APPLIED PHYSICS LETTERS **88**, 041911 (2006)

# Evidence of surface acoustic wave band gaps in the phononic crystals created on thin plates

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(Received 29 September 2005; accepted 10 December 2005; published online 25 January 2006)

Phononic structures and acoustic band gaps based on bulk materials have been researched in length in the past decades. However, few investigations have been performed on phononic structures in thin plates to form surface acoustic wave (SAW) band gaps. In this letter, we report a new type of phononic crystals manufactured by patterning periodical air-filled holes in thin plates. We confirmed the existence of SAW band gaps in the created phononic crystals through laser ultrasonics measurements. Wide multiple SAW band gaps and special structures, such as narrow pass bands within a band gap were observed experimentally. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2167794]

The propagation of acoustic waves in periodic composite materials has been studied extensively in the past decades.[1–12] Phononic crystals are created by a two-dimensional or three-dimensional periodic arrangement of two or more materials displaying a strong contrast in their elastic properties and densities. Because of the artificial periodic elastic structure of phononic crystals, there can exist frequency ranges in which waves cannot propagate, giving rise to acoustic band gaps which are analogous to photonic band gaps for electromagnetic waves in the well-documented photonic crystals. Interest in phononic crystals comes from the rich physics of acoustic and elastic systems, where both the density and velocity contrast affect wave scattering and propagation. Potential applications of phononic crystals, such as in generating soundless backgrounds for many technological devices and sound filters,[4,5] have also attracted much recent interest. At some frequency regions, phononic crystals can focus a sound beam and thus may find numerous applications in acoustic surgery.[6,7] The study of phononic crystals along with photonic crystals also furthers the study of wave phenomena such as localization,[8] phonon cavity,[9] and ultrasound tunneling.[10] By breaking the periodicity of a phononic crystal, it is possible to create highly localized defects within the acoustic band gap,[11,12] which are analogous to localized modes in photonic crystal and to localized impurity states in semiconductor.

While bulk phononic crystals have been researched in length, little is known concerning surface acoustic modes on phononic crystals and even less is understood regarding the design of these crystals to constrain the surface modes. Though infinite half-space phononic crystals exhibiting forbidden bands for surface modes[13,14] have been studied numerically.

In this letter, we report experimental evidences for the existence of surface ultrasonic band gaps in the band structure of phononic crystals in thin plates. We created phononic crystals in thin plates by patterning hundreds of air filled holes in the plates. In these structures, the acoustic modes are confined[15–17] by the two free surfaces of the plates, and result in only surface characterized modes, namely Lamb modes. The created phononic crystals on the plates would constrain these surface modes and form surface acoustic wave (SAW) band-gap structures. Acoustic band structures for two phononic crystal lattices (Fig. 1): Square lattice and modified square (MS) lattice are reported in this letter. As shown in Fig. 1, MS lattice is formed by shifting, horizontally, every other row of a square lattice by a half-spacing (the length of the dashed square in the square lattice). MS lattice can be also considered as a triangle lattice (three closest elements form an isosceles triangle). The filling fraction, which is defined as the ratio of area of holes over the area of corresponding plate, is the same for square and MS lattices providing the holes diameter and lattice constants are the same.

A laser ultrasonics instrument[18,19] was utilized to characterize the SAW band properties of the phononic crystals. The detail of current setup was described elsewhere.[19] Briefly, the broadband surface ultrasonic waves are generated by a point focused pulsed laser beam. The generated broadband ultrasonic waves propagate along the sample surface, travel through structures such as phononic crystals, and are

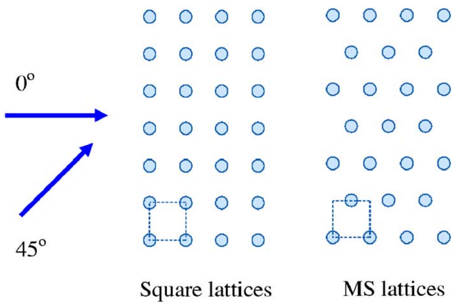

FIG. 1. (Color online) Schematic diagrams illustrating square and MS phononic crystals lattices. The arrows indicate the ultrasound propagating direction along which the acoustic transmission spectra are measured.

