



Impedance Matching Techniques of Multi-layered PZT Ceramics for Piezoelectric Energy Harvesters

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Abstract

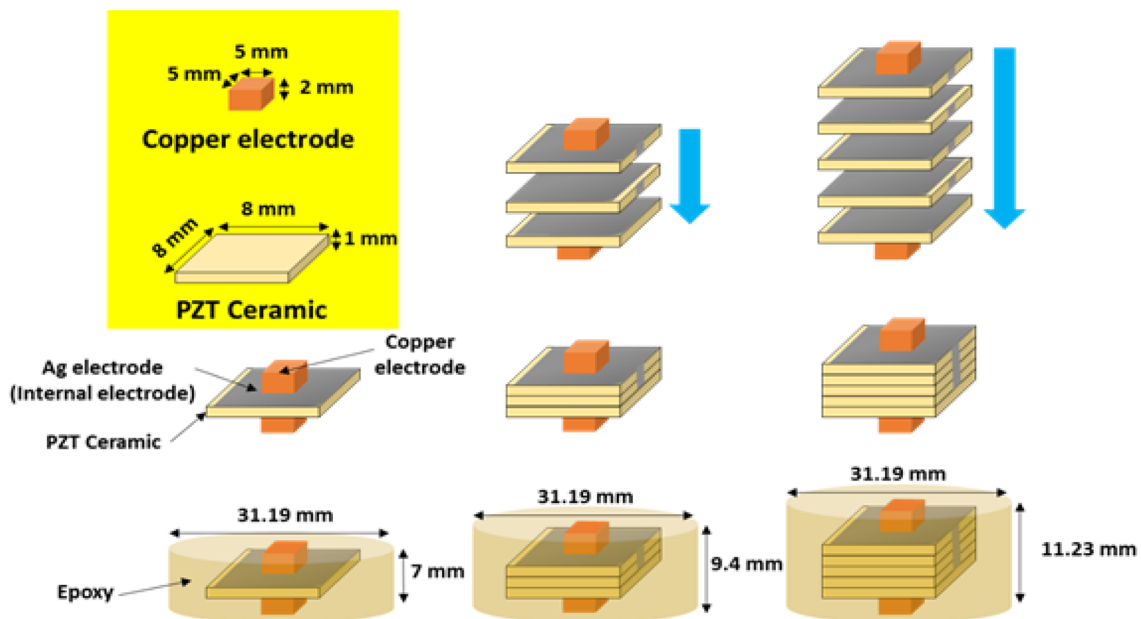
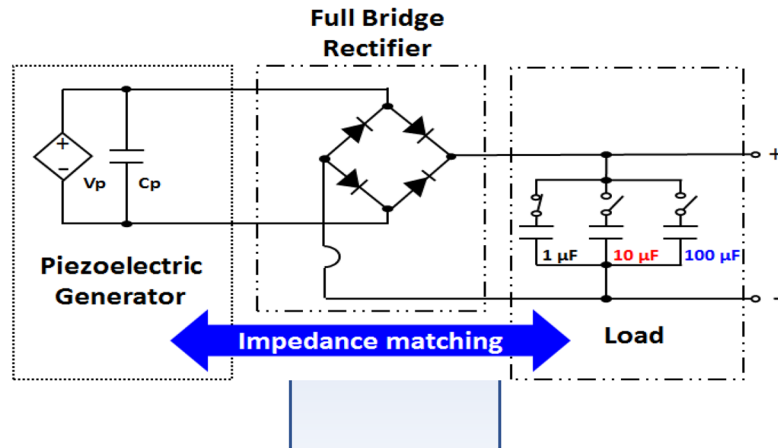
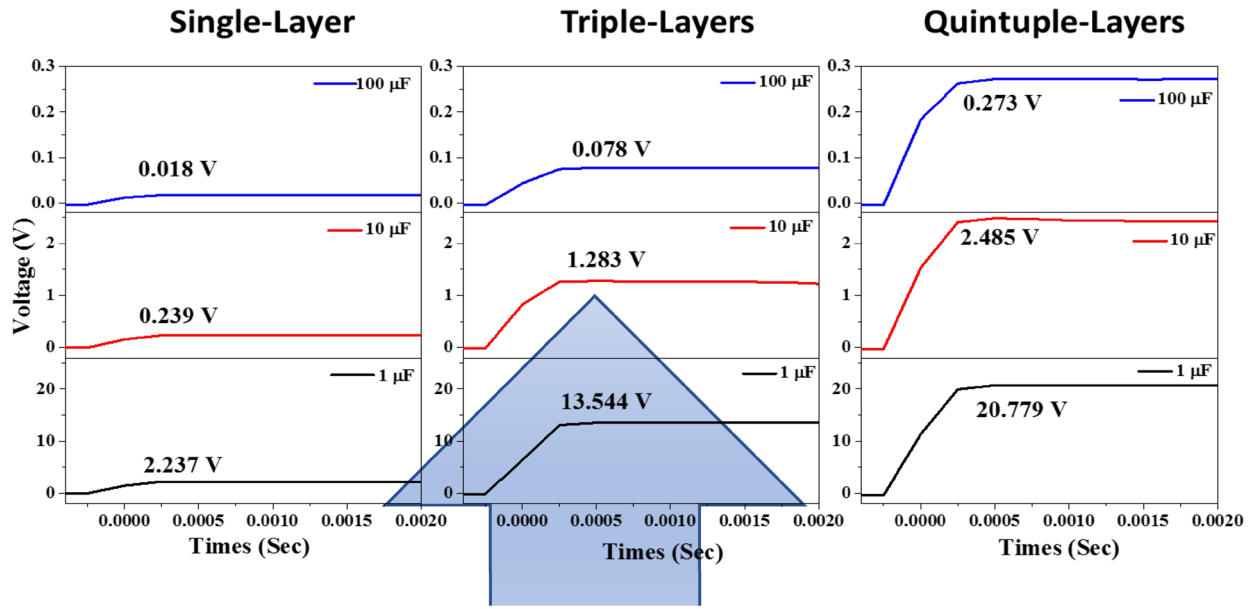
In this research, the possibility of passive damping system based on the piezoelectric energy harvesting has been proposed and tested. To apply passive damper system, piezoelectric ceramics were stacked, and impedance was matched. Piezoelectric energy harvesters were employed due to their excellent piezoelectric and robust properties. Especially, multilayered (Pb,Zr)TiO₃ piezoelectric ceramic have high piezoelectric charge coefficient d_{33} and piezoelectric voltage coefficient g_{33} for actuator and harvester applications, respectively. Multilayered (Pb,Zr)TiO₃ piezoelectric ceramics can generate comparatively high current level compared with single layered piezoelectric ceramics due to its parallel connected capacitors. In energy harvester applications, multilayered (Pb,Zr)TiO₃ piezoelectric ceramics have a role of voltage source with capacitive impedance. Due to considerable impedance in voltage sources, the role of impedance matching between the source and output terminal is more critical. By employing the piezoelectric energy harvesting system for the passive damper, output energy of 11 $\mu\text{J}/\text{cm}^3$ was obtained at the 100 μF capacitors. Therefore, impedance matching technologies were intensively investigated to obtain maximum output energy for storing capacitors.

