COMPACT LOW FREQUENCY MEANDERED PIEZOELECTRIC ENERGY HARVESTER

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Abstract: A novel meandered piezoelectric vibration energy harvester with strain-matched electrodes is presented. The device is capable of low-frequency operation within a small form factor, as compared with the traditional straight cantilever. The device consists of a laser-machined piezoelectric bimorph. The device’s method of operation, as well as simulated and experimental results, are detailed. A power output of 7.2 µW at 0.2 g acceleration and 49 Hz has been experimentally achieved. A new strain-matched electrode technique has attained a 5× increase in experimental power output, as compared to a single-electrode design. The novel strain-matched electrode increases power output by avoiding charge-cancellation.

Keywords: energy harvesting, piezoelectric, low-frequency, meander

INTRODUCTION
Reduction in power consumption of electronics coupled with an increasing demand for system mobility and service life has led to major research efforts in the field of energy harvesting [1]. A prominent application of energy harvesting is wireless sensor nodes, where battery replacement or wiring is difficult or costly [2]. Energy harvesting provides an essentially limitless energy source capable of powering wireless sensor nodes. However, in many sensor node applications, such as structural health monitoring and biomedical applications, it is desirable or even necessary to minimize sensor node size.

Numerous ambient energy sources for energy harvesting have been considered in literature, including solar, thermal gradients, acoustic waves and mechanical vibrations. The choice of energy source is heavily dependent on environmental conditions and thus application dependent [3]. Mechanical vibration is considered in this research due to our vibration rich target application.

The three main transduction mechanisms for vibration energy harvesting are electrostatic, electromagnetic, and piezoelectric [4]. Electromagnetic harvesters are generally bulky, while electrostatic harvesters require a separate voltage source. Additionally, piezoelectric generators show higher energy density (35.4 mJ cm\textsuperscript{-3}) compared with electromagnetic (24.8 mJ cm\textsuperscript{-3}) and electrostatic (4 mJ cm\textsuperscript{-3}) generators [1]. The requirement of a small self-contained sensor node leads us to the use of piezoelectric energy harvesting in this paper. The main disadvantage of piezoelectric energy harvesters is their difficulty in integrating with current microfabrication processes.

MOTIVATION
Piezoelectric materials generate an electric potential when mechanically strained, which can be harvested and stored or immediately used to power electronic circuits [1]. Typical piezoelectric energy harvesters consist of a cantilevered bimorph (Fig. 1a) or unimorph structure attached to a vibrating host
structure. The strained piezoelectric element produces an electric potential between the brass and nickel electrodes. Most purely-mechanical vibration sources’ peak vibration amplitudes occur below 150 Hz [3]. Note that the power output of an energy harvesting device generally follows Eq. 1 [1]

\[ P = \frac{m \xi_e A^2}{4 \omega (\xi_e + \xi_m)} \]

where \( P \) is power output, \( m \) is mass, \( A \) is vibration amplitude, \( \omega \) is frequency and \( \xi_e \) and \( \xi_m \) capture electrical and mechanical damping, respectively.

As seen in Eq. 1, it is desirable to operate the harvester at the lowest vibration mode containing the highest amplitude vibration to achieve the maximum power [1]. A straight cantilever harvester’s resonant frequency is inversely proportional to mass and length, therefore in order to achieve a low resonant frequency, the mass or length must be increased. In miniature systems, such as sensor nodes, size is limited, therefore limiting the mass and length of the system, and thus the power output.

The work introduced in this paper presents a novel method to reduce the resonant frequency of a piezoelectric energy harvester while maintaining a small maximum dimension. The issue of charge cancellation, which is explained later in the paper, is solved with a novel strain-matched electrode design. The following sections present an overview of device theory and operation, followed by experimental results for the first-generation design with and without strain-matched electrodes, a discussion of results, and conclusions from the work.

**Fig. 2: Material cross-section.**

**DESIGN AND THEORY OF OPERATION**

The magnitude of the voltage produced from an energy harvester is dependent upon many variables, including: mass, material properties, vibration amplitude, frequency, electrical impedance, etc. Implementing a piezoelectric energy harvester within a small volume presents a great challenge because one wants to operate at the minimum resonant peak to minimize \( \omega \) in Eq. 1. In this paper, the target resonant peak is 50 Hz. This value is based on experimental data recovered from our target application. A traditional straight cantilever design would require substantial length or mass to achieve such a low target frequency, increasing system size unacceptably high.

The energy harvesting device proposed in this paper (Fig. 1b) can be briefly described as a meandered piezoelectric bimorph cantilever. The meander shape decreases the spring constant of the device, compared to a straight cantilever of the same maximum dimension. (Note: the principle of meanders has been previously used in RF MEMS switches to reduce turn-on voltages [5]). Decreasing the spring constant provides a reduction in resonant frequency, enabling the device to operate at a vibration source’s lowest mode within a smaller package.

The device is attached to a vibrating host structure at one end, while the other extends out in a cantilevered fashion. The material cross section (Fig. 2) is a PZT-brass bimorph available from Piezo Systems (P/N: T215-A4-303Y). A tip mass is placed at the free end of the cantilevered meander to further reduce and control the resonant frequency and increase the power output. The vibrating structure induces a strain within the PZT, causing an electric potential to develop across the electrodes.

