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Surface acoustic wave band gaps and phononic structures on thin solid plates

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ABSTRACT

Novel phononic crystal structure on thin plates for material science applications in ultrasonic range (~ MHz) is described. Phononic crystals are created by a periodic arrangement of two or more materials displaying a strong contrast in their elastic properties and density. Because of the artificial periodic elastic structures of phononic crystals, there can exist frequency ranges in which waves cannot propagate, giving rise to phononic band gaps which are analogous to photonic band gaps for electromagnetic waves in the well-documented photonic crystals. In the past decades, the phononic structures and acoustic band gaps based on bulk materials have been researched in length. However few investigations have been performed on phononic structures on thin plates to form surface acoustic wave band gaps. In this presentation, we report a new approach: patterning two dimensional membranes to form phononic crystals, searching for specific acoustic transport properties and surface acoustic waves band gaps through a series of deliberate designs and experimental characterizations. The proposed phononic crystals are numerically stimulated through a three-dimensional plane wave expansion (PWE) method and experimentally characterized by a laser ultrasonics instrument that has been developed in our laboratory.

INTRODUCTION

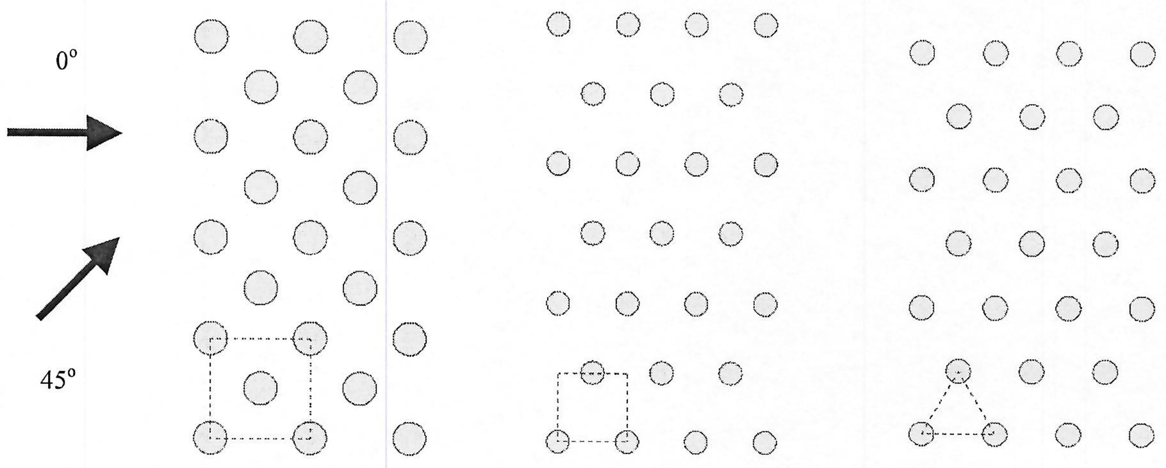
The propagation of acoustic and elastic waves in periodic composite materials has been the subject of many researchers' interest in the past decade [1-16]. Phononic crystals are created by a two-dimensional or three-dimensional periodic arrangement of two or more materials displaying a strong contrast in their elastic properties and density. Some structures are constituted of solid inclusions in a solid matrix (i.e. solid/solid phononic crystals) or mixed structures constituted of a combination of fluids and solids. Because of the artificial periodic elastic structures of phononic crystals, there can exist frequency ranges in which waves cannot propagate, giving rise to acoustic band gaps (ABG) 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, e.g., in generating soundless backgrounds for many technological devices and sound filters, have also attracted much recent interest [5-6]. Phononic crystals with point, linear, and surface defects permit manipulation of sound: they guide the acoustic waves, split, and bend them [7]. They can be used as thermal conductors [8]. At some frequency regions, phononic crystals possess a unique property that an ultrasonic beam can be negatively refracted and are able to focus [9,10], thus may find numerous applications in invasive acoustic surgery [11]. The study of phononic crystals along with photonic crystals also furthers the study of wave phenomena such as localization [12], phonon cavity [13], and ultrasound tunneling [14]. By breaking the periodicity of a phononic crystal, it is possible to create highly localized defect within the acoustic bang gap [15], which are analogous to localized modes in photonic crystal and to localized impurity states in semiconductor. Extended defects such as rows of different inclusions in the phononic lattice have been shown to guide elastic waves within the crystal band gap [16].