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Graphical Abstract



Keywords Piezoelectric energy harvesters · Impedance matching · PZT

1 Introduction

Piezoelectric energy harvesters have been intensively studied for renewable energy applications. Piezoelectric energy harvesters have many merits compared with other types of energy harvesters such as robust properties against harsh environmental circumstances. These materials can be used for several decades without extra repairing process. Therefore, piezoelectric energy harvesters have been proposed as the best candidate for energy sources for ubiquitous sensor networks [1], monitoring systems [2], and secondary energy sources [3–5]. For these applications, lead based piezoelectric materials have been intensively investigated for a lengthy time due to their stable piezoelectric properties and easy processing conditions. However due to limited output energy levels from piezoelectric energy harvesters, it is crucial to identify a method to increase generated output voltage and current levels. Since piezoelectric energy harvesters can generate output voltages only during the time for stress, generated output voltage is strongly dependent on output energy shape of external mechanical energy sources. Since generation time of output voltages is brief, it is critical to increase generation time to increase output power. Rectifying circuit should be well designed with rapid response to acquire all generated energy [6]. Otherwise before triggering the harvesting rectifying circuit, generated energy will be dissipated through resistive circuits. To increase generation time of piezoelectric energy harvesters, parallel connected energy harvesters can be accepted for devices applications in general. By connecting piezoelectric energy harvesters as parallel connected circuit, total capacitance increased as the number of layers increased. Therefore, increased total capacitance can provide more generation time of currents.

Since piezoelectric energy harvesters are based on capacitive materials, equivalent circuit for energy sources can be expressed by dependent voltage sources with variable capacitors. In general, to acquire maximum energy at output terminal, it is crucial to consider equivalent impedance level to extract maximum output energy [7, 8]. Exact impedance value with different phase between the input energy harvester, which expressed as dependent voltage sources with variable capacitors, and output terminal should be matched. Higher values or lower values of impedance in the output terminal compared with that of input energy sources can prevent to delivering the maximum energy to the system. Therefore, various output impedance levels were considered and compared to extract optimized output impedance level and output energy.

In this study, impedance values of optimized output terminal were designed and suggested to obtain maximized output energy level.

2 Experimental Procedures

The $(\text{Pb,Zr})\text{TiO}_3$ (PZT) ceramics were prepared by conventional solid-state reaction process. Powders of PbO , ZrO_2 , and TiO_2 were used as starting materials. They were ball milled in ethyl alcohol with zirconia balls for 24 h, and dried at 100 °C. Then powders were dried at 120 °C for 24 h, and calcined at 900 °C for 2 h in air. Calcined powders were mixed with 5 wt.% poly vinyl alcohol (PVA), and uniaxially pressed into disks of 12 mm diameter under 300 Mpa. These disks were sintered at 1200 °C for 2 h in air. Crystalline structures of sintered samples were investigated by X-ray diffraction (XRD) analysis (Rigaku Model D/MAX-2500 V/PC). Frequency dependence of dielectric constant (ϵ_r) and dielectric loss of samples were measured using an impedance analyzer from 100 Hz to 1 MHz (Agilent 4294A Precision). Samples were poled under a DC electric field of 4.5 kV/mm in a silicon oil bath at 80 °C for 30 min. Piezoelectric coefficient d_{33} values were measured using a Berlincourt quasi-static d_{33} m (YE 2730A). Different size of capacitors and resistors were employed in the circuit to optimize the impedance matching. Full wave bridge rectifier circuit was employed and tested to store the electric energy into the capacitors. Different size of 1, 10, and 100 μF were employed and tested to extract the output energy. By considering impedance matching technique, optimized capacitors were prepared for each condition and stored energies were calculated and compared.

3 Results and Discussion

Figure 1 reveals schematic diagram of single, triple, and quintuple layered PZT energy harvesters. As revealed in the figure, sample size of single, triple, and quintuple layered PZT energy harvesters are $8 \times 8 \times 1 \text{ mm}^3$, $8 \times 8 \times 3 \text{ mm}^3$, and $8 \times 8 \times 5 \text{ mm}^3$, respectively. Metallic electrode was attached to both of top and bottom sides to make a poling process and collect energy. As an outer metallic electrode, Cu electrode was attached. For inner electrodes, conductive epoxy was applied to make parallel connection. Measured capacitance and piezoelectric charge coefficient d_{33} for single, triple, and quintuple layered PZT energy harvesters are 0.27, 0.88, 1.5 nF and 270, 600 and 848 pC/N, respectively. Since the

