Omnidirectional low frequency energy harvester for wearable applications

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Abstract. We present an omnidirectional energy harvester with lowest resonance mode at 14.85 Hz. The geometry is designed as a spiral shaped, 500 µm thick PZT lateral bimorph to achieve a low resonance frequency while minimizing the area required. The resonance modes and frequencies of the energy harvester are investigated with COMSOL eigenfrequency study. The resonance modes of translation in x, y, z, and rotation around x, y, and z have resonance frequencies at 23.4, 22.9, 14.9, 34.0, 33.6, and 25.5 Hz, respectively. Multiple resonance modes widen bandwidth and enable harvesting energy from all directions. The energy harvester is mounted inside a 3D printed package that can be worn on a human wrist. The design of the package mimics the approximate size of a typical smartwatch, and the motion from walking is along the most sensitive axes of the harvester. It produces an output of 900 mV peak-to-peak for an optimum load of 1.8 megaohms and provided 0.45 microwatts. The output voltage is high enough to charge a battery through commercial diodes.

1. Introduction
Battery life is one of the most important concerns for practical wearable devices [1]. Harvesting energy from human motion can mitigate the problems by prolonging battery life, or completely forgoing the need for battery replacement [1-2]. Piezoelectric mechanical-to-electrical transduction has relatively high conversion efficiency and energy density [2-3]. Nevertheless, piezoelectric cantilever energy harvesters have narrow bandwidths, so they are efficient only when the vibration frequency matches with the device resonance frequency [2-3]. These devices also often have high resonance frequencies (>200 Hz), while human motion is at low frequencies [2]. Many approaches have been investigated to achieve broadband excitation in previous works, using coupling and nonlinearities [3-8]. Our approach uses the development of a low resonance frequency harvester with multiple resonance modes and relies on a unique laser cutting process to realize bimorph action in three orthogonal axes. Hence, it can harvest energy from motion at low frequency from all directions. The energy harvester can be integrated with a near-zero power wake-up circuit to further save energy when devices are not in use [9-16].

2. Materials and Methods
The energy harvester is designed as a PZT-multi-bimorph spiral to lower the resonance frequency and increase output capacitance while maintaining a compact design as shown in figure 1a [17]. The device is fabricated using a rapid laser micromachining technique on 500 µm thick APC International 840 PZT with silver electrodes on both sides [18]. The mechanical structure is formed by laser raster scanning to remove PZT through the substrate. Then, electrodes are formed by removing only the top
silver layer. This process was used for sensor and actuator fabrication, so monolithic integration of energy harvesters, sensors, and actuators is possible [9-11, 19-20]. The cross section and the top view of the PZT bimorph is shown in figure 1b, and 1c, respectively. The bottom electrode is floating, one top electrode is grounded, and another top electrode is connected to output. Bending a PZT lateral bimorph in-plane causes a voltage difference between the two top electrodes due to piezoelectric $d_{31}$ coupling. The voltage output of a bending bimorph is,

$$V_{out}(j\omega) = \frac{k_c d_{31}}{l} \left( LL_B - \frac{L_B^2}{2} \right) \frac{1}{8} \left( b^2 - a^2 \right) \frac{1}{C_T} \frac{j\omega R_T C_T}{j\omega R_T C_T + 1} y_c(j\omega)$$

where $R_T$ is total resistance, $C_T$ is total capacitance—including modified bimorph capacitance $C_0 = \varepsilon_0 \varepsilon_r \left( 1 - \frac{Y_{11} d_{31}^2}{\varepsilon_r \varepsilon_0} \right) A$, $k_c$ is the spring constant of the bimorph, $I$ is the moment of inertia of the bimorph, and other parameters are shown in figure 1b-c [9-10].

A spiral shape is created by cascading a series of bimorphs connected to a proof mass in the middle and electrodes on the outside. After fabrication, the energy harvester is mounted on a 3D printed package so that it can be worn on a human wrist. The design of the package mimics the approximate size of a typical smartwatch, and the motion from walking is along the most sensitive axes of the harvester. The size of the actuator can be made smaller, but with the tradeoff of increasing the resonance frequencies. A photograph of the device and package is shown in figure 2, along with a diagram of how it could be incorporated into a watch.

The design is first investigated using a COMSOL Multiphysics finite element simulation software with eigenfrequency study to find resonance mode shapes and frequencies. The resonance modes along $x$, $y$, $z$, $\omega_x$, $\omega_y$, and $\omega_z$ axes have resonance frequencies at 23.4, 22.9, 14.9, 34.0, 33.6, and 25.5 Hz, respectively. The simulated mode shapes are shown in figure 3. Low resonance frequency increases energy harvesting efficiency. Multiple resonance modes widen bandwidth and enable harvesting energy from all directions.

![Figure 1](image1.png)

**Figure 1.** (a) 3D model of omnidirectional and compact energy harvester construction. Cross section shows PZT lateral bimorph electrode geometry. (b) Cross section of the PZT bimorph (c) Top view of the PZT bimorph.

![Figure 2](image2.png)

**Figure 2.** (a) Photograph of PZT energy harvester (b) Photograph of device mounted on a wearable package (c) Model of harvester incorporated with watch.
3. Results

The energy harvester frequency response is measured using a Vibration Research VR9500 single axis shaker table. The energy harvester is mounted by screws on a 3D-printed converter to measure the frequency response in different directions as shown in figure 4 inset. The output is connected to a TL082 high impedance JFET op-amp buffer to minimize capacitive loading. The resonance frequency is identified by sweeping frequency from 5 to 50 Hz, close to the simulated resonance frequency. Using the identified resonance frequency, the optimum load resistance is quantified by changing resistive loads and testing at an acceleration peak of 0.005 G. The chosen acceleration is intended to mimic the accelerations that might be found during regular human activities. The output power is maximized with a load resistor of 1.8 MΩ, as shown in figure 4.

After obtaining the optimal load impedance of 1.8 MΩ, a broader frequency sweep was performed to characterize the frequency response of the energy harvester. A sweep from 5 to 200 Hz along each axis under an acceleration of 0.005 G produces the frequency response shown in figure 5. The two in-plane axes show a resonance frequency in the y mode at 26.3 Hz, which is within 15% of the simulation results. At this frequency, the energy harvester produces an output of 550 mV under the 0.005 G acceleration. There is also a resonance of the x mode at 29.4 Hz and of the z mode at 14.6 Hz. Many lower amplitude resonance modes are also present at higher frequencies.

After determining the frequency response, the energy harvester is tested as a wearable device under the same optimized resistive load. Figure 6 shows the output voltage while walking normally with the device on the wrist. It produces an output of 900 mV peak-to-peak (0.45 µW), a voltage high enough to charge a battery through commercially available off-the-shelf diodes or specialized biased diode structures [21]. The device is able to survive minor impacts when mounted in the package such as being...
dropped from a height of one meter onto the carpeted floor. However, it may break from larger impacts or if the impact is concentrated onto a small region.

4. Conclusion

An energy harvester that can convert low frequency vibration from all directions to power is developed. The output voltage is high enough to be rectified with commercial diode to charge a battery without complicated conditioning circuitry. The rapid laser micromachined PZT fabrication process allows future monolithic integration of the energy harvester, sensors and actuators. It can be integrated with low power wake up circuitry to improve system energy management. The scaling of the device to smaller dimensions is possible.

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