In the literature, phononic crystals are constituted by a set of hard rods (metal, concrete) periodically embedded in a soft medium such as a liquid, taking advantage of the high elastic contrast, and good ultrasonic transport properties of the liquid. These bulk phononic crystals which constrain bulk ultrasound have been researched in length. However little is know concerning surface acoustic modes on phononic crystals and even less is understood regarding the design of these crystals to constrain the surface modes. Numerically, infinite half space phononic crystals exhibiting forbidden bands for surface modes[17-19] have been predicted.

In this paper we report, for ~~the first~~ time, the experimental evidence of acoustic band gaps on surface ultrasonic modes.

PHONONIC CRYSTAL LATTICES ON THIN PLATES

We created phononic crystals on thin plates, a soft on hard host configuration, which consist of hundreds of patterned holes on plates. This is a different approach from the conventional constitutions of phononic crystals. The acoustic modes in the plates are confined by the two free surfaces of the plates, and result in only surface characterized modes, Lamb modes, for propagation. The created phononic crystals on the plates would constrains to these surface modes and therefore form ABG structures. A laser ultrasonics technique was utilized to characterize the acoustic band properties of the created crystals. Because of its non-contact nature (therefore no perturbation of the plate's vibration modes by the probe), and broadband generation and detection of ultrasound characteristics, laser ultrasonics is an effective tool for such purposes.



FC lattice MS lattice ET lattice

Fig 1. Schematic diagrams illustrating FC, MS and ET phononic crystals lattices. The arrows indicate the ultrasound propagating direction along which the acoustic transmission spectra are measured.

Fig 1 shows three common phononic crystal lattices: face centered (FC), modified square (MS) lattice and equilateral triangle (ET) lattice. The FC lattice can be also considered as a squared lattice (four closest elements form a square cell). The filling fraction, which is defined as the ratio of area of holes over the area of corresponded plate, is the same for FC and MS lattices if the holes diameter and lattice constants are the same, while for the ET lattices, the filling fraction will be larger under the same conditions.

When phononic crystal lattices are created on the plate, the periodic patterns modify the ultrasound propagation properties, and results in that some waves in a certain frequency range are being highly attenuated, or even being forbidden in some propagating directions. In this report, we describe the ultrasound transport properties measured for MS lattices on brass and aluminum plates, with a thickness of 0.02, 0.04 and 0.05 inch. Measurements on one FC lattice created on a 0.05 why? inch thick aluminum plate will be reported as well.

EXPERIMENT

An advanced laser ultrasonic laboratory instrument has been developed at the Institute of Paper Science and Technology at Georgia Tech [20-22]. This instrument allows automatic broadband ultrasound generation and detection at different locations on various samples. To do so, it uses a pulsed laser, a photo-refractive interferometer, and two-dimensional Fourier transformation or phase-unwrapping method for signal processing. This instrument enables the non-contact, non-destructive mechanical characterization of the properties of a large variety of specimens, ranging from different paper and paperboard grades to wood and metal plates, foils, films and membranes. The instrument can also be used to characterize phononic crystals, not only for their transport properties, but also for the dispersion of propagated waves and modes localization as well, which is not applicable by traditional contact acoustic methods. In addition, the laser ultrasonics instrument may enable the probing of some of the modes in phononic crystals that cannot be observed with traditional acoustic experimental methods, due to the incompatibility between the symmetry and the polarization of the probing wave. This wide range of possibilities indicates that the laser ultrasonic instrument constitutes a very useful resource for the study and the design of phononic crystals.