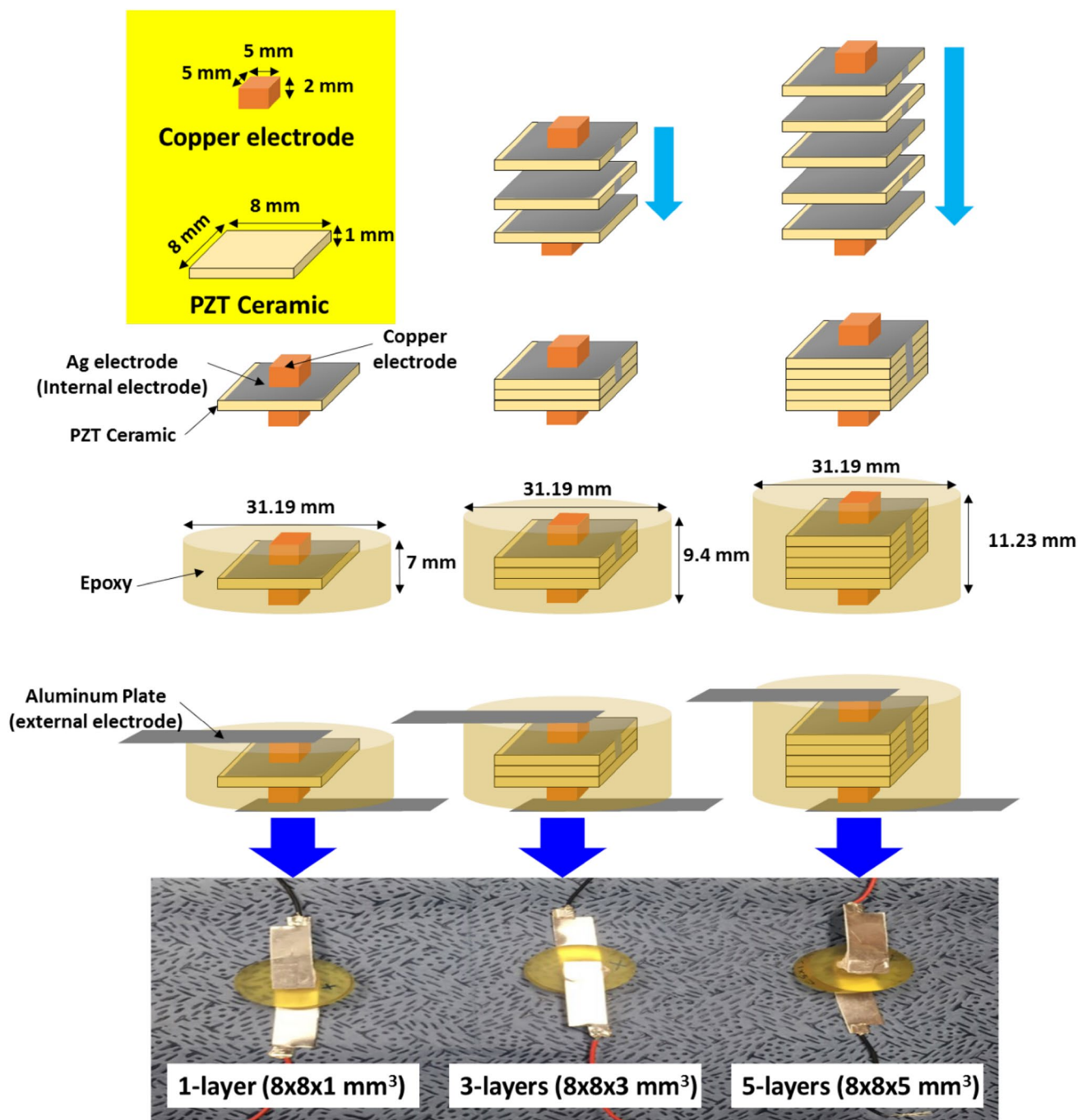


Fig. 1 Schematic diagram of the single, triple, and quintuple layered PZT energy harvesters

piezoelectric ceramics have capacitive behaviors, parallel connected piezoelectric ceramics showed parallel circuits of capacitors. It means that the capacitance and piezoelectric charge coefficient of piezoelectric energy harvesters can be increased as increasing the number of piezoelectric ceramics.