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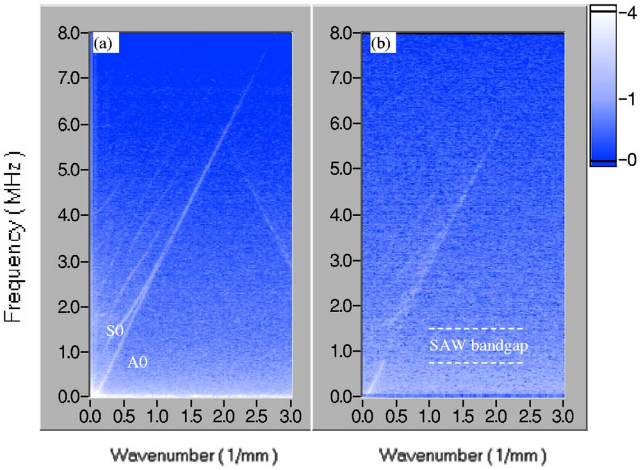

FIG. 2. (Color online) Measured 2DFT images of a nonpatterned 1.27 mm thick aluminum plate (a) and of a phononic crystal on the same plate (b). Wide SAW band gap of 0.8 to 1.5 MHz was evident in (b). The ultrasound propagates along 0° as illustrated in Fig. 1. The dashed white lines in the diagram approximate the width of the SAW band gap, to guide the eyes. The diagonal line in the right part of (a) is an artifact of the Fourier transformation.

then probed by the detector. The ultrasonic waves are often detected by an interferometer using the beam of a second continuous coherent laser. The ultrasonic packets induce displacements at the specimen surface which modulate the phase of the reflected laser beam. To demodulate the phase shift of the probing laser light, we utilize a broadband photorefractive interferometer applying the two-wave mixing[18] effect in a photorefractive crystal.

The ultrasonic wave forms can be recorded in the time domain. Their spatial domain wave forms can be obtained by taking incremental measurements in the separation distance between the ultrasonic emitter and receiver. With the spatial and temporal domains data, a two dimensional Fourier transformation (2DFT) can be performed and the Fourier magnitudes as a function of wave number and frequency can be displayed for the detected ultrasound. Examples are shown in Figs. 2 and 3, where the horizontal axis is the wave number in 1/mm and the vertical axis is the frequency in MHz. The color is the 2DFT magnitude (light color corresponds to large values and dark color to small values). The large value of the 2DFT magnitude for a given frequency and wave number indicates that the corresponding wave is a propagating mode that is generated and probed by the system.

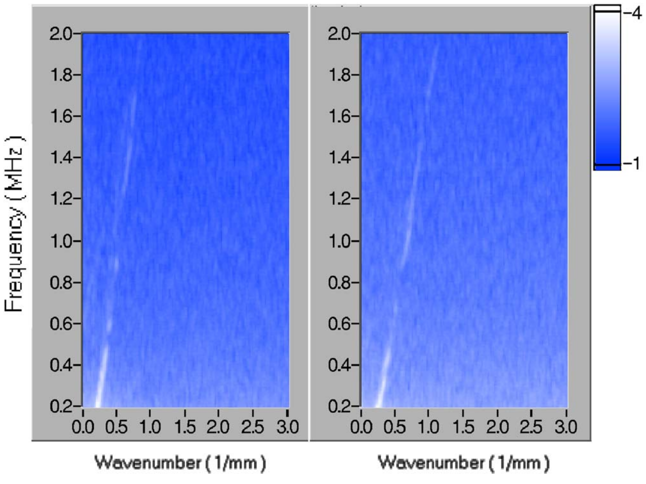

FIG. 3. (Color online) Measured 2DFT images of phononic crystals on a 0.504 mm thick aluminum plate (left image) and brass plate (right image) with the same thickness. The ultrasound propagates along 45° as illustrated in Fig. 1. Multiple SAW band gaps are evident in the images.

Figure 2(a) shows the 2DFT image of a 1.27 mm thick aluminum plate that is not a phononic crystal. The image displays the dispersion relations for the A0 (the lowest-order asymmetric Lamb mode), S0 (the lowest order symmetric Lamb mode, next to A0), and higher-order Lamb modes (the rest of the weak modes).[15,16,19] A0 mode has a large out-of-plane displacement component and hence is observed easily by the current laser ultrasonics setup. The S0 is an in-plane mode at low frequencies (below 1 MHz), however it becomes visible at high frequencies because its out-of-plane component increases with frequency. The S0 mode merges gradually with A0, and essentially both become a nondispersive Rayleigh surface mode.[15–17] Higher-order Lamb modes are standing modes that resulted from the interference of waves reflected from the two free plate boundaries. They are classified as longitudinal or transverse characterized standing modes.[15,16,19] And their Fourier magnitudes are weaker than A0's and S0's in the 2DFT image.

