes a new way of manufacturing efficient vibration energy harvesters using thick films of piezoelectrics. The presented fabrication process is based on the thinning of high-density bulk Lead Zirconate Titanate (PZT) ceramic substrates, which enables the realization of thick layers (10-100 μm). Using this fabrication approach, we prepared two types of cantilever-based vibration energy scavengers (unimorph and bimorph) operating at very low frequency (~15 Hz) with a 50 μm PZT final thickness. Given that under a harmonic 10 mg vibration the harvested mean power was 1.3 μW and 3 μW respectively, these devices rank among the best ever-reported vibration energy scavengers according to commonly accepted figures of merit. The presented fabrication approach is therefore believed to be a good candidate for the manufacturing of highly efficient piezoelectric energy scavengers operating at very low frequency.

1. Introduction

Most of the applications that could benefit from energy harvesters, such as energy-autonomous body implants for instance; require devices that can scavenge vibration energy at low frequency (10-100 Hz) within a limited volume. In combination with the minimum level of energy to be delivered, this set of constraints lead to the need of enhanced energy density. Regarding resonant piezoelectric energy harvesters, this can be achieved either by improving the piezoelectric material properties or by maximizing the amount (i.e. the thickness) of electro-active material integrated onto the harvesting structure. In this work, we focused on the latter approach.

Thick-film technologies were proposed by different teams to fill the existing gap between existing thicknesses provided with bulk devices (>100 μm) and thin-film devices (<10 μm). Approaches as screen-printing [1], sol-gel process [2], electrophoretic deposition [3], tape-casting [4], or aerosol deposition [5] have shown the feasibility of thick piezoelectric layers with thicknesses ranging from 10 to 100 μm. Some of these fabrication techniques were originally applied in high-frequency ultrasonic transducers but can be successfully transferred to energy harvesting applications. Main challenges in piezoelectric thick-film fabrication are associated with the thickness uniformity, crack-free material, high mechanical density, reproducibility, and high piezoelectric performance. These challenges are difficult to master as thick-film technologies involve processes, which are hostile and destructive to ceramic free-standing structures. For instance, the screen-printing suffers from high processing...
temperature and low volume density that both degrade resulting mechanical and piezoelectric performances of fabricated structures.

Another way offering to conserve superior piezoelectric behaviour of a bulk piezoceramic material consists in a thinning of such a bulk material bonded on a substrate. This technique, applied in [6], resulted in a harvesting device delivering a power of 10.2 $\mu$W as a response to an input acceleration of 2 g at 252 Hz. Our aim is to push the same approach, based on the bulk piezoelectric material thinning, to fabricate harvesting devices working in a frequency band from 10 to 20 Hz. Furthermore, a high density PZT (HD PZT) was selected for this work. Indeed, preliminary thinning experiments of standard PZT ceramics have shown adhesion issues when the targeted thickness is in the range of few grains size (Figure 1).

![Figure 1. SEM micrograph of PZT layer surfaces after grinding and polishing steps. (a) Low surface quality is observed with standard PZT, (b) excellent surface quality is obtained with HD PZT.](image)

2. Fabrication

The proposed fabrication process combines the bonding and the grinding/polishing of electrode plated HD PZT substrates (40 x 40 x 0.4 mm$^3$) onto metallic plates which act as electrodes. In the case of the monomorph scavengers, the ceramic substrate is firstly bonded on a 75 $\mu$m thick steel foil, while two ceramic substrates are bonded on both sides of a stainless steel foil (12 $\mu$m) for the fabrication of the bimorph scavengers. The bonding operation was done using low temperature non-conductive glue. The specificity of the proposed fabrication process is that it takes advantage of the roughness of PZT substrates to make the electrical contact between PZT inner electrodes and the metal foil. Doing so, usual thermal mismatch issues between PZT and the substrate, present in other high temperature bonding processes, are avoided. It should be noted that though such a surface roughness on the outer PZT faces may cause cracks during the bending, the mechanical integrity of the structures is not put at risk since only low strain is developed in this inner region close to the cantilever neutral plane. Before the grinding/polishing process was performed, the samples were diced at the final cantilever dimensions (5 x 40 mm$^2$). Then, during the grinding/polishing process, thickness tolerances were accurately controlled for a final PZT layer thickness of 50 $\mu$m +/- 2 $\mu$m (Figure 2).

![Figure 2. Cross section view of fabricated (a) single-layer and (b) double-layers piezoelectric scavengers.](image)

Next step was the electrode plating of the external surfaces of the ceramic layers; chromium / gold electrode was used to ensure good conductivity and immunity to air oxidation (Figure 3). The poling process was finally applied to the device in order to maximize piezoelectric properties. In the case of
the bimorph scavengers, PZT layers were poled in an anti-parallel configuration by applying the poling voltage between the inner metallic foil and the shunted outer electrodes.

![Figure 3. Pictures of the fabricated bimorph scavenger: (a) as obtained at the end of the fabrication process (b) mounted in the test clamping element and with the tip mass.](image)

3. Experimental results and discussion

For the test of the harvesters under vibrations, we used a shaker (GW-V20/PA100E from Data Physics) in combination with an Agilent 33220A wave generator. The acceleration level on the vibrating base was monitored using a highly sensitive accelerometer (355B04 from PCB Piezotronics, 1V/g). The test set-up was driven in “closed-loop” in order to overcome the non-linear response of the vibrating chain. The device output electrodes were connected to a variable resistive load (from 200 Ω to 20 MΩ) and the generated mean power was then calculated as \( P_{\text{mean}} = \frac{V_{\text{RMS}}^2}{R} \). Finally, the velocity of the cantilever tip was simultaneously measured using a laser interferometer from Polytec.