Figure 2 displays X-ray diffraction patterns for PZT ceramics after the sintering process. As revealed in the

figure, PZT ceramics have perovskite structure without pyrochlore phase. It seems that PZT ceramics were well sintered at the optimum condition in the sintering process. Since the piezoelectric ceramics are frequently operated under mechanically stressed condition, it is very important to prepare the specimens in the optimally sintering condition, otherwise the devices can be destroyed during the operating condition. PZT piezoelectric ceramics have tetragonal

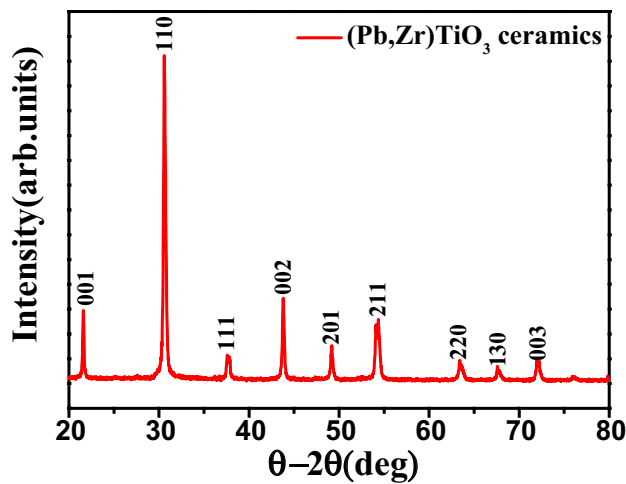


Fig. 2 X-ray diffraction patterns of $\theta-2\theta$ scan for $(\text{Pb,Zr})\text{TiO}_3$ piezoelectric ceramics measured at room temperature range

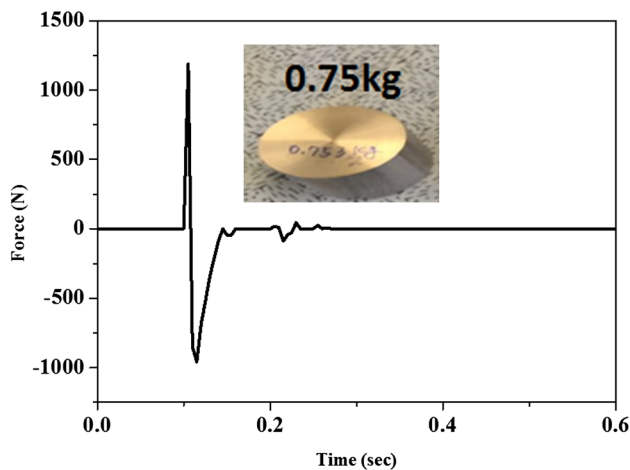


Fig. 3 Reveals generated output force from drop-weight impact testing system (a) and falling hammer of 0.75 kg

structure at room temperature range. Due to this high tetragonality of PZT ceramics, PZT ceramics have high piezoelectric charge coefficient and piezoelectric voltage coefficient, strongly related with generated output current and voltages. The lattice parameters of c and a were extracted from the XRD data. To extract the lattice parameters of tetragonal structure, Nelson-Riley formula was employed.

$$\frac{C_{\cos \theta} - C_0}{C_0} = A \cdot \cos^2 \theta \left(\frac{1}{\sin \theta} + \frac{1}{\theta} \right) \quad (1)$$

where $C_{\cos \theta}$ is an interplane distance calculated from the apparent Bragg peak position at 2θ and A is a fitting coefficient. The estimated lattice parameters of c and a are 4.15 Å and 3.94 Å, respectively.

