POWERING PORTABLE ELECTRONICS USING VOCAL FOLD VIBRATIONS

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ABSTRACT

Using a multi-stacked array of vibration-driven energy harvesters and a custom-tailored energy-harvesting (EH) circuit, we have achieved stable 3.12-mW power generation at 5.5 V_{DC} from the acousto-mechanical vibrations of the human vocal folds at 75 dB and demonstrated its use as a practical on-demand power source for portable and wearable electronics. The voltage and power outputs over 3.7 V_{DC} and 1 mW necessary for charging lithium polymer (LiPo) batteries were accomplished using a 3D-printed packaging platform whose physical design and mechanical properties maximized the vibration transfer and effectively combined 10 or more individual energy harvesters into a compact unified stack. The custom-designed LC-resonant EH circuit efficiently converted raw AC output into DC. Using our EH device, we have successfully charged 100-mAh LiPo battery and operated a portable 2×16 LCD display (requiring 2.8 V, 10 mA).

INTRODUCTION

Wearable electronics have been an emerging field of electronics that enable a wide range of applications including medical and military uses like prosthetics, electronic skins, implantable devices, and robotics [1-3]. Some smart electronic products that are wearable and portable have been commercially available, but they typically require battery packs that need to be charged periodically, which makes energy harvesting an attractive choice that could broaden the usage of wearable/portable electronics. Previously reported approaches such as triboelectrics [4], thermoelectrics [5], and solar panels [6] rely on energy sources that are occasionally or frequently unavailable. From bodily sources, researchers so far harvested very low power levels: 3.1 µW from breathing, 7 µW with jaw movements, 60 µW using shoulder bending, and 0.84 µW/cm^2 from heart-beating motion of a rat. [7-10].

In our approach, human vocal folds serve as a built-in frequency-tunable power source (Fig.1) and excites vibration-driven energy harvesters at their resonance, achieving an efficiency close to a theoretical limit. We have characterized vocal vibration frequencies during humming and reading, identified the locations of vibration hotspots on the head and neck using multiple accelerometers, and harvested constant AC power of 15.4 µW/cm^2 from the vocal fold vibrations at the human larynx using a single piezoelectric EH unit [11-12].

In this work, we stably generated 3.12-mW at 5.5 V_{DC} using a new multi-stacking packaging technique combined with a highly efficient LC-resonant EH circuit. Using this energy-harvesting device, we were able to charge a 100-mAh LiPo battery and operated a portable LCD display. Our energy harvesting method will provide a practical and efficient way to harvest energy to power portable electronics anywhere without additional charging apparatus.

Figure 1: Powering wearable electronics using the vocal fold vibrations.

EXPERIMENTS

Device Packaging and Circuit Design

We used 510µm-thick single crystal lead- zirconate-titanate (PZT) sheets to create EH cantilevers (28×12 mm^2), which were laser-micromachined to obtain desired geometries. The dimension of each cantilever beam was chosen to make it resonate at the frequency of the vocal vibrations. The target resonance frequency (f_r) of the single beam was set at 270 Hz since the frequency range of the participants' vocal vibrations when humming at 75 dB was between 260-280 Hz. Fig. 2 shows the simulated and experimental frequency responses of a single piezoelectric cantilever beam. In the same figure, the range of the participants' humming frequencies at 75 dB is highlighted in light blue. We used COMSOL Multiphysics for simulation and a vibration generator (3B Scientific's U56001) to sweep the frequency in the experiment. The resonance frequency of the single cantilever beam was found to be 274 Hz, which was close to the target resonance frequency as well as the simulation result (269 Hz).