**Fig. 3: Simulated open circuit voltage in single (a) and strain-matched designs (b) (note: brass voltage is zero).**
The constitutive equations for the piezoelectric effect state that a strain induced in the piezoelectric material produces a voltage [1]. Therefore, it is critical to understand the strain within the energy harvesting structure. Fig. 1 shows an ANSYS simulation of the strain at the PZT-electrode interface for the first vibration mode of a straight cantilever and the proposed meandered design. The strain at the PZT-electrode interface in the straight cantilever design is all of the same sign. However, the contours within the meandered design show both negative and positive strain. The negative and positive strain will produce positive and negative charges, respectively. Assuming a single electrode is placed on the PZT to collect charge, the negative and positive charges will tend to cancel, significantly reducing the extractable charge and thus power output.

The issue of charge cancellation is remedied by a strain-matched electrode design. In this design, two different electrodes are used to collect like-charges and avoid the charge cancellation caused by opposite strains. Fig. 3 shows a simulation of the open-circuit voltage produced by (a) a single-electrode and (b) a strain-matched electrode design. As evident from the figure, the strain-matched electrode produces a significantly higher voltage than the single-electrode design.

**EXPERIMENTAL RESULTS**

The single-electrode and strain-matched electrode designs (Fig. 4) introduced in the previous section were laser-machined at Birck Nanotechnology Center at Purdue University. The devices were machined using a femtosecond pulsed laser. The sample moved under the laser pulses on a high precision three-axis motion stage controlled by custom CAD-CAM software. Two electrically isolated electrodes, labeled as E1 and E2, can be seen in Fig. 4.

Using an electodynamic shaker and accelerometer at the Herrick Laboratories of Purdue University, the parts were harmonically excited at their resonant frequencies with an imposed displacement which yielded an acceleration amplitude of 0.2 g. A tip mass of 0.48 grams was attached to the tip. A picture of the mounted dual-electrode design can be seen in Fig. 5. The figure shows the wires soldered to the electrodes to connect the strain-matched electrodes. In this experiment, only the top layer of the PZT bimorph was tested, and only electrode E1 was tested for the strain-matched electrode design.

The harvester was connected to a diode bridge rectifier with filter capacitor, and the resistance was varied to find the optimal load (Fig. 6). A summary of simulated and experimental results are shown in Table 1. The simulated power and optimal load were calculated based on the simulated open circuit values using Eq. 2 and Eq. 3 [6]. $V_{OC,RMS}$ is divided by 2 because the optimal rectified voltage is half the open circuit voltage [1].

$$R_{OPT} = \frac{\pi}{2C_e\omega}$$

$$P = \left(\frac{V_{OC,RMS}}{2}\right)^2 \frac{1}{R_{OPT}}$$

<table>
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<th>Table 1: Meander simulated and measured results.</th>
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<td>1 Electrode</td>
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<tr>
<td>Freq. (Hz):</td>
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<td>$V_{AC,open}$ (V):</td>
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<td>$R_{load,DC}$ (kΩ):</td>
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<td>$P_{DC}$ (µW):</td>
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DISCUSSION

The strain-matched electrode design showed an improvement in power output of 5× over the traditional single-electrode design. However, the simulated results predicted an increase of approximately 8.8×. To verify the simulation results, several straight cantilever structures were machined, tested, and simulated with the same process as the meander devices. The simulated and measured open circuit voltage for the straight cantilevers matched very well, with less than 5% error. Due to the assumptions and simplifications of Eq. 2 and Eq. 3, including the lack of electro-mechanical coupling, the simulated and measured powers did not match well.

Several potential explanations exist as to why the simulated and measured meander results do not match. First, wires were soldered onto the electrode at points of maximum strain. Since PZT is a heat-sensitive material, it is possible the polarization of the PZT was degraded during the high temperature soldering process. Secondly, the wires and solder themselves could cause a change in damping or possibly mode shape which was unmodeled in simulation. Finally, the electrodes on the PZT are approximately 300 nm thick, which could lead to electrode fracture. All of these issues have potential solutions and will be considered in future work.

It is difficult to comprehensively compare energy harvesting devices due to the wide variation of applications and operating conditions. However, the main goal of this work was to obtain a reduced resonant frequency within a small size compared with a straight cantilever. In this discussion, we will assume a tip mass of 0.48 grams and the same material for all devices. The effective length, not including the mounting portion, of the meandered device in this paper was 21 mm. Some straight cantilever resonant frequencies are presented in Table 2 for comparison. As seen in the table, length or tip mass of the cantilever must be increased to reduce the resonant frequency to that of the meandered device. This shows that the meander effectively reduces the first resonant frequency when compared with the traditional cantilever design of the same maximum dimension.

The meander design and strain-matched electrodes proposed in this paper are scalable to micro-sized devices. Additionally, the strain-matched electrodes would benefit from micro-fabrication techniques, allowing for more robust, and less obstructive electrode connections. The strain-matched electrodes may also be utilized in traditional straight cantilevers operating at multiple modes of resonance.

CONCLUSION

A novel meandered piezoelectric bimorph cantilever for vibration energy harvesting has been presented. The key advantage of this design is its ability to achieve a low resonant frequency while maintaining a small form factor. The design presented in this paper achieves an output power of 7.2 µW under a harmonic acceleration of 0.2 g at 49 Hz. The novel strain-matched electrode design significantly reduces the effects of charge cancellation, increasing power output by 5× in experiments. Due to its compact size, this device is well-suited for miniature sensor nodes vibrating at a known resonance frequency.

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