3J2-4

Time-resolved imaging of GHz surface acoustic waves in phononic crystals at arbitrary frequencies

2 次元フォノニック結晶における GHz 帯任意周波数表面弾性波の時間分解イメージング

Hiroki Muramoto[1‡], Hiroaki Koga[1], Hiroki Nishita[1], Kentaro Fujita[1], Motonobu Tomoda[1], Osamu Matsuda[1] ([1]Hokkaido Univ.)
村本裕貴 [1‡]，古賀裕章 [1]，西田浩紀 [1]，藤田健太郎 [1]，友田基信 [1]，松田理 [1] ([1]北海道大学 大学院 工)

1. Introduction

Phononic crystals are periodic structures containing materials with different elastic properties and are used to control the propagation of acoustic waves in certain frequency range. The structure has a lattice constant comparable to the wavelength of the acoustic waves in question. The periodic structure of the phononic crystal may cause a band gap (phononic band gap) in the dispersion relation of the acoustic waves. [1] Moreover, by introducing defects into a perfect phononic crystal having a band gap, it is possible to control acoustic wave propagation within the band gap and realize various functional devices.

Two-dimensional phononic crystals support surface acoustic waves, i.e. surface modes localized near the surface of the material. Surface acoustic wave imaging can be achieved at GHz frequencies by combining the optical pump-probe method with interferometric detection. [2,3]

This measurement method has, however, a fundamental restriction on the accessible frequencies of the acoustic waves: due to the experimental requirement, a periodic optical pulse train is typically used to generate and detect acoustic waves, and thus the accessible frequencies of the acoustic waves are limited to the integer multiples of the repetition frequency of the light pulse train. Because of this limitation, the adaptability of the method is not enough to the phononic crystals having complicated dispersion relations.

For this problem, an arbitrary frequency measurement method was developed to avoid the principle constraint. [4,5] In this method, the intensity of the pump pulse train at the repetition frequency f is modulated at the frequency F. With this modulated pump pulse train, we can generate the acoustic waves at the side-band frequencies $nf \pm F$. Appropriate signal detection and processing methods allow one to deconvolute these side-band components. By varying the modulation frequency in the range $0<F<f/2$, one may investigate the acoustic waves at arbitrary frequencies.

2. Sample

We investigate the square-lattice Si phononic crystal shown in **Fig. 1**, made with a Focused Ion Beam (FIB) processing method. A square lattice of holes of radius 1.4 μm over a 108 μm square region is formed in a (100) Si substrate with lattice spacing 5.7 μm, the holes of depth 6 being aligned along the crystal symmetry directions.

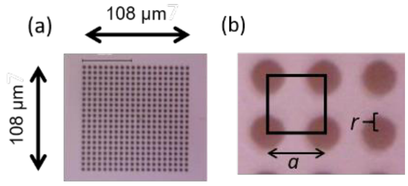

Fig. 1 (a) Microscope image of the phononic crystal we used in this experiment. (b) Magnified view of the holes of the phononic crystal.

3. Experiment

The time-resolved images of surface acoustic waves are obtained experimentally. The waves are excited in the two-dimensional phononic crystal described in the previous section. We use a method combining an interferometer and a pump probe method to acquire time-resolved images. Optical pulses with a wavelength of 830 nm, a repetition frequency of 75.6 MHz, one cycle of 13.22ns and a temporal width of ~ 100 ps are generated using a mode-locked Ti:Sapphire laser as the light source. As the pump light for exciting the surface waves, the second harmonic generated light pulses are used, whose wavelength is 415 nm. As the probe light for detecting the acoustic waves, the time-delayed fundamental 830 nm light pulses are used. Both pump and probe light are focused on the sample from the same side of the sample. Using an interferometer, the speed of displacement of the sample surface in the vertical direction is detected as a change in the reflected probe light intensity. In order to acquire a two-dimensional image of the sample surface, 4f lens system and a biaxial movable mirror are used in this study. By changing the angle of the biaxial movable mirror placed in front of the lens, it is possible to scan the probe light focusing point across a region of the sample surface. The pump spot is chosen to be close to a point between four holes in the centre of the phononic crystal. By changing the delay optical path and acquiring images one by one while changing the arrival timing of the probe light to the sample, it is possible to obtain the temporal variation of the SAW field as a movie. For each measurement, a total of 28 images are obtained at intervals of 0.47 ns in the range of delay time from 0.00 ns to 13.22 ns. In this way one can record the temporal evolution of the acoustic field.