Figure 2(b) illustrates the results for an aluminum plate with a square lattice of air-filled holes. The measurement was taken along the direction labeled 0° in Fig. 1. The spacing of this lattice is 1.077 mm (the length of dashed square in Fig. 1 square lattice). The diameter of holes is 0.762 mm, resulting in a filling fraction of air of 0.393. In Fig. 2(a), the image reveals that the acoustic modes propagate easily between 0.1 and 7 MHz in the sample. In Fig. 2(b), the generated waves can propagate through the phononic crystal freely also below 0.8 MHz or above 4 MHz. For the waves from 1.5 to 4 MHz, because of the phononic crystal, the ultrasonic waves become broad and distribute over in a comparatively large range of frequencies and wave numbers, however, the integrated magnitudes did not decrease significantly. In the frequency range from $\sim$0.8 to 1.5 MHz, the 2DFT image exhibits a very high attenuation for the waves. In other words, the phononic crystal forms a large resistance, or an acoustic band gap, to the propagated SAW mode in this frequency range. To our knowledge, this is the first experimental observation that an acoustic band gap is formed for SAWs.

To confirm the observed SAW band gap, a three-dimensional plane wave expansion (PWE) method[1] is used to simulate the laser ultrasonics band structure of the square phononic lattice. Elastic constants $C_{11}=112$ GPa, $C_{44}=27.9$ GPa, and the mass density of 2692 kg/m$^3$ for aluminum were used in the calculations. The PWE calculation is performed with 1029 reciprocal space vectors. We limit the calculation to the $\Gamma X$ direction of the Brillouin zone of the phononic crystal lattice. This direction corresponds to the direction labeled 0° in Fig. 1. The calculated SAW dispersion curves of a homogeneous aluminum slab that does not contain air holes agree well with the measurement in Fig. 2(a). Upon inserting a periodic array of air holes in the slab, the A0 dispersion curve opens a gap at the edge of the Brillouin zone. The calculated frequency gap ranges from 0.834 to 1.42 MHz, agreeing well with the experimental observation.

MS lattices were also created on aluminum and brass plates with the thickness of 0.508 mm. The spacing of this lattice is 1.5 mm (the length of dashed square in Fig. 1 MS lattice). The diameter of the holes is 1 mm and the filling fraction of air is 0.349. Figure 3 shows the 2DFT images measured from the MS lattice phononic crystals on aluminum (left) and brass (right) plates, respectively. The measurements were taken along the direction labeled 45° in Fig. 1. On the thin plates with a thickness of 0.508 mm, only the A0 mode (the lowest order asymmetric Lamb mode) can be generated and probed efficiently by the laser ultrasonics system. In the 2DFT images, only this mode is visible.

For the aluminum sample, ultrasound in the frequency ranges of 0.52–0.56 MHz, 0.6–0.86 MHz, 0.92–1.2 MHz are forbidden to propagate in the crystal, and therefore form multiple SAW band gaps in their transport spectra. These band structures can be also considered as a large band gap from 0.52 to 1.2 MHz in this phononic crystal, but with two narrow pass bands located around 0.6 and 0.9 MHz, respectively. It is interesting to notice that the transitions from pass band to stop band are very sharp. This band structure demonstrates a perfect example of narrow pass band filters: Passing the selected frequencies and rejecting all the others. And, thus, the created crystal may find numerous applications in rf devices.[7]

On the brass plate, SAW band gaps (~0.7–0.9 MHz and ~1.5–1.7 MHz) are also formed. The ultrasound in the frequency range from 0.5 to 0.66 MHz is also attenuated considerably. The ultrasound in this frequency range is immediately beneath one of the band gaps (0.7–0.9 MHz). Combining them together, one can consider them again as a special band structure that has a narrow pass band (0.66 to 0.7 MHz) within a wide band structure (0.5 to 0.9 MHz). One may notice that the structure of the three closely packed band gaps in the aluminum plate do not seem to appear in the brass plate. However, one may find a dip of magnitude around 0.38 MHz in the 2DFT image (Fig. 3 right), which suggests that the first band gap is located there. Therefore, for the brass plate, there are also three band gaps which are closely packed together, which may suggest that these band structures are caused by the created phononic lattices.

To summarize, we described a new type of phononic crystal produced by patterning holes on thin metal plates. To our knowledge, we confirmed experimentally for the first time that SAW band gaps were formed in these phononic crystals. Wide multiple SAW band gaps were evident in the experiments, together with some special band structures, such as narrow pass bands within certain band gaps.

The authors from Georgia Tech are grateful of the Georgia Research Alliance's support through Contract No. GRA.TC05.A and GRA.TC06.A.

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