Road energy harvester designed as a macro-power source using the piezoelectric effect

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Abstract

While energy harvesting is commonly used for micro-power sources, it could be applied in macro-power sources using a large-scale harvester in a spacious area. We designed and optimized an energy harvester for a busy roadway using piezoelectric cantilever beams. Using the road vibrational frequency under vehicle speeds of 60–80 km/h, we tuned the natural frequency of the beams by attaching a tip mass. Considering the typical vehicle wheel width and the depth of pavement, the designed energy harvester with a volume of 30 × 30 × 10 cm^3 contained 48 piezoelectric beams. To optimize the harvester circuit, we rectified the output current from each piezoelectric beam and connected the beams in parallel to avoid phase difference interruptions. Finally, we conducted impedance matching to maximize the output power. As a result, we realized an output power of 736 μW with a power density of 8.19 mW/m^2.

Keywords: Energy harvesting, Piezoelectricity, Road traffic, Macro-power source, Frequency matching, Impedance matching.

1. Introduction

As climate change becomes more significant, the use of fossil fuels will lose popularity, and therefore, researchers are currently focusing on renewable energy sources such as wind, solar, geothermal, and tidal power [1,2]. Moreover, there has been some interest in recycling ambient waste energy such as undesirable mechanical vibration and abandoned heat. This process is called energy harvesting, and it has been considered for low-powered electronic devices.

In particular, energy harvesting is ideal for wireless systems as it can eliminate the electrical wires connected to conventional AC power outlets or reduce the use of built-in batteries [3]. For example, for microelectromechanical systems (MEMS) designed for applications in human veins or artificial organs, energy harvesting could be very useful because changing batteries in these systems is very difficult. Further, energy harvesting is favorable in building technologies if wireless switches are powered by harvested energy because eliminating complex electrical wires inside the walls of the building can reduce building costs. Given these advantages, energy harvesting must be used effectively for smart home automation systems or the Internet of things, because it can make them batteryless and self-powered [4].

Although the nature of energy harvesting makes it readily applicable for micro-power sources, it could be potentially used for macro-power sources by installing large-scale harvesters in a spacious area. For example, an energy harvester installed under a road may be useful for macro-power sources. Such a system does not require any additional installation space because it can be located under an existing road, and this system could constantly harvest energy as long as vehicles are moving on the road. However, it is not desirable for vehicles to expend unnecessary energy by driving over a mattress-like road owing to the installed road energy harvesters. The displacement of the harvester must be minimized in order to properly harvest naturally-abandoned energy from moving vehicles.

To collect the ambient energy from the vehicles on a road, we need to convert road vibration, i.e., mechanical energy, into electrical energy. There are three possible methods for performing this conversion: electromagnetics, electrostatics, and piezoelectricity [5-8]. An electromagnetic energy harvester generates electricity from induced current in magnetic fields. It uses permanent magnets and coils of electrical wire, which require a spacious room in the harvesting module and a complex mechanical structure [3,9]. The electrostatics energy harvester captures sudden static electricity, which is difficult to store and has limited application owing to its low current [3].

On the other hand, piezoelectric energy harvesters have the widest range of output power density as well as the simplest structure among the three methods of harvesting mechanical energy [3]. This piezoelectric energy harvesting technology is gaining significant research interest [10], and has been applied for harvesting energy from human bodies [11-14], energy harvesting shoes [15,16], and sidewalk tiles [17].

Thus, using the piezoelectric effect to harvest energy from road traffic could be a new and reliable macro-energy source. Many studies have considered different types of road energy harvester designs [18,19]. Most studies have used a bulk piezoelectric ceramic owing to its structural simplicity and high output power; however, bulk ceramic is very fragile and expensive, which must be considered when implementing harvesters under a road.

In this study, we designed and optimized a piezoelectric energy harvester for a busy roadway using piezoelectric cantilever beams, which comprise piezoelectric ceramic layers and substrate layers. The substrates provide increased durability to the ceramic beams, and therefore, the piezoelectric beams are more appropriate for use in road energy harvesters. We constructed the piezoelectric energy harvester by considering important environmental conditions and design constraints and maximized its output power by conducted impedance matching to optimize the piezoelectric circuits.

