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Imaging localized phonon fields in phononic crystal slabs

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1. Introduction

Materials that have a periodic variation in their elastic properties, known as phononic crystals (PCs) [1], have many practical applications for controlling wave propagation. The periodicity results in interesting dispersion relations with complicated band structures, producing effects such as negative dispersion and band gaps. Honeycomb lattices in particular have been shown to exhibit wide complete band gaps [2,3]. Introducing defects in the periodicity presents even more possibilities, such as waveguiding and confinement.

There has been extensive work on imaging surface acoustic waves (SAWs) in PCs, which has been successful in revealing effects such as phonon collimation, waveguiding and Bloch harmonics [4,5]. Analysis of such experiments is complicated because energy may propagate away from the surface, into the material bulk. For acoustic waves excited in thin slabs, the energy is confined to the slab and gives rise to Lamb modes. In this case the dispersion relation can be calculated and the analysis may be simpler and more illuminating.

In this paper, we present results of real-time imaging of optically-induced Lamb waves in PC slab structures based on honeycomb lattices. Confinement in waveguides and cavities is investigated by introducing defects into the PC structure. In addition, we use finite element numerical simulations to investigate the mode shapes of the wave propagation in these phononic crystal structures.

2. Sample

The samples consist of microscopic honeycomb lattices of circular holes in (111) silicon-on-insulator wafers 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, and the depth of penetration is 5.8 μm.

Using the orthogonal plane wave method, the expected first complete (omnidirectional) band gap for this structure is calculated to lie between 230 and 320 MHz. Structures such as waveguides and cavities are formed by the absence of holes in different patterns.

3. Experiment

Lamb waves in the slab were excited and detected using an optical pump-probe set-up with a Ti:sapphire femtosecond laser [6]. The probe pulses, of wavelength 830 nm, repetition rate 80.4 MHz and duration ~200 fs, detect the out-of-plane surface velocity of the propagating waves. The pump beam was derived from the same laser and had a wavelength of 415 nm, exciting Lamb waves at a point by thermoelastic expansion. The 830 nm probe beam had a variable delay relative to pump beam. The beams were focused to spots of about 1 μm in diameter. While keeping the pump fixed, the probe spot was scanned across the sample to generate images over an area of ~200×200 μm^2 at various delay times, allowing animations of the surface motion to be obtained at acoustic frequencies up to ~1 GHz.

The experimental images show waves propagating through the phononic crystal structure. Fourier analysis enables the propagation to be visualized at fixed frequencies. Such images show that at some frequencies the waves propagate freely through the sample, whereas at others, for example at 240 MHz—within the expected band gap—the energy is confined to the cavity and waveguide defects. Using the simulation data we were able to visualize the cross-sectional deformation of the wave propagation. Several Lamb modes contribute to the pattern at each frequency.

4. Conclusion

Lamb wave propagation in microscopic phononic crystal slabs of Si were dynamically imaged in two dimensions at frequencies up to 1 GHz by an ultrafast optical technique. The acoustic dispersion relations obtained by spatial and temporal Fourier transforms reveal stop bands and the eigenmode patterns. Waveguiding and confinement in phononic crystal waveguides and cavities were also obtained. The experimental results are in good agreement with finite element simulations.

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