EFFICIENT POWER GENERATION FROM VOCAL FOLDS VIBRATIONS FOR MEDICAL ELECTRONIC IMPLANTS

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ABSTRACT

The availability of practical, implantable, efficient power generators will proliferate the use of medical electronic implants that can be very useful for treating and managing various medical conditions. Using a vibration-driven power generator, we have successfully generated 0.3-mW/cm^2 of electric power continuously from the acousto-mechanical vibrations that originate from the human vocal folds and propagate along the skeletal frame and air passage throughout the head and neck. Our energy harvesters are highly efficient because vocal vibrations excite them at their designed resonant frequencies at 100 and 200 Hz, which are the dominant vocal vibrations of men and women, respectively. In addition, we use laser micromachining to pattern single crystal lead-zirconate-titanate (PZT) sheets for better efficiency. Our harvesters are designed to fit into a square area (1×1 cm^2 or smaller) so that they can form a flexible large array to generate more power.

INTRODUCTION

Neurostimulators and cochlear implants are fast growing sectors in medical industry [1-4]. In addition, implantable neural prostheses also present a great potential in improving the condition of those with physical disabilities [5, 6]. However, all these medical electronic implants must use batteries, which require periodic replacement. As a result, batteries are often implanted in the chest area, and this requires running long electrical lines through the moving parts of the body such as a neck to power the stimulators in the head, causing additional reliability issues [7].

Using an implantable power generator for medical electronics could provide an effective solution to the aforementioned challenges, yet inside the human cranial cavity, harvestable energy sources are rare: there are no photons, and microscale thermal gradients are too small for practical power generation. Ambient mechanical vibrations exist, yet previously studied vibration-driven energy-harvesting approaches suffered from irregular availability and widely varying amplitudes and frequencies of ambient vibrations present in biological environments, which made the resonance-based harvesters inefficient and impractical [8, 9].

In our approach, human vocal folds serve as a energy source that functions as a built-in tunable function generator, and the air passages/skeletal frames serve as "vibration-propagation highways" through our head, neck, and upper torso (Fig. 1). At the TRF NAPA Workshop in 2015, our group has shown that the dominant vocal vibration frequencies exist between 90-300 Hz for men and women (Fig. 2), and 55-70 % of the vibration energy resides at the dominant frequencies. Also, the locations of the vibration hotspots on the head and neck have been identified and characterized by measuring the accelerations at multiple locations on the head and neck simultaneously [10]. Fig. 3 shows acousto-mechanical vibration mapping data from 25 different locations in the head and indicates that the hotspots #1 and #2 in Fig. 3 (a) at the larynx are the most efficient locations to harvest vocal vibration, while the hotspot #22 at the parietal bone still exhibits the possibility of harvesting 50 % of the energy that propagates from the larynx.

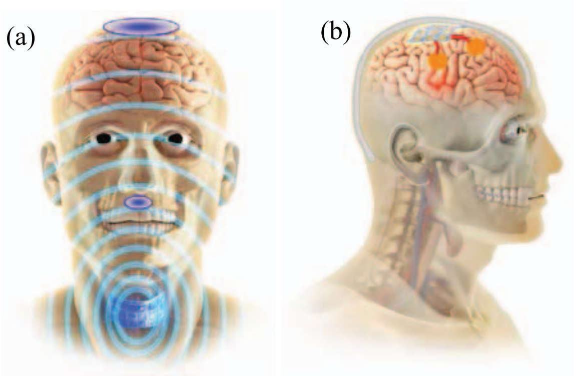


Figure 1: (a) Vibration propagation in the head. (b) Driving brain stimulators using a bone-attached energy harvester.