2. Materials and methods

Fig. 1 shows the piezoelectric cantilever beam used in this research. A well-known piezoelectric material, namely PZT-PZNM ceramic (TIOCEAN, Korea), with dimensions of 38 × 38 × 0.2 mm^3 was attached on an AISI Type 304 stainless steel plate with dimensions of 40 × 60 × 0.2 mm^3. The specific material properties are listed in Table 1.

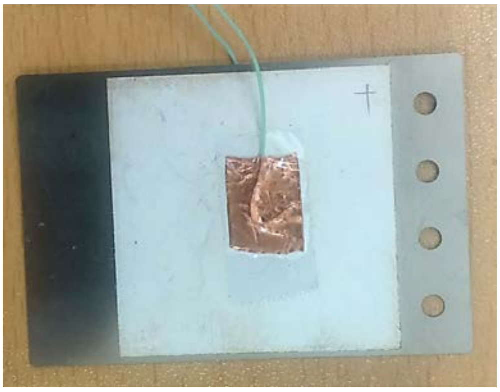

Fig. 1. Piezoelectric cantilever beam.

Table 1. Material properties of the piezoelectric cantilever beam.

Stainless steel (304SS)	Value
Density (g/cm^3): ρ	8
Young's modulus (GPa): E	193
Piezoelectric material (PZT-PZNM ceramic)	Value
Density (g/cm^3)	7.60
Dielectric constants ($\varepsilon_{33}T/\varepsilon_0$)	2300
Piezoelectric charge constants ($\times 10^{-12}$ m/V): d_{33}, d_{31}	450, -200
Piezoelectric voltage constants ($\times 10^{-3}$V·m/N): g_{33}, g_{31}	22.1, -11.1
Elastic constants ($\times 10^{-12}$ m^2/N): S^E_{11}, S^D_{11}	13.8, 11.8

2.1 Frequency analysis

A piezoelectric cantilever beam vibrates at its natural frequency when subjected to external impacts, and electricity is generated from its deformed perovskite structure. As the deformation increases, the power generated by the cantilever beam increases. Therefore, it is important to match the natural frequency of the cantilever beam to the frequency of the input source to maximize the deformation causing the resonance effect. Many previous studies have proven that a piezoelectric energy harvester shows a considerably effective mechanical–electrical power conversion at its resonance frequency [20,21]. In our case, the input source will be the road vibration.

Because vehicles move at random speeds, the road may vibrate with different frequencies. We analyzed existing studies to determine the road vibration caused by car movements under the most common car speeds of 60–80 km/h [22-25].

2.2 Frequency matching for a piezoelectric cantilever beam

We need to generate the resonance effect for our energy harvester, and it must show resonance at the most common road vibration frequency. The frequency of the beam can be described by

$$f_o = \frac{1}{2\pi}\sqrt{\frac{K_{beam}}{m_{eff}}}\,, \tag{1}$$

where f_o is the original frequency of the beam, K_{beam} is the stiffness of the beam, and m_{eff} is the effective mass of the beam. The stiffness and the effective mass of the beam can be calculated as

$$K_{beam} = \frac{b}{4L^3}\left(\sum_{i=1}^{n_1} n_i E_i h_i^2 + \sum_{j=1}^{n_2} n_j E_j h_j^2\right), \tag{2}$$

$$m_{eff} = m_t + m_o\,, \tag{3}$$

where b and L are the width and the length of the beam, respectively, n_1 and n_2 are the numbers of piezoelectric and electrode layers, respectively, m_t is the tip mass on the beam, and m_o is the mass of the beam [26]. Here E_i, ρ_i, and h_i are the Young's modulus, density, and height of each piezoelectric layer, respectively, while E_j, ρ_j, and h_j are the Young's modulus, density, and height of each electrode layer, respectively.

From equations (1)–(3), we can determine the desirable tip mass for tuning the natural frequency to the road vibrational frequency. We installed the mass on the beam and calculated its output power for different frequencies. Fig. 2 shows the experimental setup, which includes the function generator (model 33250A, Agilent, USA), power amplifier (model 2718, Brüel & Kjær, Denmark), vibration exciter (model 4809, Brüel & Kjær, Denmark), and oscilloscope (DPO4054B, Tektronix, USA).