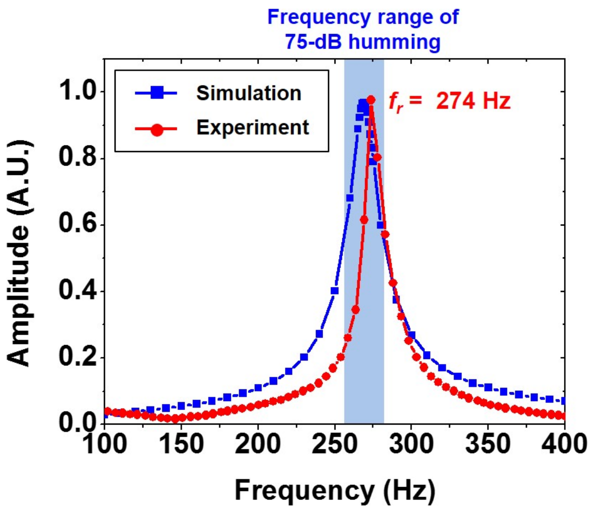

Figure 2: Simulated and experimental frequency response of a single piezoelectric cantilever beam.

Once the dimension of the single beam was determined, we printed packaging components needed for multi-stacking using polylactic acid (PLA) in a 3D printer (Ultimaker's Ultimaker 2). Each piezoelectric cantilever was placed inside an individual casing, which were then stacked and rigidly clamped, forming a multi-stack array (Fig.3(a)). Assembled 10-stacked EH array in the clamping package is shown in Fig. 3(b). To efficiently deliver the vocal vibrations from the larynx to the cantilever, the bottom part of the clamping mount included a curved surface to fit the geometry of the neck (Fig.3(c)).

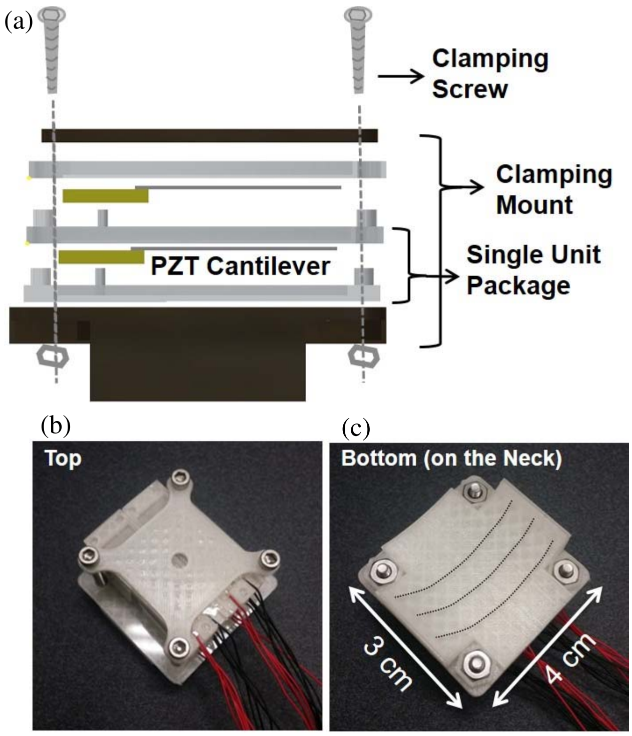

Figure 3: Device packaging with components produced using a 3D-printer: (a) an illustration of the stacking process. (b) clamping using our packaging components; and (c) a 10-stakced energy harvesting (EH) array with a curved bottom surface.

To demonstrate efficient energy harvesting capability, we designed a battery charging system using a passive LC resonant voltage double rectifier and a boost charger shown in Fig. 4. The presence of a large internal capacitance of the piezoelectric device, C_{PZT}, significantly decreases energy harvesting efficiency because its charging and discharging operation at every cycle consume a large portion of the sinusoidal output current of the PZT device. This reduces the output current to the load and consequently the output power. Therefore, it is critical to minimize charging and discharging of the internal capacitance to accomplish a higher efficiency. To solve this issue, we used a passive LC resonant rectifier because the parallel LC resonance stops the output sinusoidal current from flowing into the internal capacitance. Moreover, since the human vocal vibration frequency is stable around 260~280 Hz, potential resonant frequency mismatch of the LC resonant rectifier can be overcome.

