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Time resolved acoustic wave imaging in a one-dimensional phononic crystal with an arbitrary frequency technique

任意周波数測定法を用いた 1 次元フォノニック結晶表面音響波の時間分解イメージング

Shinya Aihara†, Kentaro Fujita, Shohei Ueno, Motonobu Tomoda, Oliver B. Wright, and Osamu Matsuda
([1]Fac. Eng., Hokkaido Univ.)
相原真哉†, 藤田健太郎, 上野翔平, 友田基信, オリバーライト, 松田理
([1] 北大院工)

1. Introduction

Phononic crystals (PhCs) are media composed of periodic arrays of materials with different elastic properties or mass densities. Because of Bragg reflection, PhCs may forbid the propagation of acoustic waves in a specific frequency band—the phononic band gap. Because of their anisotropy, phonon-focusing may also occur in PhCs.

By illuminating the surface of an opaque sample with ultrashort light pulses, surface acoustic waves (SAWs) are generated. The acoustic field of the SAWs can be detected in a time-resolved manner using delayed ultrashort light pulses, known as pump and probe light pulses for generation and detection, respectively. By spatially scanning the focused spot of the probe light across the sample surface, a two-dimensional image of the acoustic field can be obtained, producing a SAW image [1, 2]. In our previous work, this SAW imaging technique was applied to PhCs to detect SAW propagation and frequency characteristics of PhCs [3]. However, the frequency resolution is limited to the repetition frequency of the light pulses. Therefore, the propagation of SAWs in the band gap could not be revealed in detail. A previous technique based on laser-induced gratings revealed the dispersion relation of such one-dimensional PhCs in detail [4], but did not allow imaging of SAW propagation in real space.

The arbitrary frequency technique [5] overcomes the above-mentioned limitation in frequency resolution as well as allowing imaging of SAW propagation in real space. In this technique, the intensity of the pump-pulse train at the repetition frequency f is modulated at a different frequency F. With this modulated pump-pulse train, we can generate acoustic waves at the side-band frequencies $nf \pm F$. Appropriate signal detection and processing methods allow one to deconvolute the side-band components. By varying the modulation frequency in the range $0 < F < f/2$, one may thus investigate the acoustic waves at arbitrary frequencies.

The purpose of the present research is to image SAW or pseudo-SAW propagation on one-dimensional PhCs in real space, and to analyse the acoustic wave field in detail especially in the frequency region in the phononic band bap.

2. Sample

A schematic cross-section of the sample is shown in **Figure 1**. Copper lines and silicon dioxide lines both with 0.8 μm thickness are formed alternately on a silicon (100) substrate. The width of each copper line is 2 μm, and the structure period of this PhC is 4 μm.

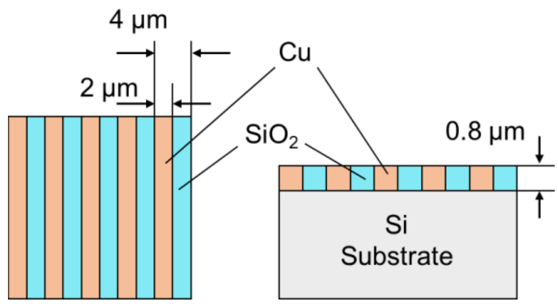

Fig. 1: Top and cross-sectional views of the sample.

3. Experiments

Figure 2 shows a schematic diagram of the experimental setup. A Ti:sapphire mode-locked laser is used as a light source, generating a pulse train at the repetition frequency 75.7 MHz with a temporal pulse width ~100 fs. A second-harmonic generation crystal converts the light pulses of wavelength 830 nm into 415 nm, which are used to generate SAWs. The pump power at the surface is 7 mW, and the focused spot diameter is ~1 μm. Pump pulses are modulated at three different frequencies, 6.31, 18.92 and 31.53 MHz. This allows the measurement to have a frequency resolution of 75.7/6 = 12.61 MHz. The light pulses with a central wavelength of 830 nm are used for the probe. The interferometer enables the probe light to detect the velocity of the displacement of the sample surface in the vertical direction. By changing the angle of a scanning mirror on a biaxial rotation stage, the probe light focused spot can be scanned across an area of 120 μm × 120 μm on the sample surface. For each measurement, a total of 28 images are obtained at intervals of 0.47 ns in the range of probe delay times 0-13.2 ns. The diameter of the probe pulse on the surface of the sample is ~1.5 μm.