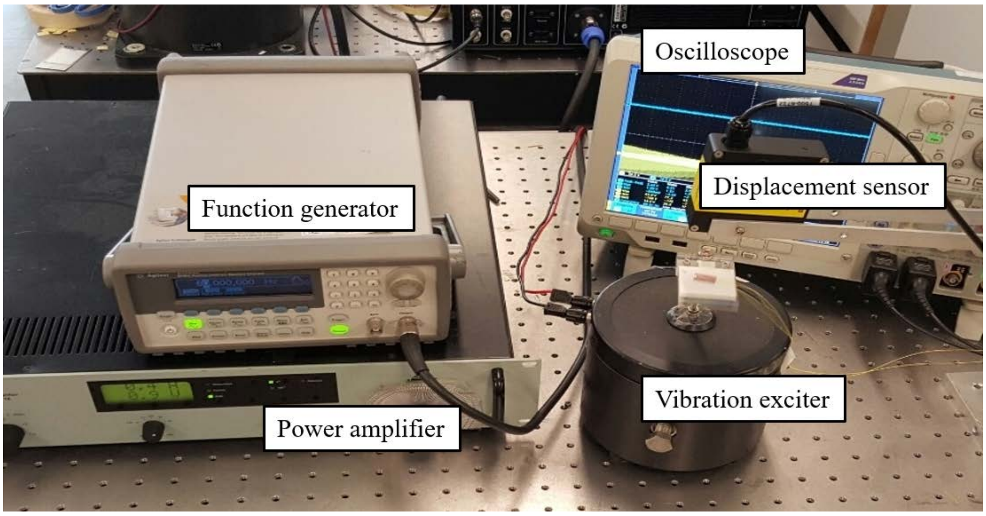

Fig. 2. Experimental setup for measuring the vibrational frequency of the piezoelectric beam.

2.3 Designing the road energy harvester

To determine the size of the harvester, we first considered the current road pavement system. For a typical Korean highway, the road is paved with 15 cm of asphalt. Because the Korean Institute of Civil Engineering and Building Technology is conducting asphalt research in order to satisfy the current standard with an asphalt depth of only 5 cm, we decided to construct our harvester with a depth of 10 cm. Moreover, we designed our harvester with a width of 30 cm, which is slightly wider than a typical vehicle wheel, so that the vehicles moving over the harvesters can activate them regardless of their position on the road. However, a $30 \times 30 \times 10$ cm^3 harvester is too big for a lab-scale harvester. Therefore, we divided the harvester into four sections; we developed four $15 \times 15 \times 10$ cm^3 harvesters, which compose a single $30 \times 30 \times 10$ cm^3 harvesting module.

Because it is not desirable for vehicles to expend more fuel when moving over the energy harvester, we need to constrain the vertical displacement of the energy harvester to minimize this energy dissipation. Therefore, we designed the energy harvester to have no more than 1 mm of vertical displacement. We used the CATIA V5R20 software to design our harvester, and we manufactured the harvester using duralumin, which is light and durable.

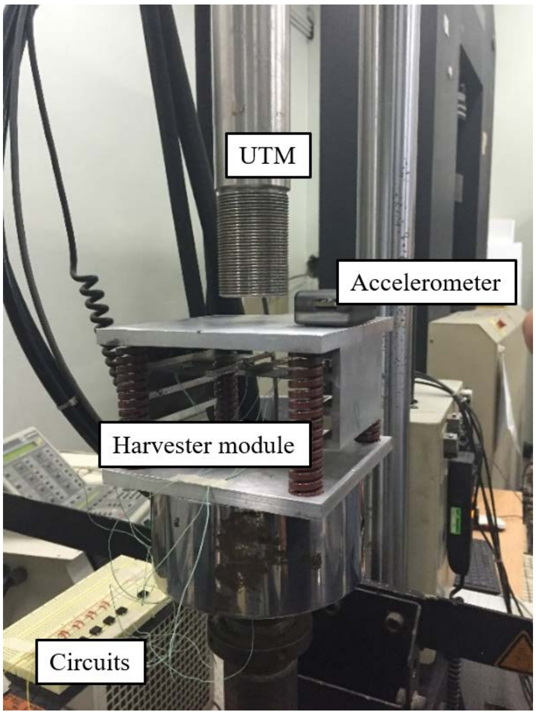

Fig. 3. Universal testing machine experimental setup.