Figure 3 reveals generated output force from drop-weight impact testing system (a) and falling hammer of 0.75 kg. Measured impulse impetus from the drop-weight impact system was 1188 N. By considering sample area ($2.5 \times 10^{-5} \text{ m}^2$) of PZT energy harvester, impact stress corresponds to 47.52 MPa, almost matched to maximum generation force of PZT based piezoelectric ceramics. By observing generation force from piezoelectric energy harvesters, at first positive force was generated and then negative force was generated. By removing the applied force from piezoelectric specimen, negative force can be developed. Therefore, full bridged rectifying circuit with rapid response is necessary to measure and store the energy properly.

Figure 4 reveals impedance matching circuit for energy harvesting systems. When the mechanical stress was applied to the piezoelectric materials, piezoelectric devices can generate output voltages. Therefore piezoelectric materials can be expressed as mechanical force or stress dependent voltage sources. Also, piezoelectric ceramics have capacitive properties. Therefore, piezoelectric energy harvesters can be expressed as mechanical force dependent voltage sources with variable capacitors. Since the piezoelectric ceramics show capacitive behaviors with piezoelectric properties, the piezoelectric generator can be express with parallel circuit of mechanical force dependent voltage sources and capacitors. And then, full bridge rectifier was connected to rectifying output voltages and output terminal, connected with 1, 10, and 100 μF capacitors with switches at the output terminal. Since piezoelectric energy harvesters can be expressed with impedance circuit in the input terminal, energy collecting output terminal connected with output impedance with similar impedance values at input impedance level. Since impedance matching technologies are based on same load values with opposite phase angle, it is vital to extract impedance of input system and load part. Therefore, different size capacitors with 1, 10, and 100 μF were selected and used for this analysis.

Figure 5 displays generated output voltage applied at storing capacitors in the energy harvester circuit. As revealed in the figure, generated output voltages applied at single, triple, and quintuple layers were 2.24, 13.54, and 20.78 V at 1 μF , respectively. However, as increasing storing capacitor size, generated voltages decreased. When storing capacitor size of 10 μF , applied voltages were 0.24, 1.28, and 2.48 V for single, triple, and quintuple layers, respectively. As increasing the size of storing capacitors up to 100 μF further, generated output voltages were 0.018, 0.078, and 0.27 V for single, triple, and quintuple layers, respectively. By comparing size of storing capacitors and generated output voltage levels, we found that generated output voltage decreased less than one tenth, even though magnitude of storing capacitors were increased by 10 times. It means that optimized storing capacitor values exist in energy storing circuits.