Based on the modeling of a single unit device, the matching inductance was determined. Also, Schottky barrier diodes (Avago Technologies' HSMS-2862) were employed in order to reduce the diode forward voltage drop. The boost charger Analog Devices' ADP5090 was used for DC voltage step-up conversion. ADP5090's maximum power point tracking (MPPT) property helps to convert the rectified voltage to a higher voltage level suitable for 100-mAh 3.7-V LiPo battery charging.

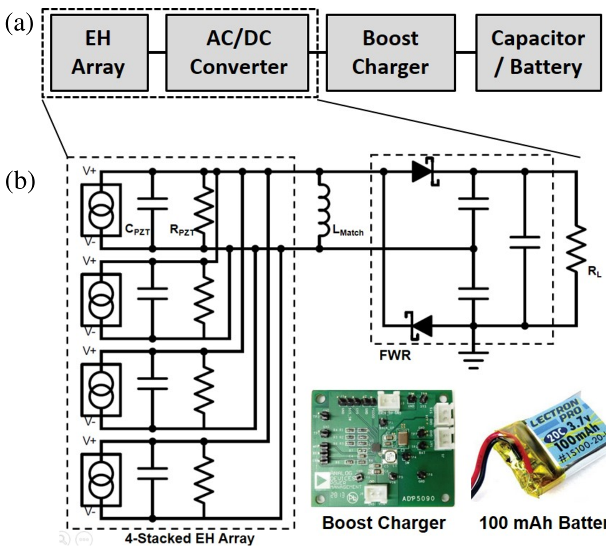

Figure 4: (a) A schematic diagram for energy harvesting system including EH circuits (b) a schematic of an AC/DC converter (resonant 2× rectifier circuit) with 4-stacked energy harvesters and the images of the boost charger and 100-mAh battery.

Power Measurements

For power measurements, the multi-stacked EH array was excited using the vocal fold vibrations of the test participants. The resulting power was measured using a DAQ board (National Instrument's X-Series). To find the optimum load for extracting the maximum power from the 10-stacked EH array, we varied the load resistance (R_L) and measured the DC output voltage. From these measurement results (Fig. 5(a)), we found the optimal load value to be 10 kOhm. Then, we characterized the output power from the EH arrays. Fig. 5(b) shows simulated and measured output voltage from each structure. The circuit simulation was performed using the Linear Technology's LTSpice. The electrical powers generated using single-, 4-, and 10-stacked EH arrays were 37 µW (0.6 V_{DC}), 0.49 mW (2.2 V_{DC}), and 3.12 mW (5.5 V_{DC}), respectively.

To charge a LiPo battery, we added a boost charger after the full-wave rectifier and removed the load resistance. Then, we connected a 100-mAh LiPo battery to the output of the boost charger. After charging for 10 minutes, the output voltage of the battery increased up to 3.1 V. Charging the battery for 10 minutes was sufficient to operate a 10-LED array (power consumption: 2.2 V, 10 mA) or 2×16 LCD unit (power consumption: 2.8 V, 10 mA) for about a minute (Fig.7). After the first 10-minute charging using vocal vibration, we set a vibration generator to mimic vocal vibration at 75 dB and used it to charge the battery for an extended period of time. Fig. 6 shows the transient charging voltage of the battery for 6 hours. The charging voltage reached up to 3.23 V after 6 hours of cumulative charging.