We measured the output power of the complete harvester using a universal testing machine (UTM). The UTM used in this work is a static hydraulic industrial model (8521S, Instron, USA), which is capable of exerting a haversine waveform load into the harvester. We set the frequency of the input wave to 10 Hz and the displacement to 1 mm.

2.4 Impedance matching

After designing and manufacturing the harvester, we performed circuit optimization based on the maximum power transfer theorem. We first rectified the output current from each piezoelectric beam and connected the beams in parallel (Fig. 4) in order to avoid interruptions from phase differences. Then, we conducted impedance matching to maximize the output power. The maximum output power $P_{\max}$ can be expressed as

$$P_{\max} = \left(\frac{V_s}{Z_x + Z_L} \right)^2 Z_L \tag{4}$$

where V_S is the output voltage of the piezoelectric beams, Z_S is the impedance of the beam, and Z_L is the impedance of the load. Equation (4) indicates that the maximum power can be obtained when the internal impedance of PZT and load impedance are the same. However, this complex impedance matching is very difficult to perform. If we want to tune the reactive part, specifically inductance, we have to design a very large inductor because the equivalent inductance of PZT would be too high to be matched [17,27]. Thus, we performed resistive impedance matching, i.e.,

$$P_{\max} = \left(\frac{V_S}{Z_S + Z_L} \right)^2 R_{L,opt} \tag{5}$$

where $R_{L,opt}$ is the optimized resistive load that yields the maximum power $P_{\max}$.

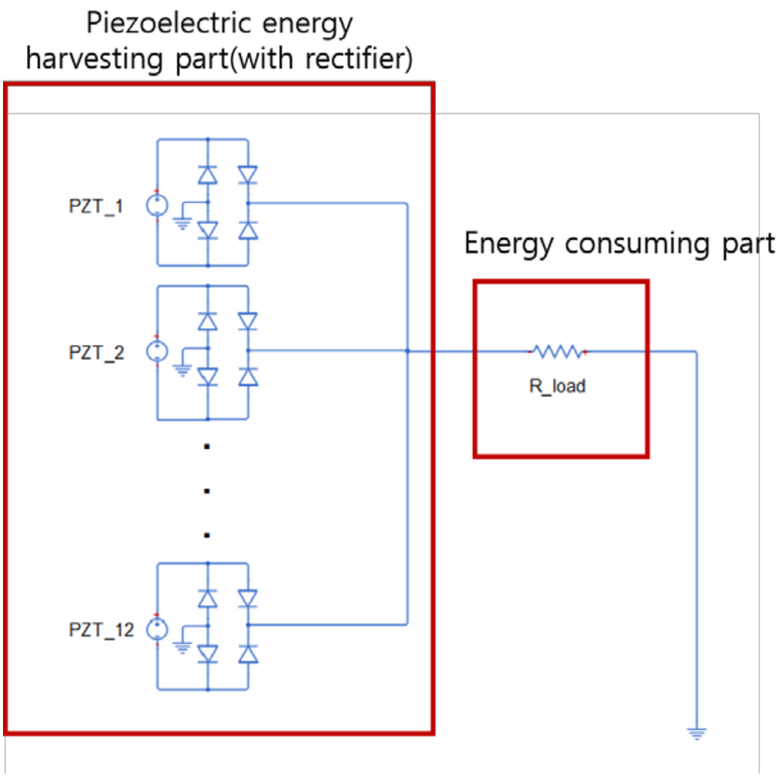

Fig. 4. Circuit diagram for the energy harvester.

3. Results and discussion

3.1 Frequency analysis

After surveying studies on road vibration, we collected the data in the chart shown in Fig. 5. The dots show the road vibrational frequencies at certain vehicle speeds, while the straight line indicates the linear regression of those values. A linear relationship clearly exists between the speed of the vehicles and the exerted road vibrational frequency. This relationship can be described as

$$f = 0.1867v - 1.2127 \tag{6}$$

where f is the exerted road vibrational frequency in hertz, and v is the speed of the vehicles in kilometers per hour. Considering both quantities are inversely proportional to time, this linear approximation is reasonable. Although this regression shows a slight error with an R-squared value of 0.8754, we conclude that the linear trend shown in equation (6) is sufficient for this study.

