Development of vibration energy harvester with 2D mechanical metamaterial structure

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Abstract. In this paper, we propose a vibration energy harvester with high power generation efficiency in low-frequency wide band. The proposed device is a bimorph type composed of two piezoelectric layers and a middle elastic layer having a flexible mechanical metamaterial structure. By controlling the flexibility of the elastic layer by the microstructure, the strain of the piezoelectric layer and the power generation amount are increased. As a result, the proposed device achieves high power generation of 47.4 µW in the low-frequency band of 21.1 Hz. This power is 1.6 times larger than that of the conventional flat plate and satisfies the minimum electric power amount required as a sensor node for WANs.

1. Introduction

Wireless sensor networks (WSNs) are composed of huge amounts of sensor nodes, and energy harvester is expected to be used for power supply of the sensors [1]. In particular, many piezoelectric cantilever type energy harvesters have been proposed due to high power generation efficiency [2]. Main vibration source such as human motion and household appliance has the low-frequency band below 30 Hz [3][4]. In the vibration power generation, the power generation amount is closely related to the resonance frequency. So, it is necessary to reduce the resonance frequency in power generation under the low-frequency wide band. However, since the resonant frequency increases as the device become smaller, it is difficult to realize high power generation efficiency in the low-frequency wide band. Most of the reported piezoelectric energy harvester usually corresponds to a high-frequency band over 100 Hz [5]. In this research, we focus on the mechanical metamaterial structure [6] to control mechanical properties exceeding the material own properties. We propose a bimorph type harvester composed of two piezoelectric layers and a middle elastic layer having a flexible mechanical metamaterial structure for vibration energy harvesting from human motion and household appliance.

2. Design of mechanical metamaterial energy harvester

2.1. Principle of mechanical metamaterial energy harvester

The proposed harvester is a bimorph type as shown in figure 1, with the neutral axis at the center of the device. Since strain and output voltage generated in the piezoelectric layer are proportional to the distance from the neutral axis, increasing the distance between the piezoelectric layer and the neutral
axis can increase the power generation amount. The proposed harvester has a flexible 2D metamaterial structure in the elastic layer and maintains low rigidity even in a thick elastic layer. Therefore, since the device can obtain large strain in the piezoelectric film while maintaining high flexibility, high power generation amount and low resonance frequency are simultaneously realized.

**Figure 1.** Schematic of the metamaterial energy harvester. The piezoelectric layer is a flexible organic material PVDF and the elastic layers are made of polymer material SU-8 which is a photoresist capable of thick film patterning. The device is fabricated by a simple process only by photolithography.

### 2.2. FEM analysis

Prior to device fabrication, we estimated the resonant frequency of the metamaterial harvester using modal analysis by FEM (Finite Element Method). Table 1 shows the resonant frequency obtained by using by FEM analysis software COMSOL Multiphysics 5.2a, and mode shape is shown in figure 2. Compared with the flat plate type, the metamaterial type has a resonant frequency of 80% and the flexural rigidity is reduced to 62%. From the results, it is found that the metamaterial elastic layer improves the flexibility under same device size.

**Table 1.** Results of FEM analysis. Each device has same thickness of the elastic layer and same device volume.

|                  | Metamaterial | Flat plate |
|------------------|--------------|------------|
| Resonant frequency 1<sup>st</sup> [Hz] | 21.1         | 26.2       |
| Resonant frequency 2<sup>nd</sup> [Hz]  | 94.2         | 122.8      |
| Resonant frequency 3<sup>rd</sup> [Hz]  | 253.8        | 314.4      |
| Flexural rigidity [Pa·m<sup>4</sup>] | 3.42×10<sup>4</sup> | 5.54×10<sup>5</sup> |

**Figure 2.** Mode shape of the metamaterial harvester at first resonant frequency. Three mode shapes of the proposed metamaterial harvester from first to third resonant frequency are as same as these of the conventional cantilever beam with the flat plate type elastic layer.
3. Experiments

3.1. Device fabrication

Figure 3 shows a photograph of the fabricated device and a SEM image of the elastic layer. As a piezoelectric layer of the device, a PVDF film (KF Piezo, Kureha Corp.) was used. The film has a film thickness of 40 μm and Al electrodes are deposited on both sides.

The fabrication process is divided into three steps by using two PVDF films. In the first step, a SU-8 elastic layer is made by photolithography on one PVDF film. Here, an elastic layer having a mechanical metamaterial structure is prepared. In the next step, the other PVDF film is separately cut out and a SU-8 thin film with a film thickness of 2 μm is formed on the film. In the final step, Using the formed SU-8 thin film as an adhesive layer, a PVDF film adheres to the metamaterial elastic layer made in the first step.

![Figure 3](image)

**Figure 3.** (a) Photograph of the fabricated metamaterial harvester, (b) SEM image of metamaterial elastic layer. The line width of the metamaterial structure is 100 μm and the aspect ratio is 2 with respect to the film thickness. The flexibility can be improved by optimizing the 2D structure by reducing the line width.

3.2. Vibration test

We evaluated the power generation and resonant frequency of the harvester by the vibration test. The experimental setup is shown in figure 4. To control acceleration under each vibration frequency, the excitation force was adjusted by an acceleration sensor fixed on the vibration table. The output voltage of the harvester was measured by an oscilloscope with an internal resistance of 10 MΩ. The power generation amount was calculated by measuring the power on one side. In the calculation, it is assumed that the same power generation amount generated because both piezoelectric films were at equal distances from the neutral axis.

The experimental frequency response curve of the fabricated device is shown in figure 5, and the power generation amount at resonant condition is shown in table 2. As a result, we achieved a high power generation amount of 47.4 μW at low-frequency of 21.1 Hz, which is 1.59 times higher than that of the flat plate type. Since the occupied volumes of the devices are equal in the two devices, the increase in the power generation amount directly corresponds to the increase in the energy density. The electric power generation by the piezoelectric cantilever is proportional to the square of the tip displacement. From table 2, the square of the tip displacement ratio of the metamaterial and the flat plate types is 1.56. This calculated value was in good agreement with 1.59 which is the ratio of actual power generation amount.

In addition, the response frequency capable of generating electric power is also widened. The bandwidth in the metamaterial harvester on the power generation amount of over 10 μW is 3 Hz, which is 1.5 times wider than one of the flat plate type harvester.
Table 2. Power generation amount at resonant condition. Oscillating condition is same as figure 5. The energy density is a value of dividing the power generation amount by the device volume.

| Resonant frequency [Hz] | Output voltage [V] | Total electric power [µW] | Energy density [µW/cm$^3$] | Tip displacement [mm] |
|--------------------------|---------------------|---------------------------|---------------------------|-----------------------|
| Meta material            | 21.1                | 15.4                      | 47.4                      | 55.4                  | 7.5                   |
| Flat plate               | 24.0                | 11.7                      | 29.8                      | 34.8                  | 6                     |

4. Conclusion
In this study, we propose the piezoelectric vibration energy harvester for the low-frequency band. In the proposed harvester, the lower frequency and the higher power generation than the conventional flat plate type harvester are achieved by the metamaterial structure of the elastic layer. In the near future, we plan to optimize the device shape such as structure and film thickness for various applications.

Acknowledgement
This research was partially supported by JSPS Science Research Grant JP17H03196, JST PRESTO Grant Number JPMJPR15R3, and MEXT Nanotechnology Platform Project (The University of Tokyo Microfabrication Platform).

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