Fig. 4 Reveals impedance matching circuit for the energy harvesting system

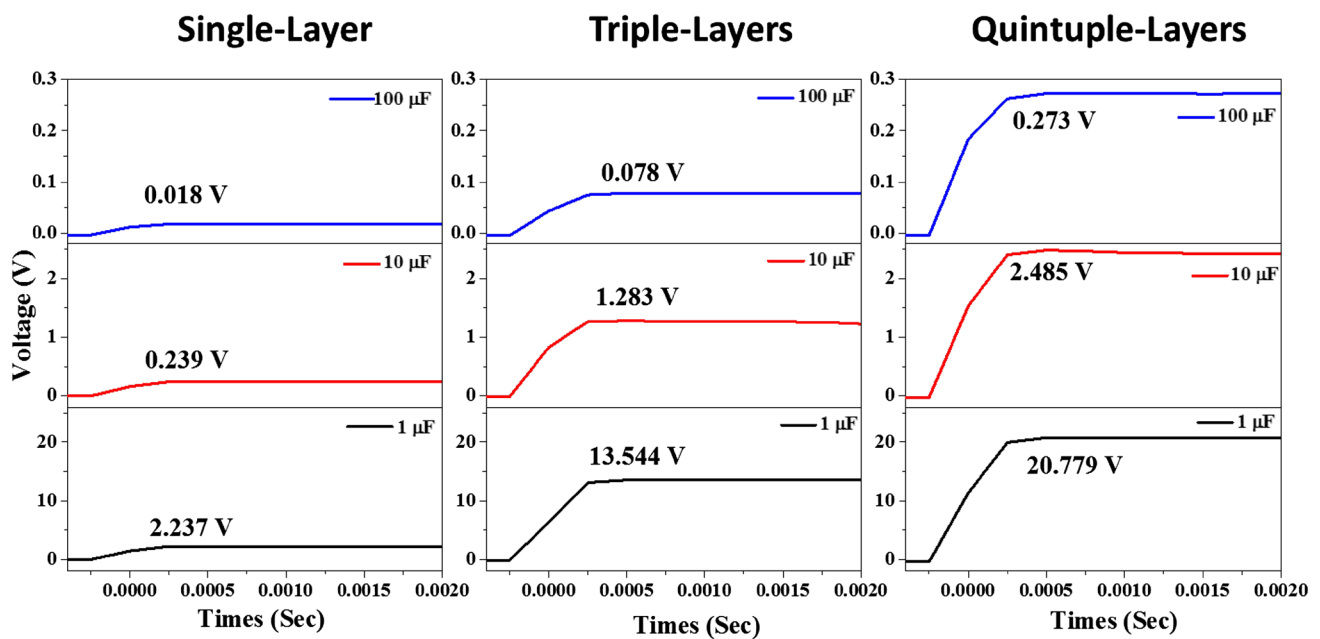
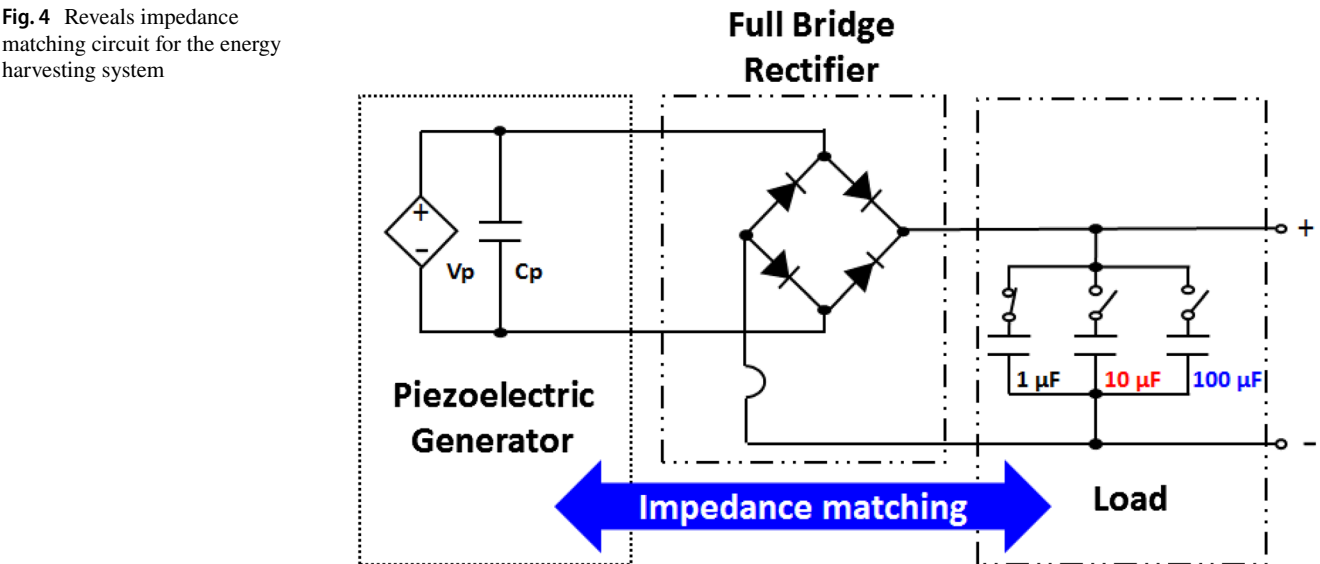