By assuming that the most common speed of vehicles on the highway ranges from 60–80 km/h, the road will vibrate with a frequency of approximately 10–14 Hz, as described by the shaded region in Fig. 5. Therefore, we have tuned the piezoelectric cantilever beam to have a natural frequency of 13 Hz.

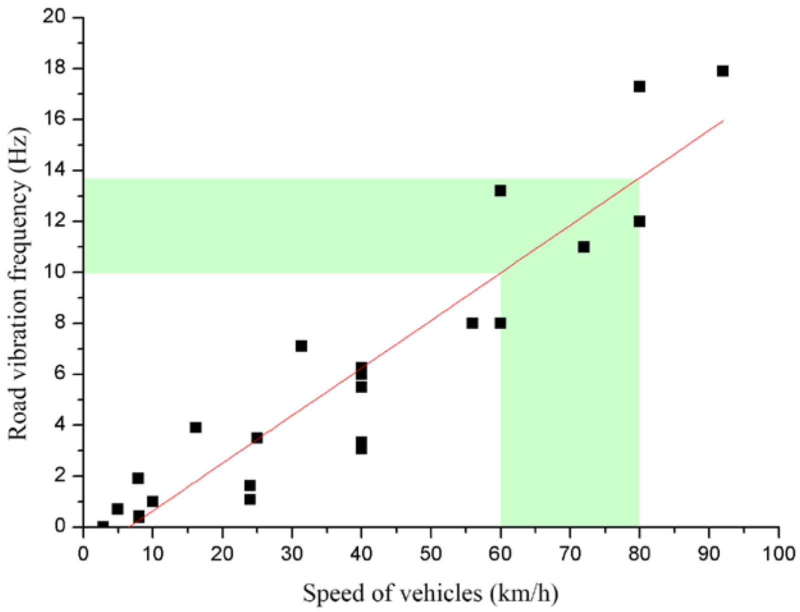

Fig. 5. Relationship between the speed of vehicles and the road vibration frequency.

3.2 Frequency matching for a piezoelectric cantilever beam

To tune a natural frequency of our piezoelectric cantilever beam to 13 Hz, we determined that we should use a tip mass of 53 g. From equations (1)–(3), we can derive an equation for the desired tip mass as

$$m_t = m_o\left(\frac{f_o^2}{f_t^2} - 1\right) \tag{7}$$

where f_t indicates the desired tuned frequency of the piezoelectric cantilever beam.

If the tip mass requires a large volume, each piezoelectric beam also requires more space. Thus, we need to minimize the dimension of the tip mass using high-density materials. Considering the prices per unit volume as well as the densities of materials, we manufactured our 4 × 1 × 1.5 cm^3 tip mass with copper, which has a density of 8.96 g/cm^3. This tip mass is attached at the free end of the beam, as shown in Fig. 6.

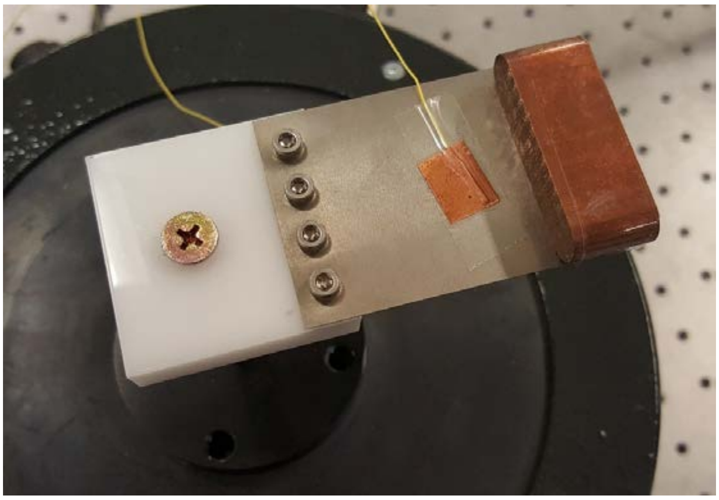

Fig. 6 Tip mass installed on the piezoelectric beam.

