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# First demonstration of *“electrically controlled phonon propagation”*

~Dynamic phononic crystal realized with MEMS technology~

Nippon Telegraph and Telephone Corp. (NTT; Head Office: Chiyoda-ku, Tokyo; President: Hiroo Unoura) has developed a phononic crystal (PnC) [*1] using micromachining technologies and demonstrated electrical control of traveling mechanical vibrations, i.e. phonons.
The ability to dynamically manipulate phonons enables MEMS[*2] resonators to be combined to not only build a new class of sensors but also to create highly functional signal processors such as amplifiers, frequency convertors and routers. The dynamic control of phonons could also be extended to realize thermo-crystals in which thermal conductivity could be tuned simply with the activation of an electrical voltage.
This result will be published in “Nature Nanotechnology” on 15th June 2014.

## 1. Introduction

Micron-sized electromechanical systems, called MEMS, have attracted enormous attention for their academic and practical applications because they can precisely control the tiny mechanical vibrations. NTT Basic Research Laboratories (NTT-BRL) have pursued the study of MEMS resonators and developed novel functional mechanical devices, for example, an ultrasonic laser (SASER) emitting highly purified ultrasonic vibrations, precise sensors that can detect extremely small mass and charge, signal processors and memories based on mechanical vibrations.
On the other hand, phononic crystals (PnC), which are an elastic analogue of photonic crystals[*3], have been developed to manipulate phonons, i.e. mechanical vibrations of an elastic structure, and they have led to the development of novel devices for sound, vibration and heat. However, most PnCs reported so far have limited active control of phonons with the application of external electrical stimulus that limits their applications. Here we have pioneered the first dynamic PnC which uses an electrically-active MEMS resonator as a unit of the periodic structure and it enables phonons to be dynamically manipulated.

## 2. Achievement

NTT-BRL has fabricated a PnC waveguide (WG) that consists of a one-dimensional array of 100 MEMS resonators, each of which has a circular membrane vibrating plate (Fig. 1).
Moreover, embedding a control MEMS resonator with an electrode into the center of the WG (Fig. 2) enables phonons to be dynamically switched (Fig. 3) or transferred to the control MEMS resonator (Fig. 4) by simply applying electric voltage to its electrode.
This result is first demonstration of active control of phonons using external stimulation in MEMS-based PnCs.

### Experiments

<1> Applying an alternating voltage at 5.5 MHz to the right edge of the WG excites the mechanical vibration due to the piezoelectric effect[*4]. The spatial measurement with an optical interferometer reveals that the vibration is confined and guided by the WG (Fig. 5 (a)).

<2> The propagation speeds at various excitation frequencies are investigated, which reveals the slow phonon effect in the vicinity of the phonon bandgap[*5] (Fig. 5 (b)).

<3> The local excitation of the control MEMS resonator embedded in the WG enables the traveling mechanical vibration to be suppressed (Fig. 3).

<4> The control excitation of the control MEMS resonator embedded in the WG enables the mechanical vibration in the WG to be transferred to the control MEMS resonator (Fig. 4).

## 3. Technical features

### (1) Fabrication of phononic crystal waveguides using a MEMS resonator array (Figs. 1, 2)

The PnC WG enables phonons to be spatially confined and guided where the periodic structure also gives rise to a phonon bandgap. However, the dynamic control of the phonons with PnCs has not been demonstrated yet. In order to overcome this drawback, we have developed a novel PnC architecture which uses an electrically-tunable MEMS resonator as a unit for the periodic structure that enables active control of the phonon propagation to be demonstrated by applying electrical voltage.

### (2) Parametric excitation to control phonons (Figs. 3, 4)

For the electrical control of mechanical vibrations, parametric excitation[*6] based on the device's nonlinearity has been employed in which the key to phonon manipulation, namely switching and transferring, is achieved by adjusting the strength and frequency of the excitation voltage applied to the control MEMS resonator.

## 4. Future plan

The PnC structure reported in this study could be used to realize higher sensitivity than conventional MEMS-based sensors by combining MEMS resonators. This could also enable highly functional signal processors to be realized which could not only amplify information but also spectrally and spatially route it. The key ingredient to achieving this objective would be higher frequency operation giving a larger operational bandwidth. These results also lay the groundwork for a thermo-crystal to be developed in which heat flow (i.e. phonons) could be controlled by converting it from a thermal conductor to an insulator with application of an electrical stimulus.

### Publication

D. Hatanaka, I. Mahboob, K. Onomitsu and H. Yamaguchi
"Phonon waveguides for electromechanical circuits"
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http://www.nature.com/nnano/journal/vaop/ncurrent/full/nnano.2014.107.html

## Glossary

*1 Phononic crystal (PnC)

The PnC is an artificial structure consisting of different elastic media which are periodically arranged on the order of wavelength of sound, vibration and heat. To control MHz mechanical vibrations, the PnC is fabricated by creating periodic air-holes in the elastic structure using conventional micromachining technique.

*2 MEMS

MEMS stands for microelectromechanical system. It is composed of mechanical structures scaled in the micrometer range and is fabricated by semiconductor microfabrication technique. Recently, nano-sized mechanical devices, called nanoelectromechanical systems (NEMS), have been also developed.

*3 Photonic crystal

The photonic crystal is an artificial structure consisting of different refractive media which are periodically arranged on the order of wavelength of light, usually fabricated by semiconductor lithography techniques. Since the photonic crystal behaves an optical insulator, extraordinarily strong light confinement becomes possible.

*4 Piezoelectric effect

The piezoelectric effect is a phenomenon in which the application of an electric voltage to certain solid-state materials gives rise to a mechanical expansion and contraction which enables mechanical vibrations to be activated.

*5 Phonon bandgap

The phonon bandgap occurs when the half wavelength of phonons matches the lattice constant of the periodic structure, which results from Bragg reflection at the interface of the different elastic structures and in turn forms standing waves, thus resulting in the suppression of phonon propagation.

*6 Parametric excitation

By applying mechanical tension, system parameters of a resonator can be modified. In this instance, the PnC spring constant is modulated which results in its resonance frequency shifting, giving rise to new physical phenomenon.

### Attachment·Reference

- Fig. 1: Phononic crystal waveguide
- Fig. 2: Control MEMS resonator embedded in the waveguide
- Fig. 3: Switching mechanical vibrations
- Fig. 4: Transferring mechanical vibrations
- Fig. 5: Spatial propagation of mechanical vibrations and slow phonon effect

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