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Design of phononic metamaterials for the control of gigahertz plate acoustic waves

GHz 帯板波を制御するフォノニックメタマテリアルの設計

Kentaro Fujita[‡], Motonobu Tomoda, Keisuke Inagaki, Oliver B. Wright and Osamu Matsuda (Faculty of Engineering, Hokkaido University)
藤田健太郎[‡]，友田基信，稲垣敬介，Wright Oliver B.，松田理（北大 工）

1. Introduction

For many ultrasonic/electronic devices, such as filters, controlling elastic waves in structures is an important issue. Various geometries were proposed to this end, e.g. controlling propagation direction or wave decay. Phononic (or acoustic/elastic) metamaterials are prime examples[1,2]. These followed the advent of electromagnetic metamaterials, as proposed by Pendry *et al* [3]. Their metamaterial consists of a periodic sub-wavelength scale structure that exhibits negative effective permittivity and magnetic permeability near a resonant frequency. Phononic metamaterials are analogous, and can exhibit negative effective mass density and elastic modulus. Using such negative effective parameters, various interesting non-intuitive properties have been demonstrated in acoustics, such as strong damping[4], negative refraction[5], or superlens effects[6].

In spite of the intense interest, few studies of phononic metamaterials at GHz frequencies have been reported. Such development would lead to many applications in ultrasonic-electronics. This scarcity in studies is caused by difficulties in fabricating complicated microscopic structures and their GHz measurement. We have addressed the latter problem by developing a technique for time-risolved two-dimensional imaging of surface acoustic wave fields up to the GHz range using ultrashort optical pulses[7-9]. This technique is effective in the study of GHz phononic metamaterials.

In this paper, we design a simple phononic metamaterial to control plate acoustic waves in the GHz range by means of numerical simulations. Sub-micron scale periodic strucutures are designed in a silicon slab. Thanks to the resonance properties of the unit cell, the proposed metamaterial shows negative refractive index over a given frequency range.

2. Structure

We design a sub-wavelength scale structure in the form of a plate of thickness 2.5 μm that acts as a uniform medium for incident waves of wavelength large compared to the structure repeat distance. A unit cell of the phononic metamaterial and its reciprocal lattice are shown in Fig. 1. The unit cells are aligned in a triangular lattice, and each consists of an outer hexagon frame, six bent ribs, and a center hexagon piece. The center piece and the ribs work as masses and springs, respectively. The slots which separate the ribs are formed across the thickness of the plate. The lattice repeat distance is 7 μm. Other parameters, indicated in Fig. 1 (a), are varied to find the acoustic response for different geometries. The center piece and the frame vibrate transversely and approximately in antiphase above the resonant frequency. This vibration typically causes negative effective mass density[2]. The center piece can also vibrate rotationally at some frequencies: the center piece pushes or pulls the frame from the inside of the frame. This type of vibration typically causes negative effective bulk modulus[2]. These negative parameters can be exploited for use in damping or for negative refraction.

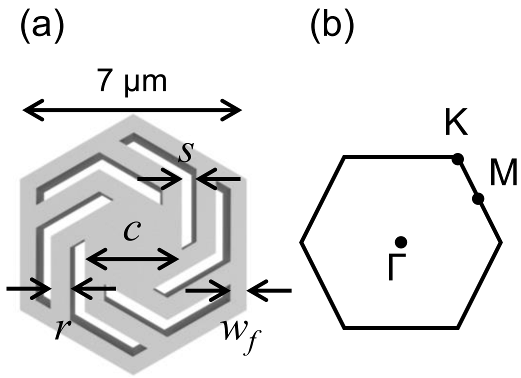

Fig. 1 (a) Top view of the phononic metamaterial. The parameters c, r, w_f and s are the width of the center piece, rib width, frame width and slot width, respectively. (b) Reciprocal lattice. Three representative points are shown.

kfujita@eng.hokudai.ac.jp

3. Simulations

Simulations are conducted using the finite element method. Figure 2 indicates the dispersion relation obtained along ΓK direction in the Brillouin zone for c = 3.0 μm, r = 0.45 μm, w_f = 0.50 μm, s = 0.53 μm (see Fig. 1(a)). The red curve indicates compressional-like modes, i.e. 0th order symmetric Lamb-like modes. The blue curve indicates shear horizontal-like modes. The green curve indicates flexural-like modes, i.e. 0th order antisymmetric Lamb-like modes (We omit "-like" in the following for simplicity). The compressional modes and the shear horizontal modes are drawn as open circles in Fig. 2: they cannot propagate in the frequency range between 0.13 and 0.14 GHz. This tiny bandgap arises from a vibrational resonance of the unit cells. The purple branch exhibits negative refraction since it possesses a negative slope. For this branch, the compressional and shear horizontal modes are coupled. Antisymmetric modes such as the flexural modes do not couple with the symmetric modes such as the compressional or shear horizontal modes because the structure is symmetric in the depth direction. Figure 3 shows a simulation at 180 MHz for negative refraction with a metamaterial prism formed in a silicon slab. The compressional waves enter the prism from the left, and waves exiting the prism show both negative and positive refraction at the right-hand boundary between the prism and the surrounding slab.

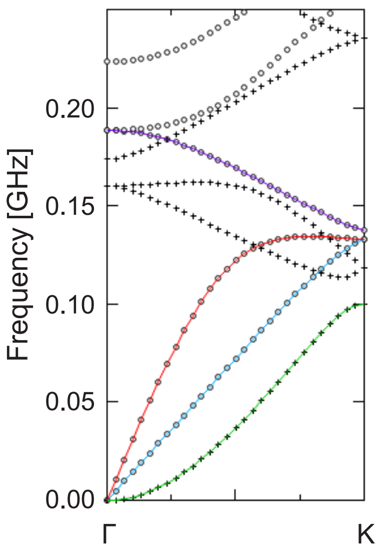

Fig. 2 Simulated dispersion relations along the ΓK direction. The red, blue and green curves indicate compressional, shear horizontal, and flexural modes, respectively. The purple branch is related to negative refraction. The plus symbols (+) represent modes with dominant out-of-plane displacement. The open circles (o) represent modes with dominant in-plane displacement.

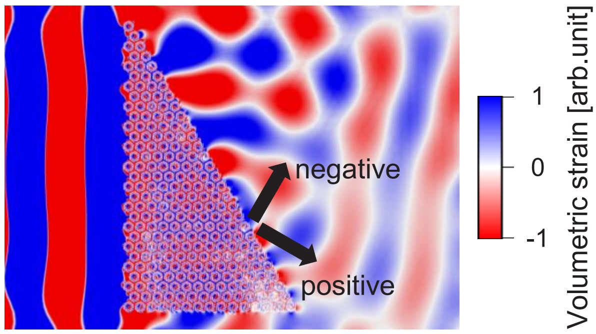

Fig. 3 A simulation of negative refraction at 180 MHz in a prism of the phononic metamaterial. The color scale shows the volumetric strain. The black arrows denote the wave propagation directions for negative and positive refraction.

4. Conclusion

By means of simulations, we have designed a phononic metamaterial that can control the propagation of GHz plate acoustic waves and that can exhibit negative refraction. This phenomenon originates from a resonance in the unit cell. The resonance frequency can be adjusted by parameters such as the mass, rib width and frame width. The results should be tested in experiment by actual fabrication and measurement of the wave fields, and may lead to new functional devices.

References

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