We conducted an additional experiment to determine the change in the output voltage caused by attaching the tip mass. We installed matched and unmatched piezoelectric beams on the vibration exciter, as described in Fig. 2, and measured the output voltages for different frequencies. The results are shown in Fig. 7, which clearly indicate that the resonance-causing natural frequency of the beam has been shifted from 73 Hz to 13 Hz. Note that the maximum voltage of the frequency-matched beam is much higher than that of the unmatched beam because the tip mass gives more inertial force to the beam, causing a greater beam deflection that generates higher output power.

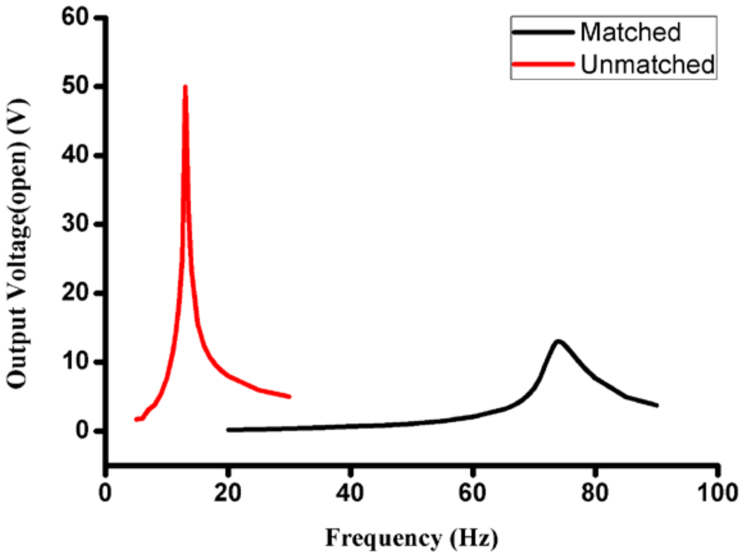

Fig. 7. Frequency matching for the piezoelectric cantilever beam.

3.3 Designing a road energy harvester

Fig. 8 shows the three-dimensional schematic for the $15 \times 15 \times 10$ cm^3 model of our piezoelectric energy harvester. The completed harvester has three layers of piezoelectric cantilever beams and four beams on each layer for a total of 12 beams. Therefore, for a full-scale energy harvester whose volume is $30 \times 30 \times 10$ cm^3, the total number of piezoelectric beams will be 48.

These cantilever beams are attached to the upper plate, which is connected to the lower plate with springs at the corners. The springs are constrained to a maximum compression of 1 mm to prevent a rough road surface and to minimize additional fuel usage.

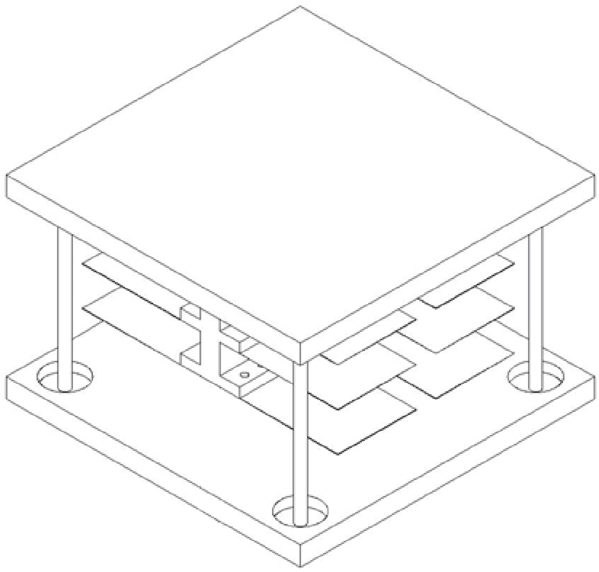

Fig. 8. Three-dimensional schematic for the 15 × 15 × 10 cm^3 piezoelectric energy harvester.

Using the completed road harvester, we conducted the UTM experiment. By exerting a haversine waveform with a frequency of 10 Hz and maximum displacement of 1 mm, we could realize an average open-circuit voltage output of 14.36 V from each piezoelectric cantilever beam.