Fig. 5 Displays the generated output voltage applied at the storing capacitors in the energy harvester circuit

Figure 6 explains generated output energies of single, triple, and quintuple layered piezoelectric energy harvesters measured applied at 1, 10, and 100 μF respectively. In every case of single, triple and quintuple layers of piezoelectric layer, as increasing storing capacitor size, generated output energy decreased. For quintuple layered piezoelectric energy harvester case, as increasing storing capacitor size with 1, 10, and 100 μF , then storing energies decreased from 0.216 mJ, 0.0309 mJ, and 3.79 μJ , respectively. By considering volume of energy harvesters, 0.216 mJ, 0.0309 mJ, and 3.79 μJ corresponds to the 674 $\mu\text{J}/\text{cm}^3$, 97 $\mu\text{J}/\text{cm}^3$, and 11

$\mu\text{J}/\text{cm}^3$ for 1 μF , 10 μF , and 100 μF , respectively. As we have discussed in the Figs. 4 and 5, proper impedance matching is important to extract maximum energy from the energy harvesters. Since the capacitance of piezoelectric energy harvester is around 0.27–1.5 nF, smaller output storing capacitor of 1 μF is more important than others. Unfortunately, sub-micro Farad of storing capacitors cannot be employed due to their high output voltages, which applied capacitors during the measurement. As we have discussed before, with proper impedance matching technology, maximum output energy can be extracted from the system.

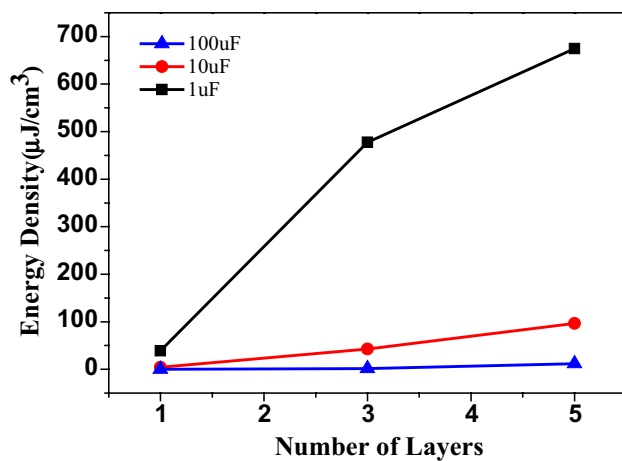


Fig. 6 Explains the generated output energies of single, triple, and quintuple layered piezoelectric energy harvesters' measurements applied at 1, 10, and 100 μF respectively

We found that impedance matching technologies have key roles in energy harvesting systems. Since multilayered piezoelectric energy harvesters have only several nano farads in input impedance, output terminal should have sub-micro level farads to have optimized impedance matching properties.

4 Conclusion

In this research, the possibility of passive damping system based on the piezoelectric energy harvesting has been proposed and tested. To apply passive damper system, piezoelectric ceramics were stacked, and impedance was matched. Multilayered piezoelectric ceramic energy harvesters were used and optimized to generate renewable energy for the passive damper system for the future energy harvesting technologies. Full bridge based rectifying system with capacitors were employed to extract maximum energy, which

applied to the passive damper system. Multilayered (Pb,Zr) TiO_3 piezoelectric ceramics can generate comparatively high current level compared with single layered piezoelectric ceramics due to its parallel connected capacitors. By employing the piezoelectric energy harvesting system for the passive damper, output energy of $11 \mu\text{J}/\text{cm}^3$ was obtained at the 100 μF capacitors. Optimized impedance matching techniques were used to maximize acquired energy level. Since impedance difference exists between input and output ports, impedance matching technologies were critical issues to acquire maximum energy. Otherwise, generated energies cannot be stored in storing capacitors.

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