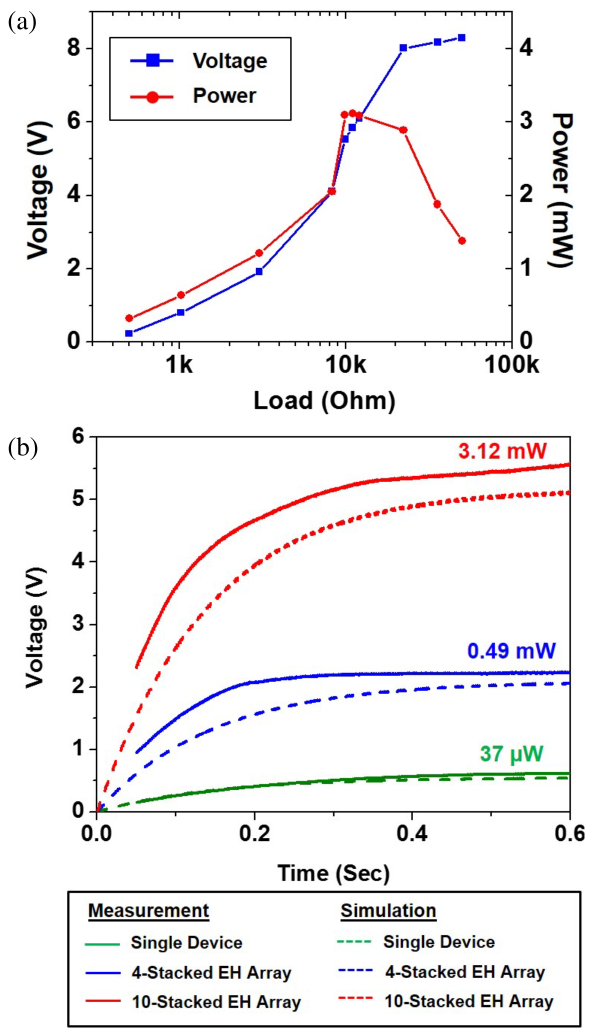

Figure 5: Output voltage characterization: (a) Load Vs. output voltage and power for a 10-stacked EH array; and (b) Simulated (dashed) and measured (solid) voltage outputs of the AC/DC converter with 10KOhm.

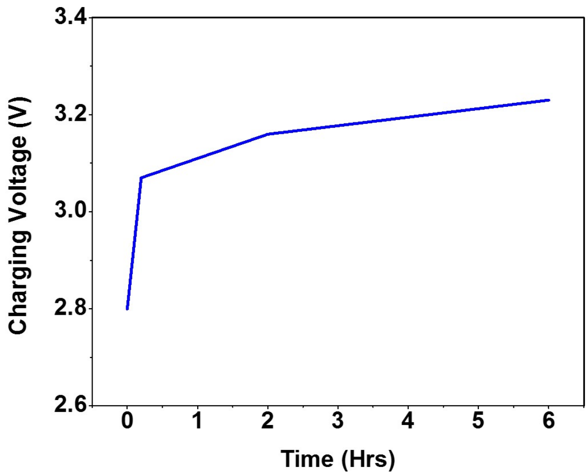

Figure 6: Charging curve (voltage) for the 100-mAh 3.7-V LiPo battery using a 10-stacked EH array.

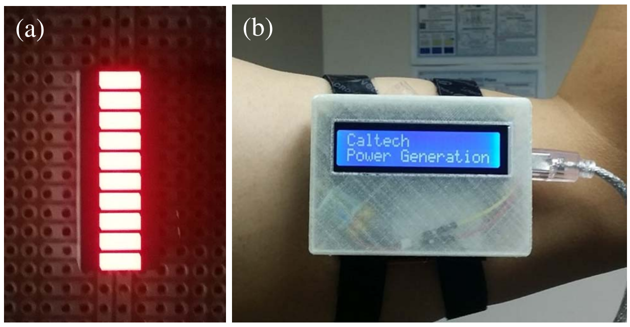

*Figure 7: Demonstration of powering portable electronics with the LiPo battery after 10-minute charging: (a) a 10 LED array (requiring 2.2 V, 1
0 mA); and (b) portable 2×16 LCD (requiring 2.8 V, 10 mA).*

CONCLUSION

Using a 10-stacked EH array with 10-kOhm load, we stably generated 3.12 mW from humming at 75 dB (Fig.4). Using this EH device, we charged a 100-mAh LiPo battery successfully, and its voltage reached up to 3.23 V after 6 hours of cumulative charging. Charging the battery for 10 minutes allowed to turn on a 10-LED array (requiring 2.2 V, 10 mA) or 2×16 LCD backlight unit (requiring 2.8 V, 10 mA) for about a minute. The output power level and power density can be improved further by adopting an efficient active rectifier and compactly packaging larger arrays of PZT devices, opening new possibilities to power portable and wearable electronics without using batteries.