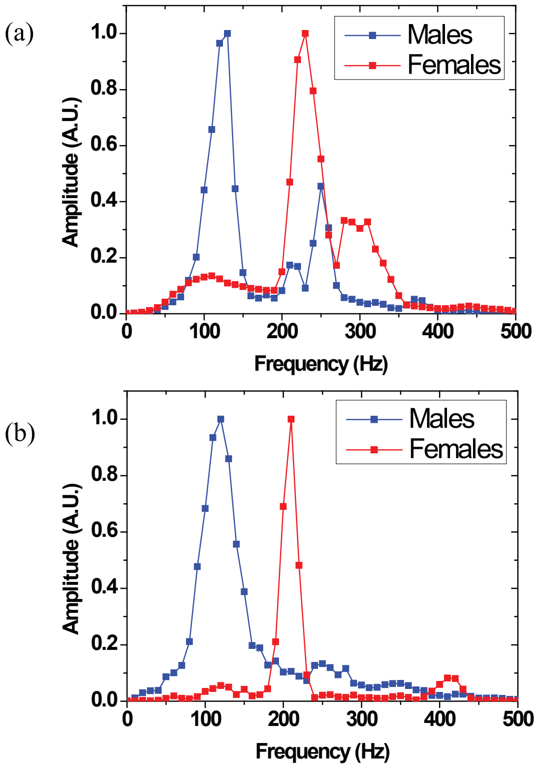


Figure 2: Dominant vibration frequencies (average) during humming (a) and reading (b)

Following the work presented at the TRF NAPA Workshop, we have harvested 0.3-mW continuous power and 1.7-mW peak power at the larynx by designing and building PZT-based vibration-driven harvesters that resonate at the vocal vibration frequencies between 90-300 Hz. Being driven at resonance, our energy harvesters exhibit very high power-generation efficiency, generating electric power at the level close to the theoretical limit. We are confident that our approach will provide a controllable and efficient way to implement practical power generators for medical implants, which can consistently generate electric power inside the human body as needed. [11, 12].

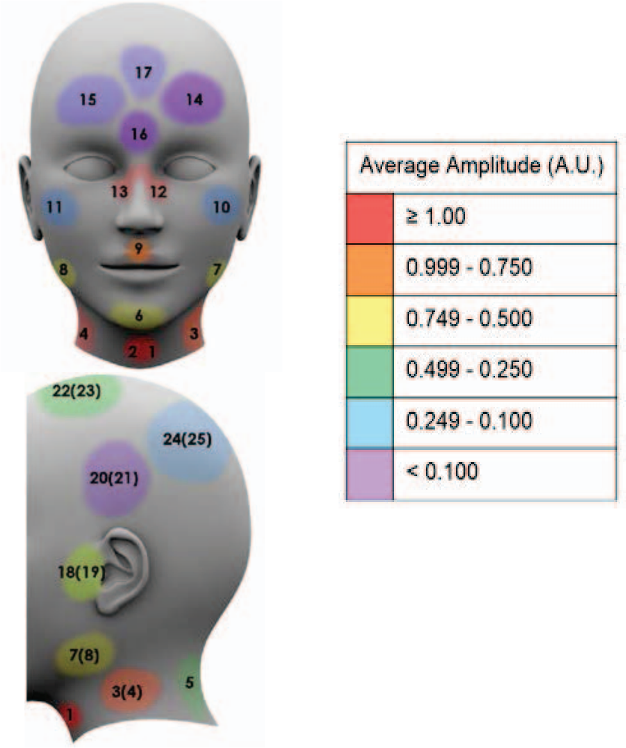


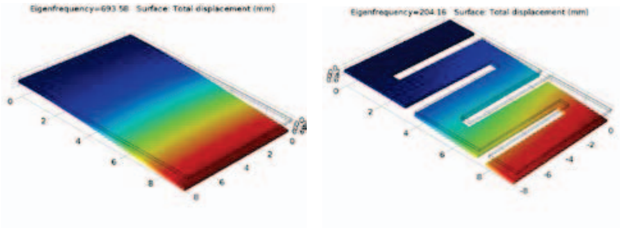
Figure 3: Vibration hotspots for constant humming.

