3Pa1-4

Ultrafast imaging and simulation of cavity modes in a phononic crystal

Paul H. Otsuka[1†], Ryota Chinbe[1], Motonobu Tomoda[1], Osamu Matsuda[1], Yukihiro Tanaka[1], Dieter M. Profunser[1], Sihan Kim[2], Heonsu Jeon[2], Istvan A.Veres[3], Alex A. Maznev[4] and Oliver B. Wright[1] ([1]Hokkaido Univ.; [2]Seoul National Univ.; [3]Recendt, Research Center for Nondestructive Testing, Austria, [4]Department of Mechanical Engineering, Massachusetts Inst. Tech.)

1. Introduction

To control waves in solids one can introduce periodic variations in the elastic properties of the medium to form a phononic crystal (PC) [1]. The periodicity results in a modification of the acoustic dispersion relation, producing effects such as negative dispersion and band gaps, in a similar way to those observed for electronic and photonic materials. Such effects have been used to produce, for example, waveguiding and confinement of acoustic waves. The nature of the periodicity influences the acoustic band structure. In particular, inclusions arranged in a honeycomb array have been shown to exhibit wide complete (omnidirectional) phononic band gaps (CPBGs) [2], [3].

Imaging is a natural way to study wave propagation in complicated geometries, and this has previously been successfully employed to reveal effects such as phonon collimation, waveguiding and Bloch harmonics [3–5].

Here we present results of time-resolved imaging of optically-generated acoustic waves in a PC slab structure based on a honeycomb lattice. Confinement in a cavity is investigated by introducing a defect into the honeycomb array. In addition, we compare our experimental results with finite-element numerical simulations.

2. Experiment

Our sample consists of a microscopic honeycomb lattice of circular holes in a (111) silicon-on-insulator wafer produced by a dry etching process. The insulator (silicon oxide) was removed by etching to leave free standing crystalline Si slabs of thickness 6.5 μm. The spacing of the holes is 6.6 μm, their diameter is 5.8 μm, and their depth of penetration is all the way through the slab.

Based on frequency-domain numerical simulations (as described later), we expect the first complete band gap for this structure to lie between 230 and 320 MHz.

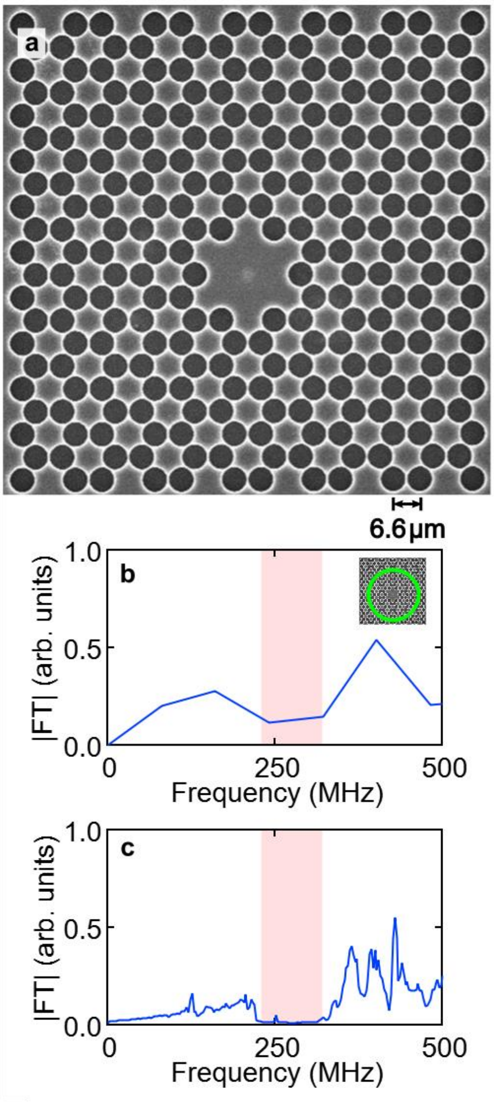

Fig. 1 (a) SEM image of the sample surface. (b) Frequency spectrum outside the cavity measured by experiment in the region shown by the green circle in the inset. The pink shading indicates the theoretically predicted band gap. (c) Frequency spectrum outside the cavity obtained by simulation in the same region shown in (b).