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REFERENCES

[1] D.-H. Kim, N. Lu, R. Ma, Y.-S. Kim, R.-H. Kim, S. Wang, J. Wu, S. M. Won, H. Tao, A. Islam, K. J. Yu, T.-I. Kim, R. Chowdhury, M. Ying, L. Xu, M. Li, H.-

J. Chung, H. Keum, M. McCormick, P. Liu, Y.-W. Zhang, F. G. Omenetto, Y. Huang, T. Coleman, J. A. Rogers, "Epidermal Electronics", *Science*, vol. 333(6044), pp. 838-843, 2011.

[2] J.-Y. Sun, X. Zhao, W. R. K. Illeperuma, O. Chaudhuri, K. H. Oh, D. J. Mooney, J. J. Vlassak, Z. Suo, "Highly Stretchable and Tough Hydrogels", *Nature*, vol. 489, pp. 133-136, 2012.

[3] W. Zeng, L. Shu, Q. Li, S. Chen, F. Wang, X.-M. Tao, "Fiber-Based Wearable Electronics: A Review of Materials, Fabrication, Devices, and Applications", *Adv. Mat.*, vol. 26(31), pp. 5310-5336, 2014.

[4] K. Zhang, X. Wang, Y. Yang, Z. L. Wang, "Hybridized Electromagnetic–Triboelectric Nanogenerator for Scavenging Biomechanical Energy for Sustainably Powering Wearable Electronics", *ACS Nano*, vol. 9(4), pp. 3521-3529, 2015.

[5] Y. Sun, H. Cheng, S. Gao, Q. Liu, Z. Sun, C. Xiao, C. Wu, S. Wei, Y. Xie, "Atomically Thick Bismuth Selenide Freestanding Single Layers Achieving Enhanced Thermoelectric Energy Harvesting", *J. Am. Chem. Soc.*, vol. 134(50), pp. 20294-20297, 2012.

[6] D. J. Lipomia, Z. Bao, "Stretchable, Elastic Materials and Devices for Solar Energy Conversion", *Energy Environ. Sci.*, vol. 4, pp. 3314–3328, 2011.

[7] A. Delnavaz, J. Voix, "Electromagnetic Micro-Power Generator for Energy Harvesting from Breathing", IEEE IECON 2012, pp. 984-988.

[8] A. Delnavaz, J. Voix, "Flexible Piezoelectric Energy Harvesting from Jaw Movements", *Smart Mater. Struct.*, vol. 23, no. 10, pp. 984-988.

[9] W. Song, B. Gan, T. Jiang, Y. Zhang, A. Yu, H. Yuan, N. Chen, C. Sun, Z. L. Wang, "Nanopillar Arrayed Triboelectric Nanogenerator as a Self-Powered Sensitive Sensor for a Sleep Monitoring System", *ACS Nano*, vol. 10(8), pp. 8097-8103, 2016.

[10] Q. Zheng, B. Shi, F. Fan, X. Wang, L. Yan, W. Yuan, S. Wang, H. Liu, Z. Li, Z. L. Wang, "In Vivo Powering of Pacemaker by Breathing-Driven Implanted Triboelectric Nanogenerator", *Adv. Mater.* vol. 26(33), 2014.

[11] S. Chen, J. Rosenberg, A. Balakrishna, Y. Ma, H. Cho, J. O. Lee, H. Choo, "On-Demand Power Source for Medical Electronic Implants: Acousto-Mechanical Vibrations from Human Vocal Folds", *NAPA Institute 2015 Workshop on Enabling Future Health Care: the Role of Micro and Nano Technologies*, Napa, CA, August 24-26, 2015.

[12] H. Cho, A. Balakrishna, Y. Ma, J. O. Lee, H. Choo, "Efficient power generation from vocal folds vibrations for medical electronic implants", IEEE MEMS 2016, pp. 363-366.

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