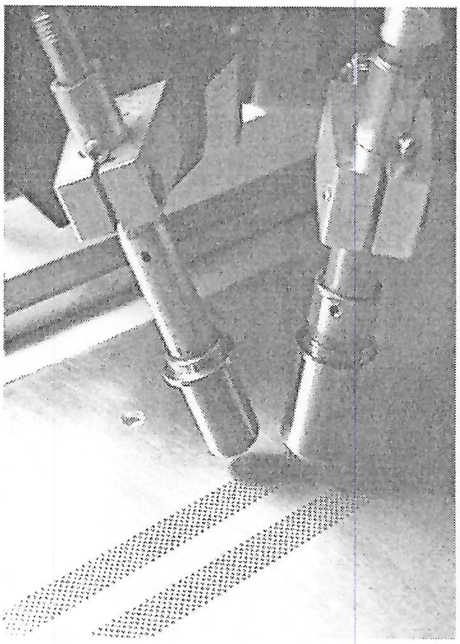


Fig. 2 Picture of the generation and detection optical probes

The broadband ultrasonic waves are generated by a point focused pulsed laser beam. The resulting ultrasonic waves are often detected by an interferometer using the beam of a second CW coherent laser. The ultrasonic packets induce displacements at the specimen surface which modulate the phase of the reflected CW laser beam. To demodulate the phase shift of the CW laser light, we utilize a broadband photorefractive interferometer using the Two-Wave Mixing (TWM) effect in a photorefractive crystal. The interferometer measures the displacement in the line of the detection beam. Since the beam is typically normal to the sample surface, the interferometer measures out-of-plane displacements. Its optical setup is very similar to the one described in detail in reference [22].

The LU instrument records the ultrasonic waveforms in the time domain. Fourier transformation (FT) of the time domain displacement can provide magnitude and phase of the detected ultrasound as function of frequency in the Fourier domain. With suitable signal processing such as phase unwrapping, phase velocities of the modes as functions of frequency can be obtained and stemming from them, the mechanical constants of the sample can be extracted.

However, an advanced method has been recently developed using a 2-Dimensional Fast Fourier Transform (2D FFT). The 2D FFT enhances the original signal processing functions and can provide more valuable information. This approach is implemented by taking incremental measurements in the separation distance between the ultrasonic emitter and receiver to obtain a second spatial dimension, corresponding to wave vector (k) domain after a Fourier transformation.

With this spatial and temporal domains data, a 2D FFT can be performed and the Fourier magnitude as function of frequency and wavenumber can be displayed for the detected ultrasound; examples are shown in Fig. 3-5, where the horizontal axis is the frequency in MHz, and the vertical axis is the wavenumber in mm^{-1}. The color is the 2D FFT magnitude (white color corresponds to large values and blue color to small values). The 2D FFT magnitude distribution is interpreted as the projected (out of plane component) density of the state (DOS) or intensity for the corresponding mode. The large value of the DOS for a given frequency and wavenumber indicates that the corresponding wave is a propagating mode that is generated and probed by the system. The zero value of DOS for a given frequency and wavenumber reveals that the mode is either not a propagating mode or it is a propagating mode that cannot be probed by the system (for example, a purely in-plane mode). In Fig. 3-5, the DOS exhibits the propagating ultrasound strikingly.

The 2D FFT procedure not only displays beautifully all excited ultrasonic modes, but also separates them and provides a direct way to measure the properties for each individual mode such as its dispersion, frequency range, DOS distribution, etc. The later is an obvious advantage of the procedure for a thick sample, where high order Lambs modes can propagate. This is demonstrated in Fig. 3 (a) on a (0.05 inch) 1.27 mm thick aluminum plate, where a number of high order Lamb modes are supported by the plate and probed by the laser ultrasonics system. From the time domain displacement curve or its FT frequency domain curves, it is impossible to distinguish the contribution of individual modes and analyze their properties. But, from 2D FFT image, by tracing the maximum of the DOS image, the phase velocity dispersion of individual modes can be directly obtained for each individual mode. An automatic code has been built into the software package, so that the needed properties will be automatically calculated and displayed with minimum human intervention.