EXPERIMENTS

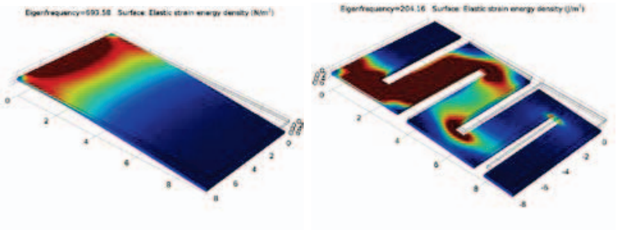
Material Choice, Design, Fabrication, and Packaging

To generate power more efficiently and reliably from vibration, we decided to use thick single crystal PZT sheets. We purchased 127 μm-thick single crystal PZT sheets from Piezo Systems Inc. which have Ni top and bottom electrodes.

Generally, thick piezoelectric material may not be proper for use in low frequency applications because the bending stiffness of a material is proportional to the cube of the material thickness, making it stiffer and resulting in a higher resonant frequency. We overcame this difficulty by choosing the serpentine-beam design. Based on our previously reported characterizations of the vocal vibrations [10] (Fig. 4), we designed low frequency (100-300 Hz) energy harvesters that could fit within 9.5×8.5 mm^2. Using COMSOL simulations, we chose serpentine-shaped beams to increase the effective beam length within a given area, so that the range of the resonant frequencies will be between 100-300 Hz. According to our simulation results, resonant frequencies of the rectangular and serpentine beams (Fig. 4) were 694 Hz and 204 Hz, respectively, within the same given rectangular volume (9.5×8.5×0.127 mm^3). The serpentine beam resonates at a frequency much closer to that of the human vocal vibrations while its total displacement and elastic strain-energy density remain at the levels very similar to those of the rectangular beam (Fig. 4).



(a) Displacement



(b) Elastic strain energy density

Figure 4: COMSOL simulations: (a) displacement and (b) elastic strain energy density for rectangular and serpentine beams (The strain energy is proportional to the square of the strain.)

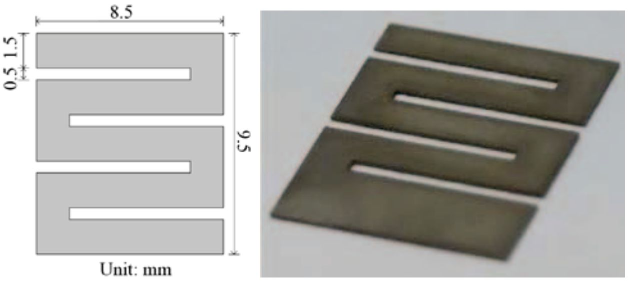


Figure 5: (a) Design of the serpentine beam. (b) Serpentine shaped PZT after laser cutting.

Once the design parameters were determined from the simulations, we moved onto device fabrication. To fabricate the device, we used two different cutting methods to pattern the PZT sheets. Straight edges were defined using scriber-breaker (Dynatex GST-150) while more complex patterns such as serpentine shapes were defined by using a laser micromachining tool (Nd:YAG-UV355) integrated with scanning optics. Fig. 5 (a) shows design of the serpentine beam and Fig. 5 (b) shows the fabricated structure using the laser-micromachining technique (b).

When packaging the patterned beams, we paid a special attention to minimize unnecessary damping that could occur while passing the vocal fold vibration from the surface of the skin to the PZT beams. To accomplish this, we mounted and soldered the patterned PZT beams onto a very solid and light, custom-made mini-PCB boards, on which the soldered end of a PZT beam would serve as anchors.

Resonant Frequency and Power Measurements

The resonant frequencies of the beams were characterized by testing them systematically with a frequency-tunable vibration generator (3B Scientific U56001). The voltages generated by the beams were then measured using a National Instrument X-Series DAQ board (Fig. 6) with 12.1 kΩ load and analyzed using an in-house written LabView program. The resonant frequency (f_r) of the laser-micromachined serpentine PZT beam was measured to be 201 Hz, which closely matched the COMSOL simulation result of 204 Hz (Table 1), whereas f_r of the rectangular beam was 470 Hz.