3.4 Impedance matching

We connected a resistance decade box to our harvester as a resistive load and measured the output voltage by changing the connected resistance under the UTM. By exerting an input load with a frequency of 10 Hz and a maximum displacement of 1 mm on the harvester, we obtained the results shown in Fig. 9. The maximum power of 184 μW was observed at 70 kΩ, which could be interpreted as a matched resistive impedance, with an output voltage of 3.59 V. At this optimum point, the power density was determined to be 8.19 mW/m^2.

Because the power density was obtained from one-fourth of our harvesting module, the output power of the full-size harvesting module will be four times larger than the experimented value. Therefore, we can expect that the maximum power from the 30 × 30 × 10 cm^3 harvesting module will be 736 μW.

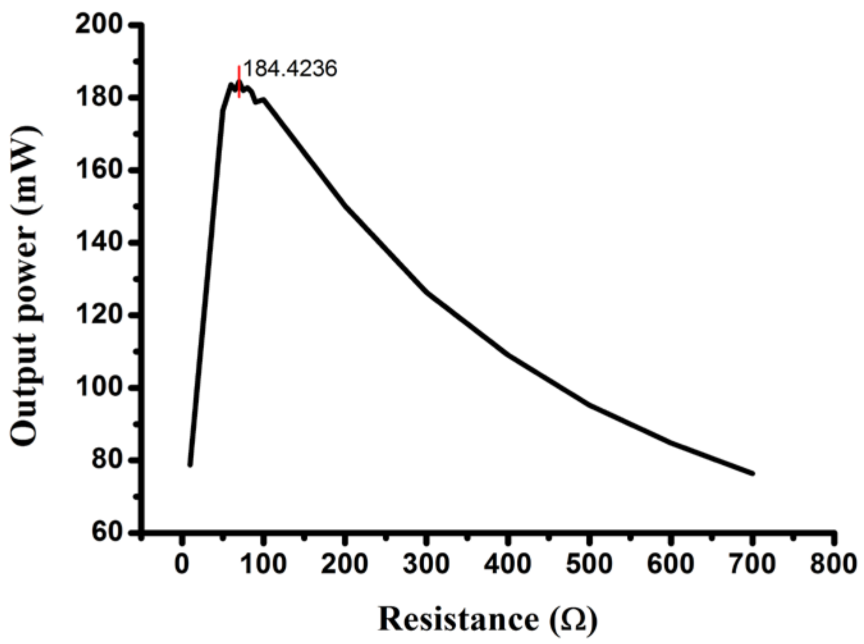

Fig. 9. Output powers from the quarter-sized harvester for different resistances.

4. Conclusions

We designed and manufactured an energy harvester that collects energy from road traffic using the piezoelectric effect. One 30 × 30 × 10 cm^3 harvesting module contains 48 piezoelectric cantilever beams, where the surface area of a beam is 40 × 60 mm^2. The harvesters are designed for implementation under 5-cm-thick asphalt. The asphalt and the harvester will have a total height of 15 cm, which is the conventional pavement thickness for Korean highways.

One 15 × 15 × 10 cm^3 energy harvester, which comprises one-fourth of the harvesting module, can generate an output power of 184 μW with a power density is 8.19 mW/m^2. Thus, the output power of a full-scale harvesting module is expected to be 736 μW. If there are 600 vehicles passing the harvester per hour, the total output energy density for an hour will be 4.91 Wh/m^2. If we could install harvesters along a 1-km road along two straight lines, we could generate a total output energy of 2.95 kWh per hour assuming a constant rate of 600 vehicles on the road per hour, considering a vehicle has wheels on both the left and right sides.

Though we have adjusted the expected environmental conditions into quantifiable values for this lab-scale study, demonstrations under actual road conditions are required for further verification of these harvesters. Moreover, studies designed to increase the output power of the harvester are imperative. Continued studies on energy harvesters will enable a new clean energy era of harvesting abandoned energy from road traffic.

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Highlights

- An energy harvester designed and optimized for a busy roadway
- Harvester designed to use piezoelectric cantilever beams
- The natural frequency of the beams tuned by attaching a tip mass
- Impedance matching conducted to maximize the output power
- An output power with a power density of 8.19 mW/m^2 realized