RESULTS AND DISCUSSIONS

Fig.3(a) shows the linear frequency response of a 0.05 inch thick aluminum plate that is not a phononic crystal. The image displays the dispersion relations for the A0 (the lowest order asymmetric Lamb mode, upper most mode), S0 (the lowest order symmetric Lamb mode, next to A0) and higher order Lamb modes (the rest of the weaker modes) [23-24]. A0 mode has a large out-of-plane displacement component and hence is observed easily by the laser ultrasonics instrument. The S0 is an in-plane mode at low frequencies (below 1 MHz), however it becomes visible at high frequency because its out-of plane component increases with frequency. The S0 mode merges gradually with A0, and essentially both become a non-dispersive Rayleigh surface mode. 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 (L) or transverse (T) characterized standing modes [23-24]. It is noted that the current laser ultrasonics set-up can depict the whole spectrum for the A0 mode. For the S0 and higher Lamb modes, others system configurations are necessary in order to display the whole frequency spectra for the corresponding modes.

Fig.3(b) illustrates the results when a special pattern FC lattice was produced on the plate. The spacing of this lattice is 1.524mm or 0.06inch (the length of dashed square in Fig. 1 FC lattice). The diameter of the hole is 0.762mm (0.03inch). In Fig.3(a), the image reveals that the acoustic modes propagate easily between 0.1 and 8 MHz in the sample. In Fig.3(b), the 2D FFT image exhibits a very high attenuation region in a frequency range of 0.9 to 1.4 MHz caused by the phononic crystal. In other words, the phononic crystal forms a large resistance, or acoustic band gaps, to the propagated ultrasound modes in this frequency range. To our knowledge this is the first experimental observation that an acoustic band gap can be created for surface waves. not

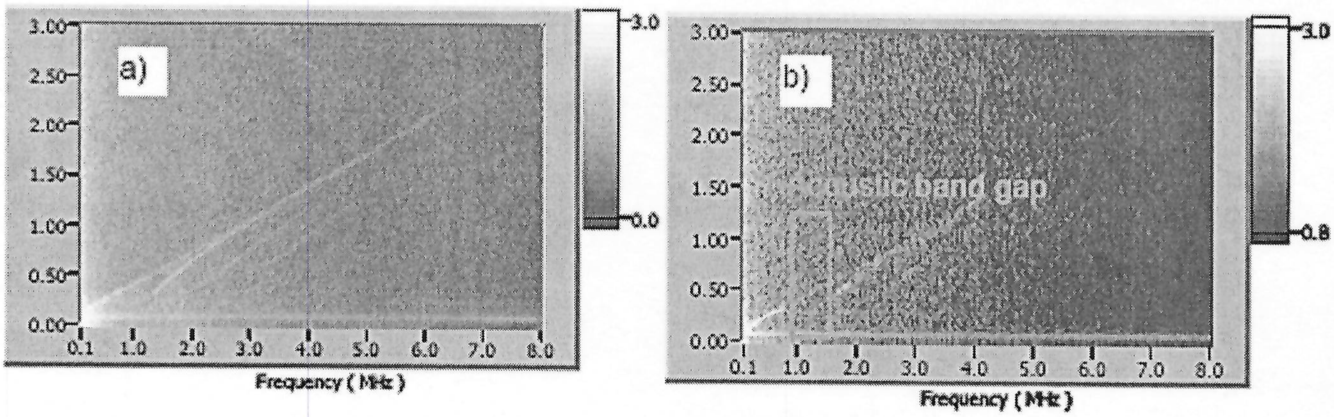


Fig.3: Measured frequency responses of a non-patterned 0.05 inch thick aluminum plate (a) and of a phononic crystal on the same plate (b). (45°)

A MS lattice was also created on a series of aluminum and brass plates with thickness of 0.02, 0.04 and 0.05 inches. The spacing of this lattice is 1.5 mm (the length of dashed square in Fig. 1 MS lattice). The diameter of the hole is 1 mm. Laser ultrasonics measurements were taken on these created phononic crystals. Some results are described and discussed in the following sections.

