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Tunable Ultrasonic Energy Harvesting for Implantable Biosensors and Medical Devices

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Abstract. This work reports a tunable ultrasonic energy harvesting (UEH) device capable of high power output and/or large bandwidth based on concentric piezoelectric ring-shaped structures. Two different designs are presented: (1) the single ring-shaped UEH (r-UEH), and (2) concentric r-UEHs. Concentric r-UEHs can save space and therefore can provide benefits in powering low-power implantable biosensors and medical devices. This paper presents results of simulation studies and initial experiments of a single r-UEH.

1. Introduction

With the recent development of the Internet of Things (IOT), wireless communication technology, and wireless sensors node (WSN) architectures, the lack of long-term batteries has become a practical problem for microsystems operating in hazardous and inaccessible areas such as the human body. In this regard, finding a replacement for the battery is one of the main issues of modern biosensors and implantable medical devices (IMDs) like implantable cardiac defibrillators, deep brain stimulators or pacemakers. Depending on how active the devices are, patients with IMDs currently need to undergo a surgical procedure for battery replacement every few years, increasing the medical risk and costs. As such, recent research efforts on wireless power transfer technology have received great attention and have potential to mitigate this problem.

Researchers have focused on RF and magnetic based wireless power transfer technologies due to their ease of application. However, because of their short transfer distances and low efficiencies caused by heavy attenuation in water (e.g., the human body), these approaches are limited when the human body is considered as the transfer medium. Furthermore, electromagnetic coupling with other devices is another concern that needs attention [1]. For deep IMDs, the ultrasonic frequency range is an advantageous alternative. On the other hand, the main challenge to using ultrasound energy harvesters (UEHs) is the selection of the frequency, which should carefully guide the transducer design [2]. This work reports a tunable acoustic energy harvesting (AEH) device capable of high power output and/or large bandwidth based on concentric piezoelectric ring-shaped structures as shown in Fig. 1. The silicon substrate acts as a mechanical anchor so that the topographic geometry of each ring-shaped structure can be represented by a mean radius r_0 and width w.

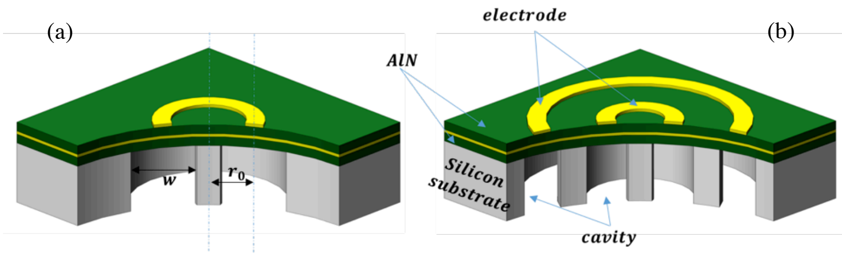


Figure 1: Model representation of: (a) single r-UEH, (b) concentric r-UEHs, where r_0 is the mean radius and w the width of the ring.

2. Ring-shape AEH Designs

Two different designs are presented: (1) the single ring-shaped UEH (r-UEH), and (2) concentric r-UEHs, see Fig. 1. The former shows the working principle of the r-UEH, while the latter is an extension that aims to improve the output power or operation bandwidth with multiple individual r-UEHs that can harvest either the same or different targeted frequencies. Contrary to conventional circular UEHs, concentric r-UEHs can save space and target several frequencies, thereby providing critical benefits in powering low-power implantable biosensors and devices.

Taking advantage of the fabrication process used in our group for other projects [3-4], the fabricated devices are shown in Fig. 2

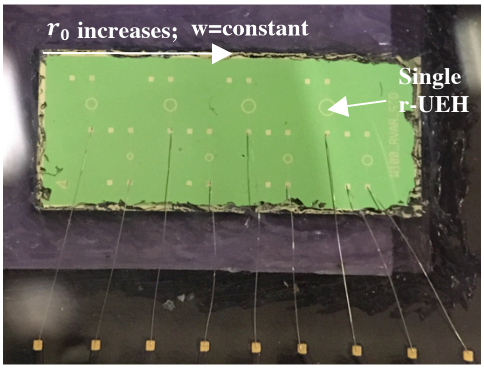


Figure 2: eight fabricated r-UEHs in the same chip mounted in a PCB, with wire bonding. In the same chip, the ring width (w) of the r-UEHs is kept constant and the mean radius (r_0) increases from left to right, bottom to top.

2.1. Key parameters and simulations of r-UEHs

One advantage of the r-UEHs is that the resonance frequency is not significantly dependent on the mean radius r_0 and rather only depends on the width of the ring w, as shown by simulation in Fig. 3. Fig. 3a shows the I_{sc} for fixed w as we change r_0, resulting in a mere 9% change in resonance frequency as r_0 is increased by 3x; Fig. 3b presents the effect of changing w at constant r_0=250µm, showing the dependence of the resonance frequency on the ring width. This allows for the design of concentric r-UEHs with the same resonance frequencies in order to achieve high power output, or with different resonance frequencies (by changing w) to achieve a large bandwidth. Moreover, it is trivial to target lower frequencies by increasing the width of the rings, however, other parameters such as the thickness or material composition of the diaphragm could also be changed. In this work, we assumed the latter parameters, among others, as constraints in order to match the devices fabricated from previous works in our group [4].

