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Design of Composite-Structured Acoustic Metasurface toward Wideband Energy Harvesting
広帯域環境発電に向けた構造複合化音響メタ表面の設計

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1. Introduction

Energy harvesting is one of the important technologies for the low-carbon society because it enables us to use electric devices without any power sources. Such a technology is also a key to implementations of IoT and wearable devices into the society. Our aim is to design and fabricate an efficient energy harvester with passive structures in scope of practical applications. Acoustic energy is one of the environmentally disposed energy sources, and its harvester is a promising candidate for our aim. It has been, however, difficult to develop such a harvester by using commercially available technologies, because of low conversion efficiency to electricity. We here focus on the acoustic metasurface [1], a two-dimensional structure composed of small and thin resonators. At the resonant frequency, metasurface resonators play a role as an efficient sound absorber effective to convert pressure into electric power by using piezoelectric materials.

In this study, we aimed to develop such a metasurface energy harvester on the basis of a hybridized metasurface structure, called “Decorated Membrane Resonator (DMR) [2,3].” Here we propose a novel DMR structure toward efficient sound absorptions for a wider frequency range.

2. Simulation method

A set of numerical simulations regarding the metasurface model was performed by using a commercially available 3D Finite Element Method (FEM) software, COMSOL Multiphysics®[4] developed by COMSOL AB. This tool can deal with several physics (constituent equations) at the same time, e.g., fluidic equation for air pressure and solid mechanics along with materials dispersions and/or interfacial losses. This feature was essential for our study where we needed to evaluate energy conversions quantitatively.

3. Metasurface model

Figure 1 shows schematics of two types of the unit cell of our metasurface models, consisting of aluminum base, aluminum platelet, air cavity, and PolyProylene (PP) membrane. The previous DMR model depicted in Fig. 1(a) has shown nearly perfect absorption at the resonant frequency with very narrow dispersion [5]. To realize broadband operation, we here propose a new model, illustrated in Fig. 1(b), which has multiple resonant properties in one unit cell. The purpose of designing this composite-type structure is to generate two or more absorption peaks near the DMR’s original peak. Such a multiplication of absorption peak by introducing composite resonator structure is our primary strategy in the present study.

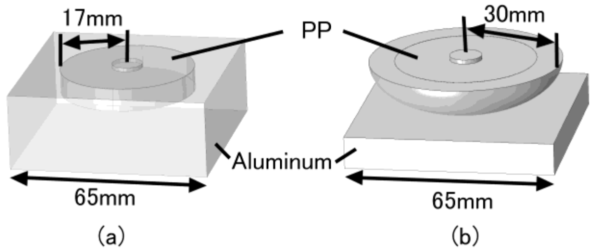

Fig. 1 Two types of DMR models. (a) The previous DMR model and (b) a new model with a bowl-like resonator.

4. Results

To evaluate the absorption characteristics of the DMRs, we calculated the absorption coefficient based on the transfer-function method [6]. Using the FEM calculations for the DMR structure illustrated in Fig 1(b), we found resonant peaks at 1455, 1840, 2820, and 3210 Hz in the range of 1000-5000 Hz. In the case of the previous DMR structure in Fig. 1(a), the resonant peak is located only at 2560 Hz. Through the simulation, we thus confirmed that four resonant modes appear in the new DMR structure, demonstrating an efficient widening of resonant band toward broadband operation.

To better understand the underlying mechanism of the multiplication of the resonances, we show the displacement and sound intensity with sound pressure distribution at each peak in Fig. 2. The sound intensity indicates distribution of magnitude and direction of the acoustic power flow.