Fig. 4 shows the linear frequency response images measured from the MS lattice phononic crystals on 0.02 inch thick aluminum and brass plates, respectively. On such thin plates, only the A0 mode (the lowest order asymmetric Lamb mode) can be generated and probed efficiently by the laser ultrasonics system. In the 2D FFT image, only this mode is visible.

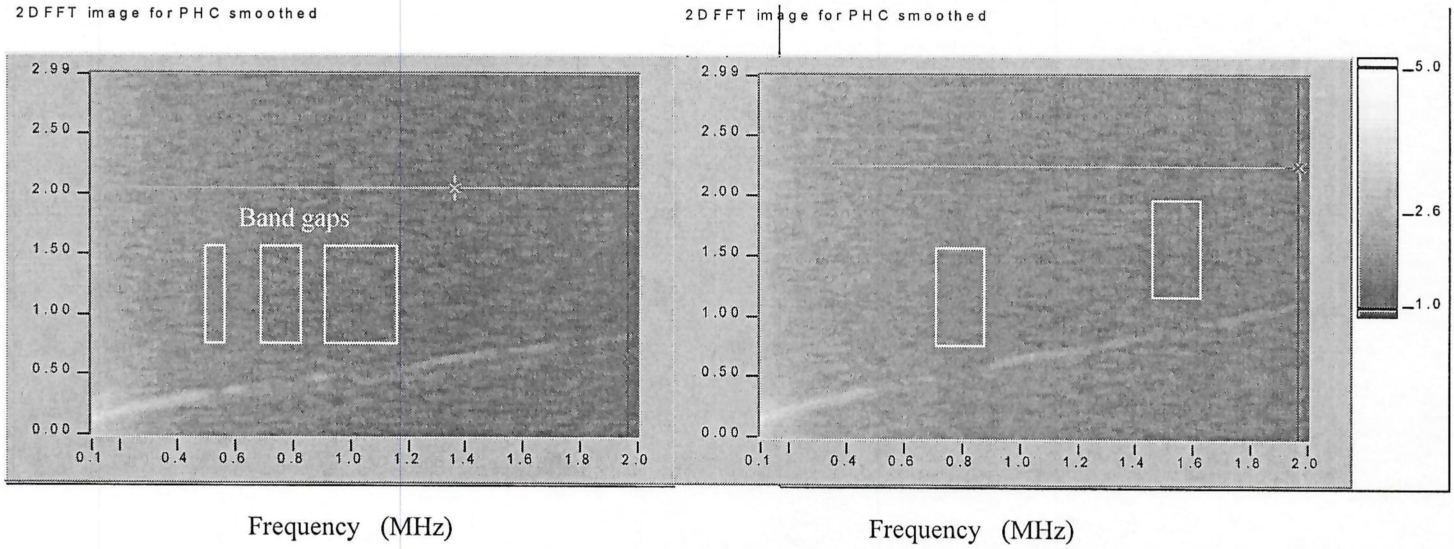


Fig. 4, Measured frequency response images of phononic crystals on a 0.02' thick an aluminum plate (left image) and brass plate (right image) with the same thickness. The ultrasound propagates at 45 degree from the phononic crystals. The white rectangles in the diagrams approximate the positions of acoustic band gaps.

