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Time-resolved imaging of GHz acoustic waves in two-dimensional phononic crystals with an arbitrary-frequency technique

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Abstract

By irradiating a medium with picosecond light pulses one can generate GHz surface acoustic waves. Their propagation can be monitored in the time domain with delayed probe light pulses. In addition, by spatially scanning the probe light focusing position, it is possible to monitor the spatiotemporal variation of the acoustic field. This can be used to study acoustic properties such as the dispersion relation of the surface acoustic waves in a medium. For such measurements, a periodic source of light pulses with a repetition rate of around 80 MHz is usually used, and so the frequency of the generated acoustic waves is limited to integer multiples of the repetition rate. We recently developed a technique to generate and detect arbitrary acoustic frequency components through the intensity modulation of the excitation, i.e. pump, light pulse train. In this paper, this arbitrary-frequency imaging technique is applied to study the acoustic properties of two- dimensional phononic crystals. The sample contains a square array of micron-scale holes on a Si substrate, and exhibits a phononic band gap around 0.5 GHz. We will present experimental results concerning acoustic wave propagation at frequencies around the phononic band gap.

Keywords: surface acoustic waves, time-resolved imaging, phononic crystals

1 INTRODUCTION

Tailoring acoustic wave propagation has been realized by the usage of artificial structures including phononic crystals, which are the periodic array of materials with different acoustic properties (1,2). The phononic crystals may have phononic band-gap and can be applied to functional devices such as filters (3). For these applications, the characterization of acoustic wave propagation in phononic crystals is essential.

By irradiating a medium with picosecond light pulses one can generate GHz surface acoustic waves therein. The propagation of acoustic waves can be monitored in the time domain with delayed probe light pulses through the photoelastic effect and/or the surface/interface displacement (4). In addition, by spatially scanning the probe light focusing position across the sample surface, it is possible to monitor the spatiotemporal evolution of the acoustic field of the surface acoustic waves (SAWs) (5). This imaging technique is useful for the investigation of acoustic properties, such as dispersion relations, of media such as phononic crystals and phononic metamaterials.

2 PRINCIPLE

We have developed the above mentioned SAW imaging system based on the optical pump-probe technique (5,6). A mode-locked Ti-sapphire laser is used as a light source, which generates light pulses at a central wavelength of 830 nm, a temporal width of 100 fs, and a repetition frequency of $f_{\mathrm{rep}} = 80$ MHz. The frequency doubled light pulses (pump light pulses) with the wavelength 415 nm are focused to the sample surface with the radius $\sim$1 μm, to generate the acoustic waves. The fundamental light pulses (probe light pulses) with the wavelength 830 nm are also focused to the sample surface with the radius $\sim$1 μm, to probe the acoustic field through the surface displacement using a modified Sagnac interferometer. The focusing of the pump and probe light is done by a common single microscope objective. The probe light focusing position can be scanned laterally with a $4f$ relay lens pair with a motorized mirror, while the pump light focusing position is fixed. Figure 1 shows the schematic diagram of the optical setup. It is capable of observing acoustic waves up to or beyond GHz

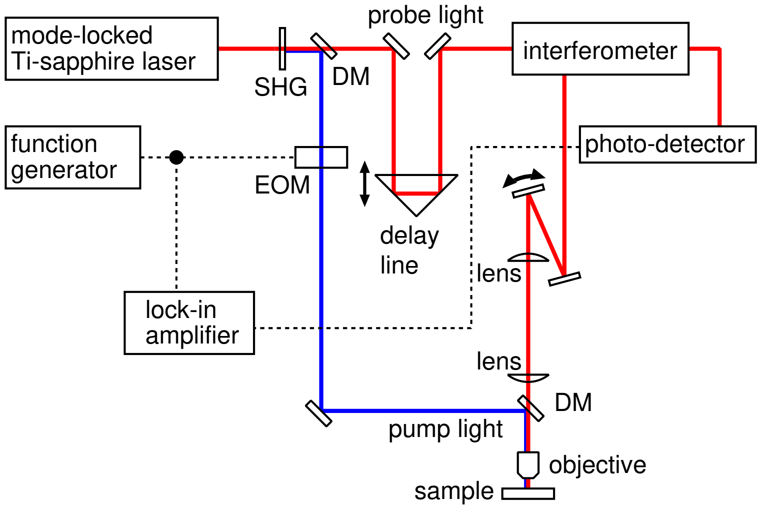

Figure 1. Optical setup for the time-resolved surface acoustic wave imaging. SHG: non-linear optical crystal for secondary harmonics generation, DM: dichroic mirror, EOM: electro-optic modulator.

frequencies with a lateral spatial resolution of 1 μm.