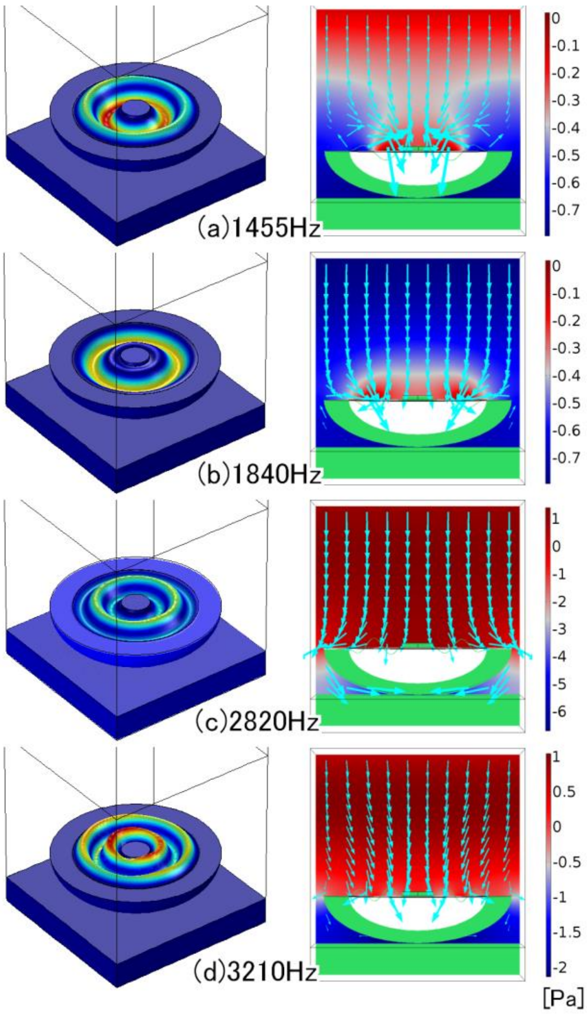

Fig. 2 Displacement (left) and sound intensity (arrows in right) and sound-pressure distributions (color in right) at each resonance frequency. Color bar represents sound pressure in Pa.

Figures 2(a) and **2(b)** indicate that vibrations of the PP membrane are dominant for absorption of the acoustic energy On the other hand, **Figure 2(c)** shows that the bowl and narrow space between the bowl and the substrate play main roles of absorption like in the Helmholtz resonator [7]. At the forth frequency in **Fig. 2(d)**, the absorption occurs at both the membrane and the bowl.

Figure 3 depicts the absorption spectra calculated by the FEM for the present DMR model with a membrane made from PolyVinylidene DiFluoride (PVDF), a piezoelectric polymer. The (maximum) piezoelectric voltage generated in the membrane by sound vibrations is also depicted in Fig. 3. Here we set the ground (V=0) at the platelet, and the voltage is measured at the surface of PVDF.

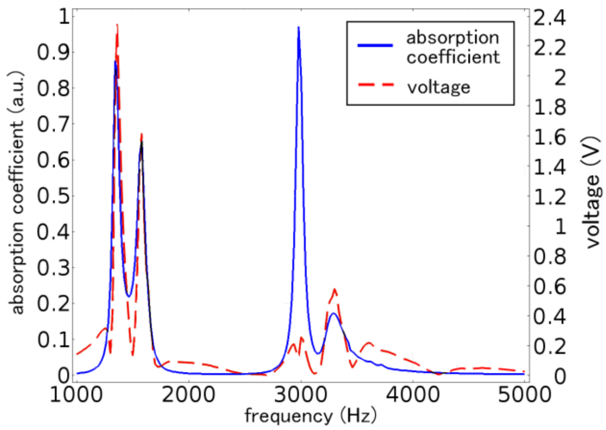

Fig. 3 Frequency spectra of absorption coefficient (blue line) and piezoelectric voltage (red line).

The figure indicates that an efficient absorption is obtained at each resonant peak of the DMR structure. The absorption peaks at 1360, 1695, and 2990 Hz exceed 60% and were expected to be effective for practical acoustic energy harvesting. However, at the third peak, the piezoelectric voltage is small compared with the other peaks. As shown in Fig. 2(c), the mode profile and the sound intensity at the third peak involve mainly horizontal component on the membrane. Such a vibration cannot make effective strains of PVDF membrane for piezoelectric polarization. Further designs of resonant mode and/or configuration of piezoelectric materials in the DMR structure are thus necessary for realizing an efficient broadband harvester.

References

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