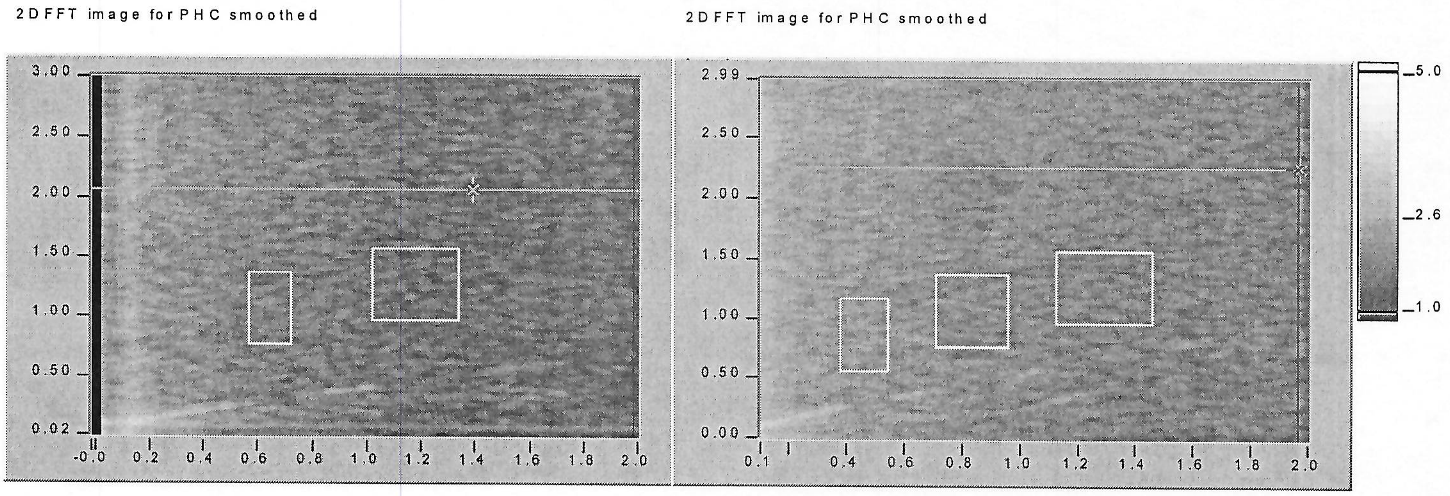


Fig. 5 Measured frequency response images of phononic crystals on a 0.05' thick aluminum plate (left) and a brass plate (right). The ultrasound propagates at 0° from the phononic crystals. The rectangles in the diagrams approximate the positions of acoustic band gaps.

For the aluminum sample, ultrasound in the frequency ranges of 0.52-0.56 MHz, 0.7-0.86MHz, 0.92-1.2 MHz are forbidden to propagate in the crystal, and therefore form multiple acoustic band gaps in their transport spectra. This 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. On the brass plate, the band gaps also form but with different bandwidths and frequencies (~0.7-0.9 MHz and ~1.5 to 1.7 MHz). Unlike the aluminum case, these two band gaps are well separated. The images in Fig. 4 demonstrate that not only multiple acoustic band gaps can be formed by the phononic crystals created on thin plates, but also that some band gaps can be very wide and have complex band structures, such as narrow pass-bands with a wide stop band [16]. Please note that the transition from pass band to stop band is very sharp. This band structure demonstrates a perfect example of narrow pass band filter: passing the selected frequencies and rejecting all the others.

The acoustic band structures also differ with the ultrasound propagating directions. The arrows in the Fig 1 show two common wave propagating directions, along which the ultrasonic transport properties are measured. 0° is the direction perpendicular to the phononic crystals. 45° is the direction along which the ultrasound propagates at 45° from the perpendicular direction to the phononic crystal. The measurements on the samples illustrated in Fig. 4 are at 45° degrees from the phononic crystals. Fig. 5 shows the acoustic band gaps measured at 0° from the phononic crystal for the aluminum and brass plates of 0.05 inch thick. In the aluminum plate, two gaps (0.6 to 0.74 MHz, 1.02 to 1.4 MHz) are clearly displayed in the image, while on the brass plate, three gaps are visible. They are located around 0.4 to 0.54, 0.74 to 0.96, 1.1 to 1.5 MHz, respectively. Those band structures are drastically different from those obtained at 45° (not shown in this paper).