The arbitrary frequency measurement method enables excitation and detection of surface acoustic waves at desired frequencies by selecting the modulation frequency of the pump light. We use the pump light modulation frequency at three frequencies of 6.3 MHz, 18.9 MHz, and 31.1 MHz using an electro-optic modulator (EOM). This set of modulation frequencies allows one to investigate the acoustic properties at 75.6/6=12.6 MHz step. Furthermore, we can acquire the dispersion relation about 2-dimensional wavevector space by performing spatiotemporal Fourier transformation on the image data in the spatiotemporal region obtained by these.

Figure 2 shows the Fourier amplitudes as the equi-frequency curves at 374 MHz, 409 MHz, 574 MHz, 624 MHz, 813 MHz, and 1040 MHz in the 2-dimensional k-space, where the wave vector of the equi-frequency curve lies near the Brillouin zone.

There are two schemes to display the equi-frequency curves in the wavevector space: the extended and reduced zone schemes. For Fig. 2, the extended zone scheme is taken. At 374 MHz, the equi-frequency curve is nearly a circle centered at the Γ point. With increasing the frequency, the radius of the equi-frequency circle gets larger and eventually the equi-freuquency curve come close to the Brillouin zone boundary. Further increase of the freuqnecy makes the equi-frequency curve segmented, and the directional band-gap opens around k_x=0 and k_y=0 on the zone boundary (409 MHz). At 574 MHz, the fragments of the equi-frequency curve are further pushed to the corner of the Brillouin zone, and the band gap opens for most of the directions. At 624 MHz, the circlular equi-frequency curves appear around the four corners of the Brillouin zone. At 813 MHz, the circles at 624 MHz grows. At 1040 MHz, the circles are transformed to some short straight segments in the higher order Brillouin zone.

In this way, the measurement allows one to investigate the dispersion surfaces of the system in detail.

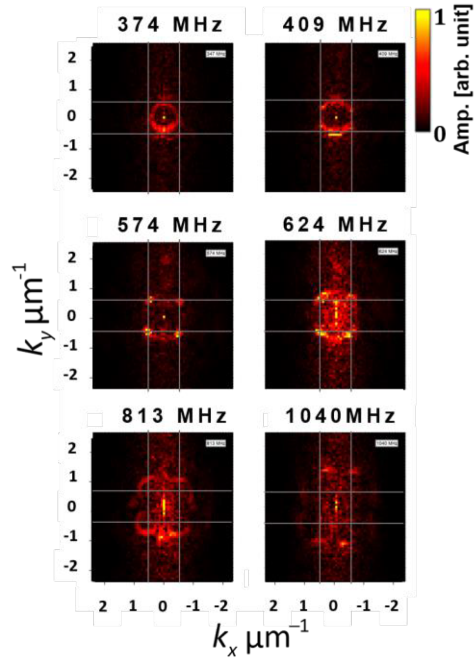

Fig. 2 Equi-frequency curves at 374 MHz, 409 MHz, 574 MHz, 624MHz, 813 MHz, and 1040 MHz.

4. Conclusion

We have performed the time-resolved two-dimensional imaging of the surface acoustic waves propagating on the two-dimensional square-lattice phononic crystal with the arbitrary frequency generation and detection technique. We succeeded to acquire the dispersion relation with frequency resolution 6-times higher than that of the conventional case, and experimentally clarified the characteristic feature of the dispersion near the band gap. This research forms a foundation for studying phononic crystals and other structured media with more complex dispersion relationships.

References

1. J. O. Vasseur, P. A. Deymier, B. Chenni, B. Djafari-Rouhani, L. Dobrzynski1, and D. Prevost, Phys. Rev. Lett. **86**, 3012 (2001).
2. T. Tachizaki, T. Muroya, O. Matsuda, Y. Sugawara, D. H. Hurley, and O. B. Wright, Rev. Sci. Instrum. **77**, 043713 (2006).
3. Y. Sugawara, O. B. Wright, O. Matsuda, M. Takigahira, Y. Tanaka, S. Tamura and V. E. Gusev, Phys. Rev. Lett. **88**, 185504 (2002).
4. S. Kaneko, M. Tomoda, and O. Matsuda, AIP Advances **4**, 017124 (2014).
5. O. Matsuda, S. Kaneko, O. B. Wright, and M. Tomoda, IEEE. Trans. Ultrason. Ferroelec. Freq. Contr. **62**, 584 (2015).