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Piezoelectric Energy Harvester with Piezo-Magnet Stack for Ultrasonically-Powered Brain Implants

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***Abstract*—This paper presents a novel approach to improve the performance of Piezoelectric Energy Harvesters (PEHs) applicable to a variety of applications, *e.g.* biomedical implants. This is brought by stacking a magnet over the piezoelectric material, *i.e.* a piezo-magnet stack. Using the proposed piezo-magnet stack, an improvement in the generated power on the piezoelectric receiver from ultrasonic waves is observed. This is attributed to the interaction of amplified force induced by the magnetic material and the manipulation of the polarization of the piezoelectric material making the receiver more sensitive to mechanical waves. Experimental results show an output power of up to $3.27mW$ when equipping a $1mm^3$ Lead Zirconate Titanate (PZT4) cube as piezoelectric material with the same-size cubic Neodymium (NdFeB) magnet, which is 18% higher compared to the piezoelectric cube without the magnet. The PZT showed 13% frequency shift of the resonance frequency to a higher frequency, when it is stacked with the magnet.**

***Index Terms*—Implantable devices, piezoelectric, magnet, ultrasonic waves**

I. INTRODUCTION

During the last decades, acoustic power transfer through different materials like air, water, concrete, human tissue, etc have received considerable attention for various applications *e.g.* underwater wireless communication [1], haptics [2], structural health monitoring [3], and biomedical implants [4]–[8]. Among the aforementioned applications, large portion of resources have been allocated to biomedical implants to monitor, diagnose, and cure human diseases. Piezoelectric energy harvesters (PEHs) which are comprised of pure PZT, have been widely used for biomedical implants due to their high aperture efficiency, leading to the development of various devices such as neural recording microsystems [9] and implantable pacemakers [10].

When a PEH is linked with ultrasonic waves, a larger surface area for the PEH is preferable since it results in absorbing a larger share of the incoming waves and consequently higher harvested energy for powering a device. However, for implantable devices inside the human body especially inside the brain, ultra-miniaturized devices are preferred to minimize the tissue damage caused by the implant. Miniaturization of such wirelessly-powered devices, *e.g.* stimulators for treatment of neurological disorders, is still challenging due to power constraints [11]. For instance, we envision to modulate genetically-manipulated neurons using a micro-scale light-emitting-diode (μLED), a method known as *Optogenetics* [7]. For such micro-scale devices, the size of the PEH is the bottleneck and should be at least a few hundred micrometers, while the maximum allowable volume of the envisioned device including the PEH, μLED and the electronic integrated chip should be in the order of 500x500x500 μm^3. In such a system, there is a high power demand by the μLED, which shows the importance of having a high aperture efficiency for the PEH. To compensate for shortages in power budget and enhance the aperture efficiency of PEH, researchers have used different approaches. Such techniques are employing 1-3 composite materials to reduce the acoustic impedance mismatch with the medium [12], introducing materials with higher mechanical-electrical coupling factor [13], or optimization of electrical loads on the receiver with power maximization approach [14]. Here, as a completely different approach, we propose a novel method: adding a layer of magnetostrictive material to the PEH to enhance its aperture efficiency. As will be explained later, the proposed method takes the advantages of Villari effect and magnetoelectric phenomena for this goal. Throughout this paper, we will describe the theory behind how mechanical stress due to ultrasonic waves can increase the generated power from the piezo-magnet stack in section II with simulations, and then experiments will be presented to validate the theory in section III.