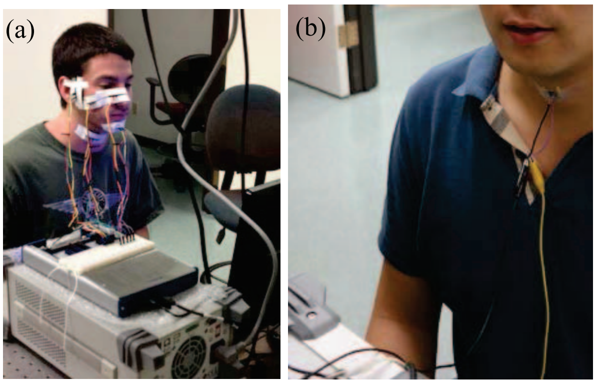


Figure 6: (a) Frequency and hotspot identification. (b) Harvesting energy from larynx.

Table 1: Resonant frequencies of rectangular beam and serpentine beam from simulation & experimental result (9.5×8.5×0.127 mm^3)

Beam Type	Simulation	Experiment
Rectangular Beam	694 Hz	470 Hz
Serpentine Beam	204 Hz	201 Hz

To maintain the consistency among our measurements, a sound-level meter (Extech 407730) was placed 3 feet away horizontally from the face of each test participant, and the measurements were taken at their larynx for simplicity. The advantage of driving the resonance-based harvester at its resonant frequency is well illustrated in Figs. 7 and 8, which show the frequencies, voltages, and power generated from the rectangular beam and serpentine beam when excited with 70-dB humming at 100 Hz and 200 Hz respectively. The serpentine harvester shows 2-folds increase in voltage swing over the rectangular at 100 Hz. In Fig. 8, the increase in voltage swing and generated power becomes much larger at 200 Hz since the serpentine beam is vibrating at its resonant frequency. Our power harvester continuously generated 6.9 and 15.4 μW/cm^2 at 100 Hz and 200 Hz respectively. With 100-dB voice, the harvester produced 0.3 mW/cm^2. For voice around 120 dB at 200 Hz, the power harvester generated an instantaneous peak power of 1.7 mW/cm^2. The power generation can be further increased by creating an array of the energy harvesters. For example, using an area of 5×5 cm^2, we can generate continuous power of 7.5 mW or peak power of 42.5 mW, which are more than sufficient to power most medical electronic implants used presently and to be used in the near future.

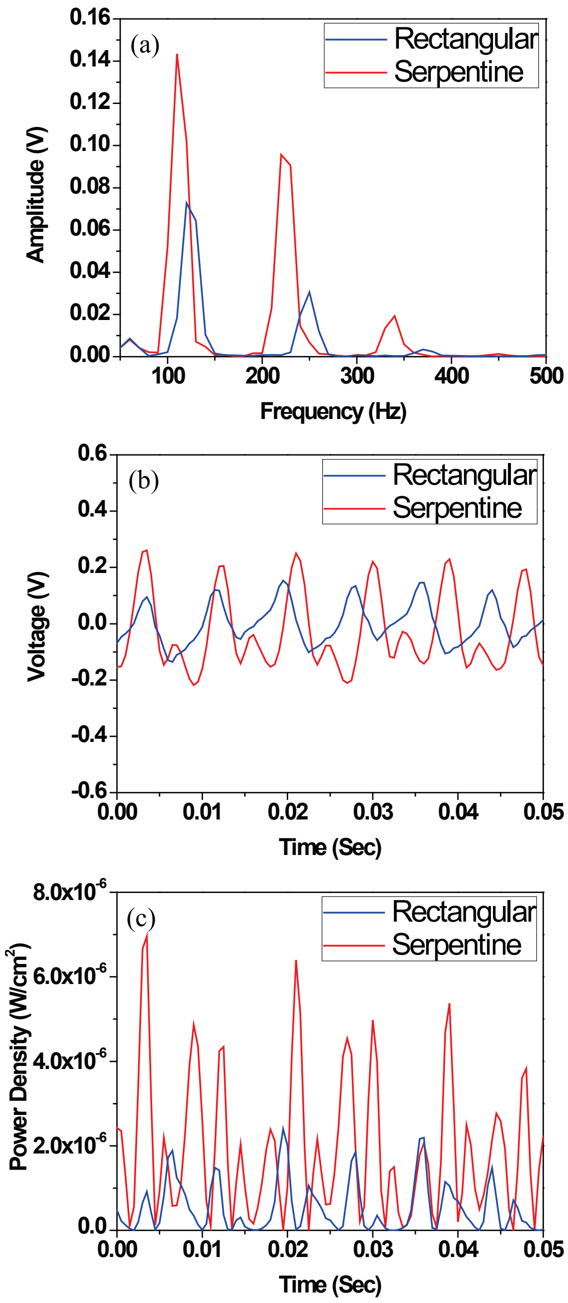
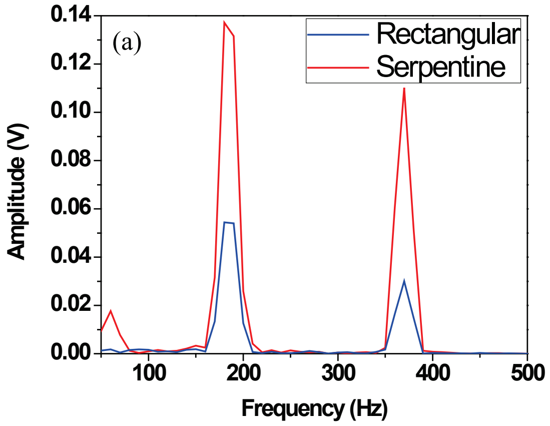