3.1. Unimorph energy harvester

We firstly tested the monomorph energy scavenger (Figure 2 (a)). As previously mentioned, the metallic substrate is used as a bottom electrode. We added a 5.4 x 6.15 x 5 mm³ proof mass made of tungsten (2.36 g) in order to decrease the resonance frequency of the device down to 15 Hz. The total length was 31 mm. Under a harmonic excitation of 10 mg only, the mean power transferred to a 150 kΩ resistance was 1.3 μW \( (V_{\text{RMS}} = 0.43 \text{ V}) \) and the transverse displacement amplitude is 300 μm.

3.2. Bimorph energy harvester

3.2.1. Electrical impedance measurement. The impedance of the double-layers scavenger (Figure 2 (b)) was first measured using an Agilent 5061B Network Analyser in order to assess the quality of the piezoelectric coupling.

![Figure 4. Impedance amplitude and phase angle of the double-layers scavenger with no tip mass.](image)
However, it must be noted at this point that it was not possible, due to the limitation of the Agilent 5061B in Gain-Phase Series mode, to measure the high value of the impedance at low frequency for the device with the tip mass. We therefore tested the scavenger without the tip mass since it presents lower impedance than in the previous case as this one can roughly be considered as inversely proportional to the frequency - if the motional contribution is omitted. The measured impedance of the device with no tip mass is illustrated in Figure 4. It can be noted that since the impedance phase angle spans up to positive values, there are two frequencies with a 0° phase angle. These two specific frequencies correspond to the resonance \( f_r \) and the anti-resonance \( f_a \) frequencies of the device. Such an impedance phase angle curve illustrates a high piezoelectric coupling, which is also commonly given by the coupling coefficient \( k = (f_a^2/f_r^2 - 1)^{1/2} \). The resonance point is characterized by the frequency of 85.8 Hz and by the real impedance of 23 kΩ. The anti-resonance point corresponds to the frequency of 88.0 Hz. The measured anti-resonance impedance is beyond the accuracy limit of the Agilent 5061B.

3.2.2. Harmonic characterization. The bimorph scavenger (with no tip mass) was then characterized in sensor mode. Since the PZT layers are polarized in opposite directions (anti-parallel configuration), the voltage output was measured between the top and bottom electrode.

![Figure 5. Mean harvested power from a harmonic vibration signal by the bimorph scavenger (a) with no tip mass, 40 mg acceleration (b) with a 1.5 g tip mass, 10 mg acceleration.](image)

Figure 5 (a) illustrates the measured mean power with 40 mg input acceleration. As anticipated through the impedance analysis, the measurement results show a piezoelectric coupling that is high enough to allow the existence of an antiresonance power peak. A quality factor of \( Q \sim 95 \) of the structure is obtained from the tip displacement response of the structure. In combination with the coupling coefficient \( k = 0.23 \) obtained from the impedance measurement, we can assess the piezoelectric coupling figure of merit of the structure \( k^2 Q = 4.95 \). The mean power is found to be 0.65 \( \mu \)W with an RMS voltage of 0.12 V across an optimal resistive load of 20 kΩ, which corresponds to the device impedance at the resonance frequency. In that case, the displacement amplitude of the cantilever tip is 150 µm.

Next, we added a 1.5 g tungsten seismic mass at the tip of the cantilever (Figure 3 (b)) in order to decrease the natural frequency of the structure. The test results at 10 mg acceleration are presented on Figure 5 (b). The mean harvested power is measured at 3 \( \mu \)W at the resonance frequency (16 Hz), and a corresponding RMS voltage of about 0.66 V across a 150 kΩ optimal resistance. The main cause of the increase of this optimal resistance is the lower resonance frequency. Here again, the antiresonance power peak can be observed, but it appears to be closer to the resonance power peak. Though the antiresonance has the same normalized frequency (1.025) as in the previous case, and the coupling coefficient remains unchanged \( (k^2 = 0.05) \), the “valley” between the two peaks is less pronounced than previously. This effect is linked with a lower quality factor \( Q = 64 \). The coupling figure of merit \( k^2 Q \) is now 3.5. It is believed that the lower quality factor is due to the larger tip displacement (590 µm).
induced by the lower natural frequency. Additional damping mechanisms are likely to appear because of this larger displacement.

Figure 6. Comparison of different PZT-based scavengers: Mitcheson’s FoM (a), Marzencki’s FoM (b).

4. Conclusion

We have presented the fabrication process based on a thinning of the bulk piezoceramic material bonded on a substrate. We have applied such a process for the fabrication of three different piezoelectric energy scavengers operating at very low frequency (~15 Hz): unimorph, bimorph with no tip mass, and bimorph with a tip mass. Based on the test results presented in the previous section, we have evaluated the corresponding figures of merit (FoM) according to Mitcheson and Marzencki. The Mitcheson’s FoM for unimorph, bimorph with no tip mass, and bimorph with a tip mass scavengers are 21%, 5%, and 55%, respectively (Figure 6 (a)). The Marzencki’s FoM corresponding to the same structures are 64500, 136000, and 315000, respectively (Figure 6 (b)). As can be seen from Figure 6, comparing different PZT-based scavengers developed by other teams, FoM of our devices are situated among the highest values, especially taking into account the low frequency band of operation.

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