Since the imaging system uses a periodic train of pump light pulses, a simple conventional setup allows one to generate acoustic waves only at integer multiples of the light pulse repetition frequency $f_{\rm rep}$. This frequency resolution is too coarse in many applications. This difficulty can be resolved by the intensity modulation of the light pulse train at frequency F so that the acoustic waves are generated at the side-band frequencies $nf_{\rm rep} \pm F$ with arbitrary positive integer n. The upper side-band (USB at $nf_{\rm rep} + F$) and the lower side-band (LSB at $nf_{\rm rep} - F$) are discriminated using a dual-phase lock-in amplifier and appropriate signal processing of the in-phase and quadrature outputs of the lock-in amplifier. In this way, by varying F from near 0 to $f_{\rm rep}/2$, one can generate and detect arbitrary frequency acoustic waves/vibrations (7,8).

3 EXPERIMENT AND RESULTS

In this paper, the arbitrary-frequency imaging technique is applied to study the acoustic properties of two-dimensional phononic crystals (PCs). The sample is made on a Si (100) substrate by drilling a square array of holes of radius 1.4 μm, depth 1.3 μm and lattice constant $a = 5.6$ μm over an area of 100 μm $\times$ 100 μm using the focused ion beam technique. The SAW imaging is achieved by focusing the pump light at the center of a square PC region to a circular spot of 1 μm in diameter, or at the aside of the PC region to a line of 1 μm width parallel to the PC square region edge. The out-of-plane surface particle velocity is recorded as a function of the probe position and the delay time between the pump and probe light pulse arrivals at the sample. By discriminating the USB and LSB components, the data consist of a spatial map of the out-of-plane surface particle velocity amplitude at each selected frequency with a frequency resolution of 6.3 MHz. The data are then Fourier transformed in two-dimensional space to give the Fourier amplitude as a function of frequency and two-dimensional wave vector. Figure 2 shows a density plot of the modulus of the Fourier amplitude along some representative directions in two-dimensional wave-vector space (**k**-space), i.e. $\Gamma MX\Gamma$. Since a finite amplitude is expected for the combination of the frequency and wave vector which satisfy the dispersion relation of the medium, the measured curves consisting of arrays of bright spots indicate the experimentally obtained dispersion relation. The directional band gap around 0.3 GHz at the X point ($\mathbf{k} = (\pm\pi/a, 0)$) and around 0.5 GHz at M point ($\mathbf{k} = (\pm\pi/a, \pm\pi/a)$) are evident.

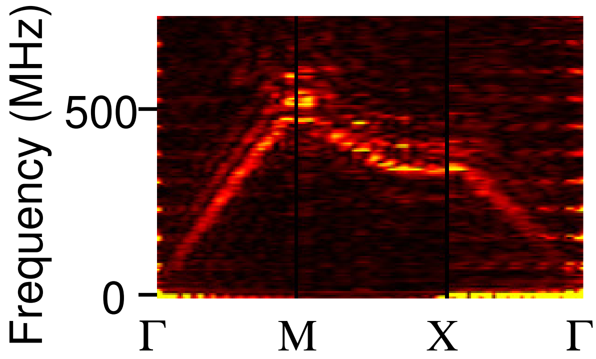

Figure 2. Dispersion relation of the surface acoustic waves in the two-dimensional phononic crystal.

4 CONCLUSION

The surface acoustic waves up to GHz frequency region in two-dimensional phononic crystals are investigated with the time-resolved two-dimensional imaging of the acoustic field. The arbitrary frequency technique is used to analyze the wave propagation properties with 6.3 MHz frequency resolution. The spatiotemporal Fourier transform of the obtained data reveals the dispersion relation of the surface acoustic waves. The method can be widely used for the evaluation of acoustic properties of various structures such as phononic crystals and phononic metamaterials.

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