Time-resolved images of SAW propagation can be spatiotemporally Fourier transformed to acquire the acoustic dispersion relation in two-dimensional wavevector space. The quantity k_x is the wavevector component along the direction of periodicity of the PhC structure, whereas k_y is the wavevector component along the PhC line direction. **Figure 3** shows the Fourier amplitudes as equi-frequency curves at 409, 498, 523, 535, 674 and 838 MHz. Blue dotted lines indicate $k_y = 0$. At around 409 MHz, the equi-frequency circle due to the Rayleigh wave (RW) branch is evident. At 485 MHz there are three circles, one bright circle in the first Brillouin zone and two adjacent circles outside this zone (not shown). In the frequency range from 485 to 498 MHz, these three circles come into contact with each other near the zone boundary at $k_x \sim \pm 0.78$ μm^{-1}, and the Fourier amplitude at $k_y = 0$ is smaller than that for $k_y \neq 0$: this corresponds to the appearance of the first band gap in the range 485-498 MHz. At 523 MHz, the RW branch is folded at the zone boundary, and it touches the less prominent inner circle (Sezawa wave branch, i.e. SW) in the first Brillouin zone. A second directional band gap appears as an avoided crossing of the RW and SW branches in the range 535-662 MHz. At 674 MHz, the Fourier amplitude reappears at $k_y = 0$, and the circle gets larger as the frequency increases.

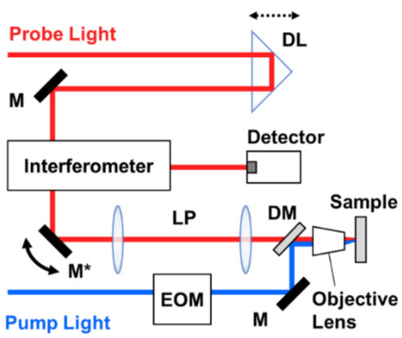

Fig. 2: Schematic diagram of the optical system: DL optical delay line; M mirror; M* mirror on biaxial rotation state; LP lens pair; DM dichroic mirror; EOM electro-optical modulator.

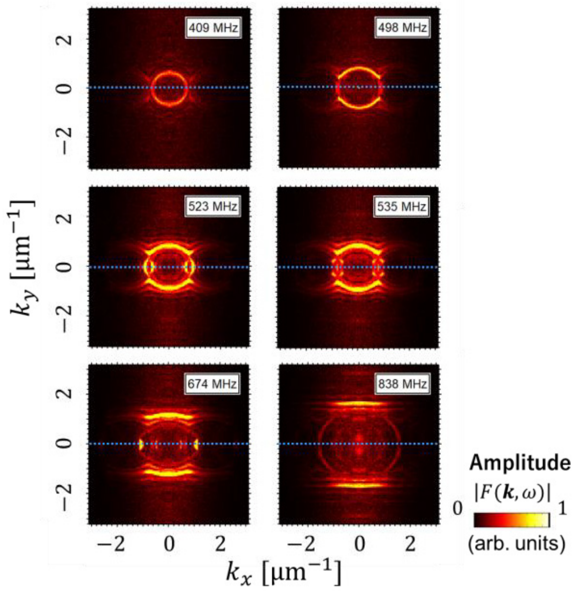

Fig. 3: Equi-frequency curves at different frequencies.

4. Conclusions

We have applied the arbitrary frequency technique to one-dimensional PhCs, and have acquired a six times higher frequency resolution compared to that in previous real-time imaging. This allows the characteristic features of the dispersion near and within the band gap to be revealed. Our method represents a solid foundation for studying phononic crystals and other acoustic devices with complex dispersion relations.

References

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