THEORETICAL SIMULATIONS

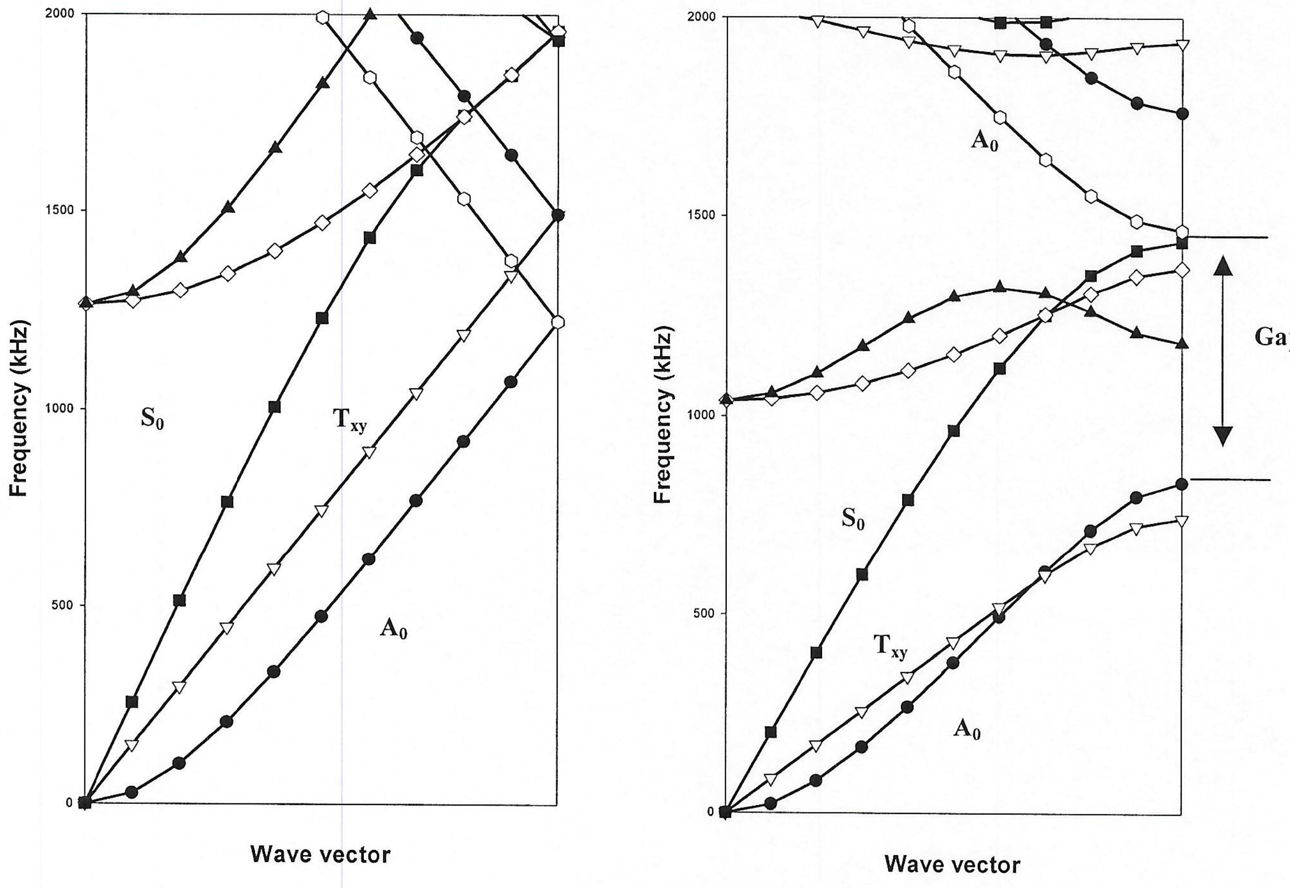


Fig. 6 Elastic band structure of a homogeneous slab of aluminum in air (left) and a slab of aluminum in air containing cylindrical air holes arranged on a FC lattice (right). The curves labeled A_0, T_{XY}, and S_0 are, respectively, the lowest order asymmetric lamb mode, transverse mode polarized in the plane of the slab and the lowest order symmetric Lamb mode.

We have used a three-dimensional plane wave expansion (PWE) method to calculate the elastic band structure of the FC phononic lattice [25]. The periodicity of the three-dimensional unit cell is that of the two-dimensional period of the FC (square) lattice, a=1.077mm or 0.0424inch (spacing between holes in Fig. 1), in the XY plane, and l=8a in the Z direction. The diameter of the hole is 0.762mm (0.03inch). The thickness of the aluminum slab is d=0.05inch or 1.27mm, representing approximately 15% of the height of the cell. With this configuration the slab does not interact significantly with its periodic image along the Z direction thus mimicking the behavior of a single phononic lattice slab in air. To perform the calculation we have employed the following data for the elastic constants: C_{11}=112 GPa and C_{44}= 27.9GPa. The density of aluminum takes on the value 2692 kg/m^3. We have chosen the following small values of $C_{11}=C_{44}=1\times10^{-3}$GPa with a density of 1×10^{-4} kg/m^3 for air in order to remove unphysical flat frequency bands [26]. The PWE calculation is done with 1029 reciprocal space vectors. We limit the calculation to the ΓX direction of the Brillouin zone of the phononic crystal lattice. This direction corresponds to the direction labeled 45° in Fig. 1. We report in Fig. 6 (left) the elastic band structure of a homogeneous aluminum slab that does not contain air holes. We have labeled the three dispersion curves that pass through the origin. The first dispersion curve labeled A_0 is the lowest order asymmetric lamb mode. The second curve labeled T_{XY} is a