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II. METHODS

A. Theory

In this section, first we will briefly describe the theory about piezoelectric, magnetoelectric, and villari effect. Then, our proposed structure with simulations will be explained. In piezoelectric materials, the piezoelectric effect provides a coupling between mechanical deformation and the electric field through a direct or an indirect effect. The constitutive piezoelectric equations are as follows [15]:

$$S = s^E T + d^t E \tag{1}$$

$$D = dT + \epsilon^T E \tag{2}$$

where the mechanical terms are strain (S) and stress (T), while the electrical terms are electric field (E) and electric displacement (D). s^E is the compliance at constant electric

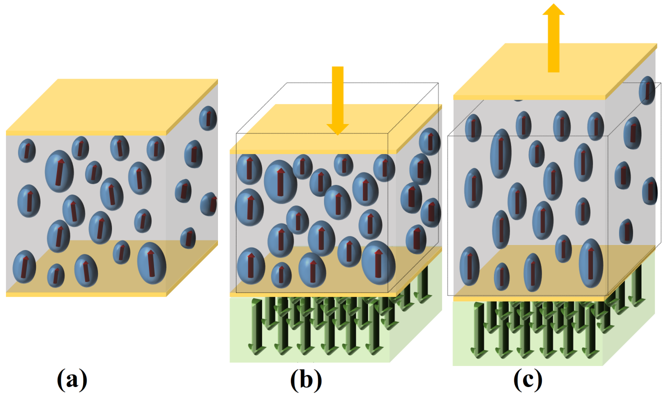

Fig. 1. PZT4 cube in (a) initial mode before ultrasonic stimulation. Piezo-magnet stack during ultrasonic powering in (b) compression, and (c) tension.

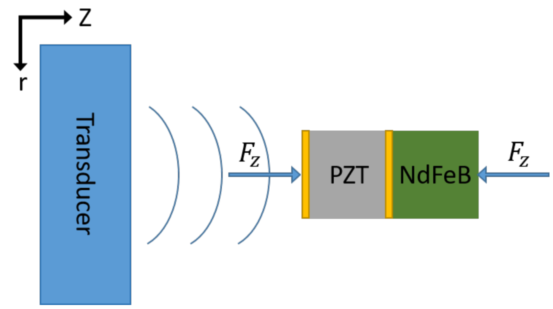

Fig. 2. Diagram of the piezo-magnet stack under the influence of mechanical force.

field, d^t is the piezoelectric constant, and ϵ^T is the dielectric constant at constant stress.

On the other hand, a coupling between electric and magnetic field is realized in magnetoelectric effect with another group of materials e.g. multiferroics and composite materials. Among these composite materials, piezoelectrics and magnetostrictives couple strain and magnetization through linear magnetomechanical coupling equations [16]:

$$S = s^H T + dH \tag{3}$$

$$B = d^* T + \mu^T H \tag{4}$$

where s^H is the compliance at constant magnetic field H, d and d^* are the piezomagnetic coefficients, and μ^T is magnetic permeability at a constant stress.

A mechanical stress on the composite will strain the magnetostrictive material, and consequently the magnetization will change due to the inverse magnetostrictive effect or Villari effect. A change in the magnetization induces a magnetic field on the composite, which results in a change of the polarization of the piezoelectric material through the magnetoelectric effect. Hence, a mechanical stress which can be the result of ultrasonic waves hitting the surface of the PEH may increase the generated power.

B. *Proposed Structure*

Ultrasonic waves are longitudinal waves in fluids, where particles move back and forth in the direction of wave propagation. Therefore, they induce compressive and tensile forces on the PEH, which is the reason for the AC output current on the PEH [17]. The resulting force of the ultrasonic waves is as follows:

$$F_z = PA \tag{5}$$

where P is the acoustic pressure, and A is the area of the PZT. The acoustic pressure emitted from the transducer can be formulated as:

$$P = \sqrt{2IZ} \tag{6}$$

where I is the acoustic intensity emitted from the transducer and Z is the acoustic impedance of the medium. As mentioned in the previous section, induced magnetic field due to the mechanical stress may manipulate piezoelectric polarization. In other words, as shown in Fig. 1, when the acoustic wave applied to the PEH is compressive (Fig. 1.b), the piezoelectric dipoles get closer to the magnet. Therefore, magnetic force will be increased. In tension (Fig. 1.c), the piezoelectric dipoles get farther from the magnet, thus, magnetic forces will be decreased. In conclusion, in both cases, the proposed magnet induces forces on the piezoelectric dipoles, thereby increasing the aperture efficiency of the PEH. As a result of the magnetoelectric effect, the generated electric field intensity in piezoelectric material due to the force as shown in Fig. 2 is calculated by:

$$E = \frac{d_{33} F_z}{\pi r^2 \epsilon_0 (\epsilon^T - 1)} \tag{7}$$

where d_{33} is the piezoelectric coefficient, ϵ_0 is the vacuum permittivity, and r is the radius of the PEH. We speculate that the magnetic field will enhance d_{33}, and consequently increase the electric field generated in the PZT.