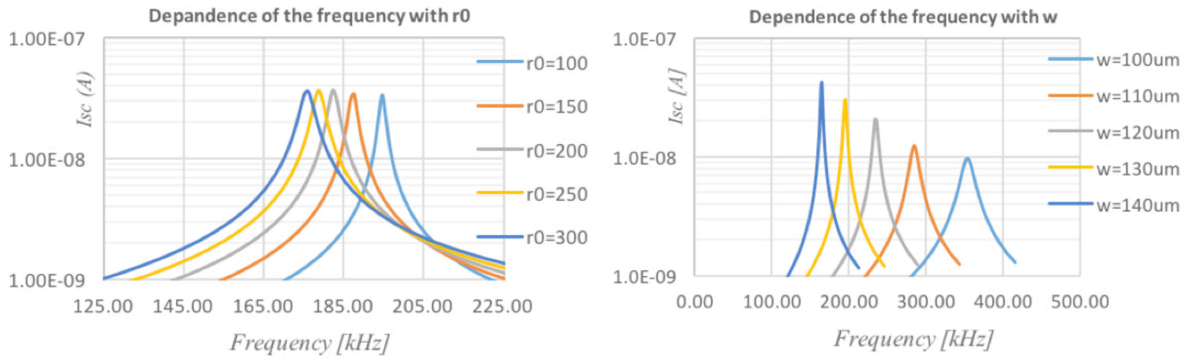


Figure 3: Short circuit current (Isc) vs. frequency for water-coupled devices. (a) effect of changing r_0 at constant w=135µm, showing less than a 9% change in resonance frequency as r_0 is increased by 3x; (b) effect of changing w at constant r_0=250µm, showing the dependence of the resonance frequency on the ring width.

2.1.1. Power output simulation. As a representative case, COMSOL simulations in Fig. 4 indicate that the normalized power output (P_o) is P_o = 2.4nW/(Pa*cm^2), which shows promising results and guidelines for the reported UEHs. As an example, in the case of pacemakers, it is expected to have ~3-4 cm^2 available for the power systems and several Pascal of applied pressure, suggesting that the power output can be on the order of µW. This is taking into account the concentric r-UEHs with the assumption that all of the 3-4 cm^2 of available space is used.

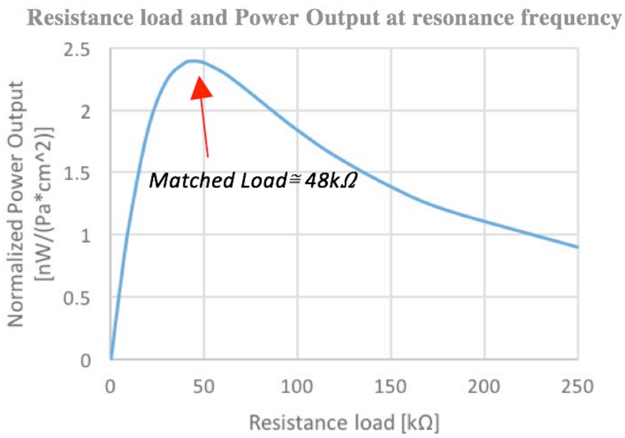
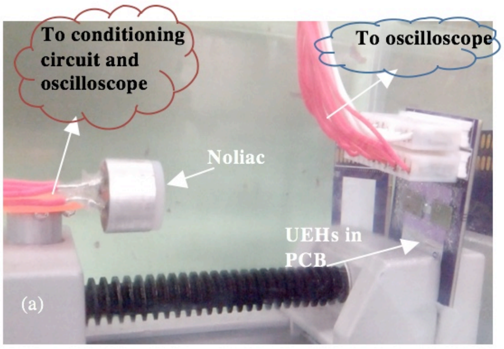


Figure 4: Power output for a single r-UEH with r_0=100µm and w=150µm operating at its resonance frequency with a variable external resistance load.

3. Experimental setup and single r-UEHs results

Fig. 5 shows the experimental setup and the first promising experimental results of a single r-UEH with r_0=200µm and w=135µm, operating in "reverse-mode" by driving the r-UEH with an applied 500mV AC voltage peak to peak and reading V_{pp}=220mV from a commercial ultrasonic transducer (Noliac UZ250). It is believed that due to acoustic reciprocity, these results should be indicative of the ability of r-UEH to receive ultrasonic energy as well; however, an optimized readout circuit is needed to acquire a reliable signal from the r-UEHs.



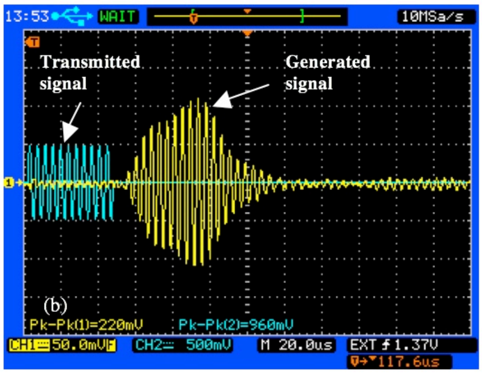


Figure 5: (a) Experimental setup and (b) promising experimental results of single r-UEH at r_0=250μm and w=135μm at 240kHz, in "reverse-mode" operation if applied 500mV AC voltage and reading the voltage, which is proportional to the pressure generated due to the reciprocity in the transduction of the energy

4. Discussions

In this work we present the design, simulations, and experimental results of a ring-shaped acoustic energy harvester (r-UEH), which is an advantageous design as the mean radius of the rings can be changed as needed without significantly affecting the resonance frequency. As a consequence, it is possible to design concentric r-UEHs in order to save space and therefore provide benefits in powering low-power implantable biosensors and medical devices. Depending on the applications, it is also possible to harvest different frequencies by using concentric r-UEHs with different widths in order to create a large bandwidth array. In the case of implantable medical devices, because ultrasonic waves are safe for the human body, one could conceivably think to reduce the dimensions of the battery - and therefore the battery life - and charge the devices more often (e.g., once a year) using r-UEHs for wireless power transfer.

References

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