Figure 7: Frequency (a), voltage (b), and power (c) characteristics of rectangular and serpentine beams in 70-dB humming at 100 Hz condition.



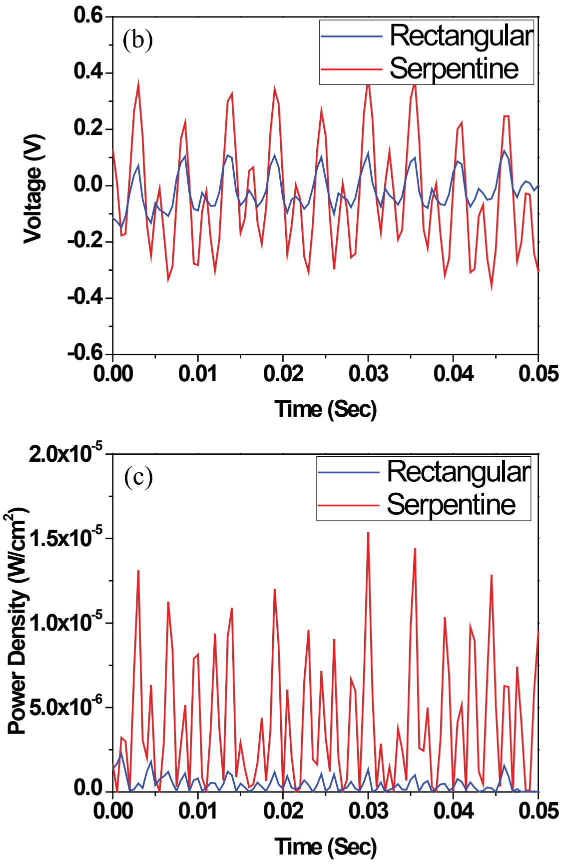


Figure 8: Frequency (a), voltage (b), and power (c) characteristics of rectangular and serpentine beams in 70-dB humming at 200 Hz condition.

CONCLUSION

Using a laser-micromachined serpentine-shaped single-crystal-PZT beam, we have demonstrated efficient and practical energy harvesting from the human vocal folds vibrations. We have harvested at the larynx 0.3-mW/cm^2 continuous power and 1.7-mW/cm^2 peak power when the test participant speaks at 70 and 120 dB, respectively. These power levels are large enough to satisfy the power requirements of present and future medical electronic implants. We strongly believe that our ongoing research effort will lead to the implementation of practical implantable power generators for medical implants.

ACKNOWLEDGEMENTS

The project has been funded by the Caltech CI2 program, Powell Foundation, and Heritage Foundation.

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