C. *COMSOL Simulation*

To simulate the effect of the magnet stacked behind the piezoelectric crystal, COMSOL Multiphysics 5.4 is used. For simulation we computed solid mechanics, electrostatics, and magnetic fields. PZT-4 and neodymium (NdFeB) are selected as piezoelectric material and magnet, respectively. Fig. 3 (a) shows PZT with a fixed boundary condition on the bottom and it is stimulated with ultrasonic waves from the top, and Fig. (b) illustrates the same boundary conditions applied on PZT (top) and magnet (bottom). In this figure, we have investigated the effect of magnetic field because of the magnet on the resulting stress and we have shown the piezo-magnet experienced more stress and as a result more electric field will be generated.

III. Experimental Results

A. *Power Measurement*

In this section, experimentals results which are including power and frequency measurements will be presented. Based on the Food and Drug Administration (FDA) regulations [18], the time averaged maximum allowed acoustic intensity for the human body is $7.2 mW/mm^2$, this maximum intensity is used

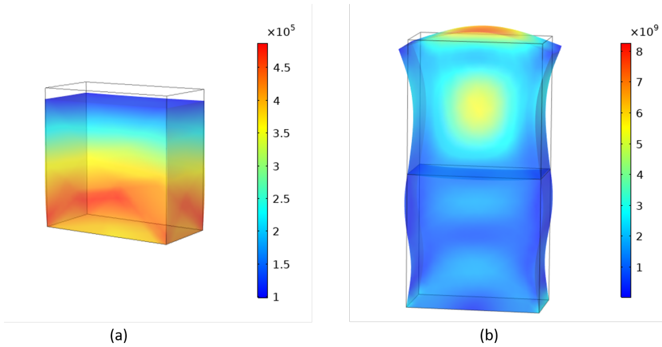

Fig. 3. Simulation of stress on PZT (a) and piezo-magnet stack (b) with a fixed boundary condition on the bottom and ultrasonic waves from the top.

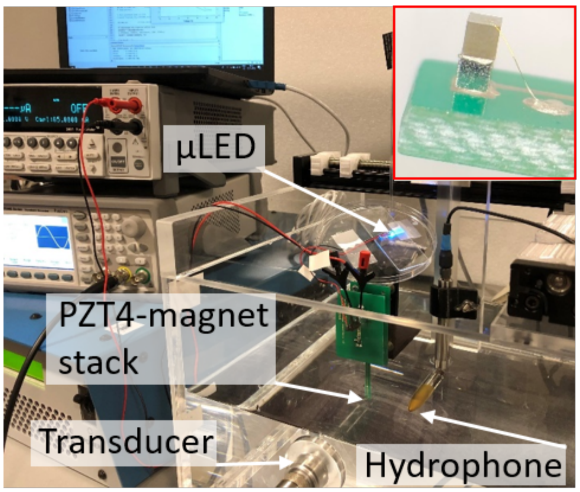

Fig. 4. Measurement setup with the piezo-magnet stack, μLED, ultrasonic transducer, and hydrophone. The inset shows enlarged piezo-magnet stack wirebonded to the PCB.

for all of our experiments. As shown in Fig. 4, measurements are done in a water tank. Acoustic absorbers have been installed in the water tank to absorb the reflected waves. A hydrophone HGL-0400 is used for measuring the acoustic intensity emitted from the Olympus immersion transducer. PZT and neodymium are stacked together and connected using silver epoxy, and then wire-bonded to the printed circuit board (PCB). A diode bridge rectifier is used in our measurements for rectification of the signal at the piezoelectric receiver's terminals. Furthermore, a Keithley 2401 source meter is connected to sweep the voltage and measure the current. The blue μLED is attached to the piezo-magnet stack to test the output power, which is envisioned to be used for optogenetics within this project.