†paul@eng.hokudai.ac.jp

A cavity is formed by the absence of 6 holes near the centre of the sample. Figure 1a shows an SEM image of the sample surface.

We use ultrashort optical pulses from a mode-locked Ti:sapphire laser of repetition rate 80.4 MHz as a pump beam to excite a broadband acoustic field inside the cavity [6]. Surface displacements are detected via an interferometer consisting of a frequency-doubled probe beam derived from the same laser as the pump. The time delay between the arrival of the pump and probe pulses can be controlled to obtain time-resolved signals. Spatial imaging is achieved by scanning the probe spot over the surface by use of an objective lens. We thereby obtain a real-time animation of the acoustic propagation over the sample surface through a map of the out-of-plane surface particle velocity.

We use spatiotemporal Fourier analysis to extract constant-frequency images in real- and **k**-space. Figure 1b shows a plot of the experimental Fourier amplitude at each frequency averaged over a region (indicated by the green circle in the inset) outside the central cavity. The pink shading indicates the position of the simulated band gap between 230 and 320 MHz obtained from frequency-domain COMSOL Multiphysics simulations. The plot shows a lower amplitude in this region, as expected. However, this result is limited by the relatively low experimental frequency resolution. (~80 MHz) A numerical simulation was therefore performed to investigate this further.

3. Simulation

To improve on the frequency resolution, we performed a finite-element time-domain numerical simulation using PZFlex (Weidlinger Associates Inc.). The geometry and pulsed excitation source in the simulation are chosen to match the experimental frequency spectrum, except that a single pulse is used for excitation rather than the periodic pulse train of the experiment. The simulation yields the instantaneous velocity at each node at each time step, from which animations of duration up to 125 ns—equivalent to 10 cycles of the experimental data—are obtained. The model consists of a (111)-cut crystalline silicon slab with a surface extending over a 200 μm×200 μm area and with a thickness of 6.5 μm (as in experiment). Absorbing boundary conditions are applied at the side surfaces, so the model approximately represents an infinite free-standing slab. The temporal discretization of the model (6 ps) is chosen for numerical stability, and is derived from the smallest element dimension and the maximum wave velocity. Figure 1c shows the simulation result corresponding to the experimental result in Fig. 1b. There is a clear and obvious dip in amplitude corresponding closely to the shaded region, confirming the presence of a CPBG. We will also discuss numerical methods for extracting the Q factor of the cavity, in particular at 241 and 402 MHz, inside and outside the bandgap, respectively. The latter value of Q was found to be much smaller than that of the former.

4. Conclusion

In conclusion we have investigated the propagation of acoustic waves in a honeycomb phononic crystal structure using an ultrafast optical method. Two-dimensional maps of the time-resolved acoustic field were obtained both experimentally and by simulation, and the results compared. We identified a large phononic crystal band gap and how it confines energy inside the cavity.

Acknowledgment

This work has been supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

References

1. M. Sigalas and E. N. Economou: Solid State Comm. **86** (1993) 141.
2. S. Mohammadi, A. A. Eftekhar, A. Khelif, W. D. Hunt and A. Adibi: Appl. Phys. Lett. **92** (2008) 221905.
3. F. L. Hsiao, A. Khelif, H. Moubchir, C. C. Chen and V. Laude: Phys. Rev. E **76** (2007) 056601.
4. D. M. Profunser, O. B. Wright, and O. Matsuda: Phys. Rev. Lett. **97** (2006) 055502.
5. A. Khelif, A. Choujaa, S. Benchabane, B. Djafari-Rouhani and V. Laude: Appl. Phys. Lett. **84** (2004) 4400.
6. T. Tachizaki, T. Muroya, O. Matsuda, Y. Sugawara, D. H. Hurley, and O. B. Wright: Rev. Sci. Inst. **77** (2006) 043713.