transverse mode polarized in the XY plane. The third curve corresponds to the lowest order symmetric lamb mode. Because of the periodicity imposed by the choice of the unit cell in the XY plane, these dispersion curves fold at the edge of the Brillouin zone. The other curves correspond to higher order Lamb modes. The calculated band structure of the homogeneous aluminum slab compared well with that measured in Fig. 2(a). Upon inserting a periodic array of air holes in the slab, the dispersion curves open up gaps at the edge of the Brillouin zone. Since the T_{XY} mode, S_0 mode and higher order Lamb modes cannot be visualized with the experimental set-up we used over the complete frequency spectrum, the gap observed in Fig. 6(right) corresponds to a gap between the lower and upper branches of the A_0 mode. This calculated gap ranges from a frequency of 834 kHz to 1.42MHz which is in reasonably good agreement with the experimental observation.

CONCLUSIONS

In this paper, we described a new type of phononic crystal produced by patterning holes on thin metal plates. Up to our knowledge, we confirmed for the first time, through laser ultrasonics measurements, that acoustic band gaps were formed by these phononic crystals. Wide multiple acoustic band gaps were evident by the experiments, together with some special band structures, such as narrow pass-bands within certain band gaps. The transition regions from pass band to band gap were very narrow in some situations. We also demonstrated that, the phononic crystal lattices, the material the plates were made off, the plates' thicknesses, the propagating directions of the ultrasound, can all affect the acoustic band gaps structures. Modifying these parameters, therefore, provide valuable approaches to fine tune the band gap structures. The FC phononic crystals are numerically stimulated through a three-dimensional plane wave expansion (PWE) method. The calculations agree fairly well with laser ultrasonics experiments.

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