To achieve the maximum power efficiency, the piezoelectric receiver and the Olympus transducer should operate at the resonance frequency of the PZT. Figure 5 illustrates the measured load power of the $1mm \times 1mm \times 1mm$ piezoelectric receiver (blue curve) and the same size piezo-magnet stack (green curve) over a voltage load sweep. Results showed an

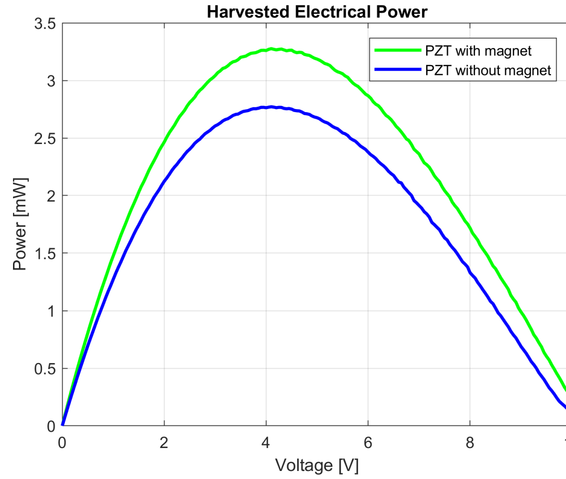

Fig. 5. The Measured harvested power by the PZT4 cube (blue) and the piezo-magnet stack (green) versus output voltage.

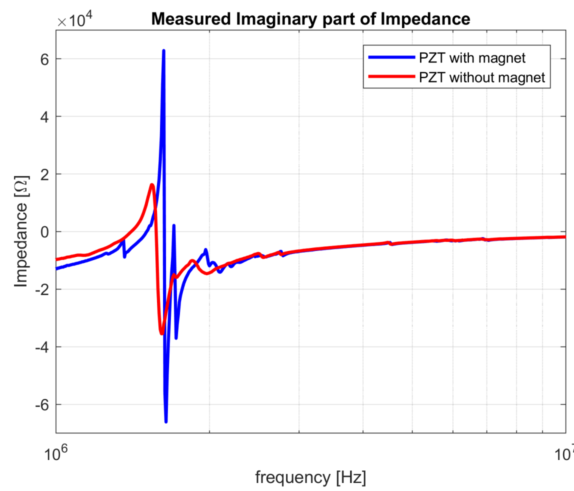

Fig. 6. Measured electrical impedance spectrum by network analyzer for PZT4 with (blue) and without (red) magnet.

18% improvement in the harvested power with the piezo-magnet stack.

B. Frequency Measurement

We use an ENA E5071C network analyzer to measure the frequency spectrum. Figure 6 shows the measured electrical impedance spectrum of the cubes. The piezo-magnet stack (blue curve) has 13% larger resonance frequency than the piezoelectric receiver without magnet (red curve). The resonance frequency is proportional to $\sqrt(k/m)$ where m is the mass of the mechanical system and k is the spring constant of the system. Adding a magnet to the system increases its mass and we therefore expected to have lower resonance frequency. However, we speculate that the magnet also increases the spring constant of the PZT, thus increasing the resonance frequency of the system.

IV. Conclusion

In this work, we proposed a new structure by stacking a magnetic layer on the back side of a piezoelectric material to improve the harvested energy of a piezoelectric harvester. This can improve the possibility of scaling down the size of the piezoelectric harvester which could be applied for implants where the size is the main bottleneck. Measurement results show that the proposed structure improves the generated power of the PEH by 18%, and the resonance frequency by 13%, which require more exploration.

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