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Transmission and Focusing of Ultrasound in a Solid Two-Dimensional Phononic Crystal Made from Steel Rods in PDMS

Anatoliy Strybulevych[1†], Charles Croënne[1], J.H. Page[1], Jim Bucay[2], and P.A. Deymier[2]
([1]Physics and Astronomy Dept., Univ. of Manitoba, Winnipeg, Canada;
[2]Materials Science and Engineering Dept., Univ. of Arizona, Tucson, AZ 85721, USA)

1. Introduction

Phononic crystals (PC) are composite materials made of periodic arrays of inclusions embedded in a physically dissimilar matrix. Due to their periodic structure, PCs can exhibit absolute band gaps where the propagation of acoustic or elastic waves is forbidden in all directions [1]. It was first demonstrated for phononic crystals by Yang *et al*. [2] that focusing could be achivied using a flat lens, in which incident waves undergo negative refraction. More recently, direct experimental and theoretical evidence for negative refraction and super resolution focusing has been demonstrated [3,4]. The authors used a simple phononic crystal structure containing stainless steel rods immersed in methanol, with the surface of the crystal covered by a very thin plastic film. For practical applications, it would be interesting to build a PC with a solid matrix that exhibits similar focusing properties.

2. Materials and Methods

Experiments were performed on a PC sample made out of 1.02 mm diameter stainless steel rods and assembled in a triangular 2D crystal lattice with a lattice constant of 1.27 mm. The crystal has 6 layers of rods, with each layer being perpendicular to the ΓM direction. The matrix is made from PDMS, thereby ensuring high density and velocity contrast between the steel rods and the matrix. Thus, most of sound energy is scattered by the rods and concentrated in the PDMS over the range of frequencies investigated.

Two types of ultrasonic experiments were performed. To measure transmission coefficient, the sample was placed between pairs of broadband planar transducers, selected to cover the frequency range between 50 and 750 kHz. To improve the measurement accuracy, the transmitted signals were averaged over 25 lateral positions of the sample.

Imaging experiments were performed using the set-up depicted in **Fig. 1**. With the sample fixed in position, the transmitted field was scanned in a square grid lying in the *x*-*z* plane (41 by 41 steps, with a step length of 0.5 mm in both directions) using a hydrophone. Experiments were performed in a similar frequency range using a focusing transducer with a small aperture to approximate a point source.

For the simulations, the commercial finite element code ATILA was used.

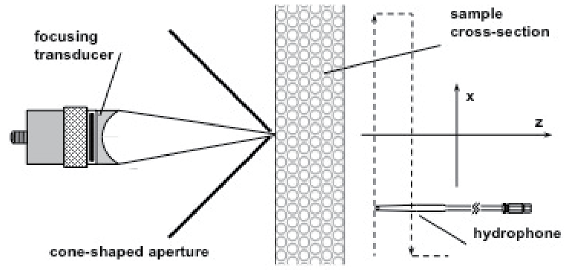

Fig. 1 Experimental set-up.

3. Results and Discussion

The experimentally determined amplitude transmission coefficient (top graph) is compared with simulations (bottom graph) in **Fig. 2**. The experiment shows a maximum in transmission between 250 and 350 kHz, followed by a dip centered near 450 kHz where the lowest band gap is expected. Below 200 kHz, the attenuation is very

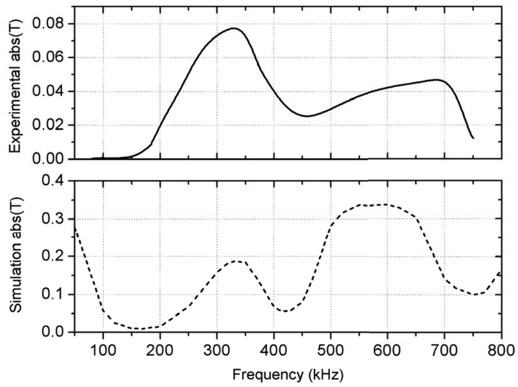

Fig. 2 Experimental (top) and theoretical (bottom) transmission coefficients (ratio of transmitted to input pressures).

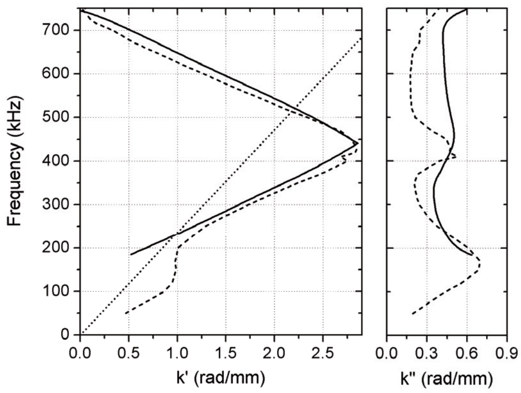

Fig. 3 Experimental (solid lines) and simulated (dashes) dispersion curves (left panel) and imaginary part of the wave vector (right panel). The dotted line is the dispersion curve for water.

large, an effect that may be attributed to the presence of bubbles in the matrix, as well as viscoelastic losses in the PDMS matrix. The effect of bubbles in the PDMS on its acoustic properties was confirmed by separate experiments on PDMS prepared the same way but without the steel rods. The observations may be explained with finite element simulations in which the effect of bubbles on the velocity and attenuation in the matrix is included [5]. Reasonable correspondence between theory and experiment is seen, although the experimental values of the transmission above the band gap are less than expected theoretically, a result that may be caused by imperfections in the crystal structure [4].

Fig. 3 shows the dispersion curve along the ΓM direction, together with the imaginary part of the wave vector to indicate the frequency dependence of the attenuation. At low frequencies, the effect of the bubbles is shown by the theoretical calculations, although the attenuation is too large to see this behavior experimentally. The experimental dispersion curve shows surprisingly little structure near the band gap, which can still be revealed by plotting the derivative of the phase velocity v_p with frequency, as shown in **Fig. 4**. Since $dv_p/df = (1 - v_p/v_g)/k$, this derivative is positive in the band gap region, where the group

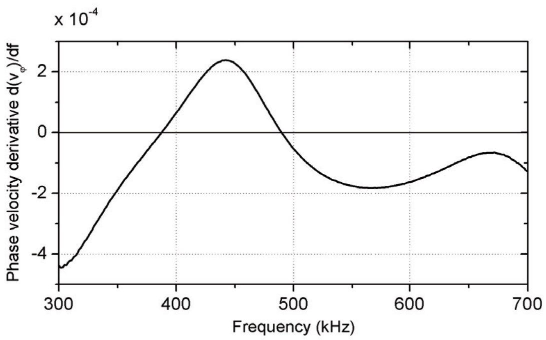

Fig. 4 Phase velocity derivative vs frequency.

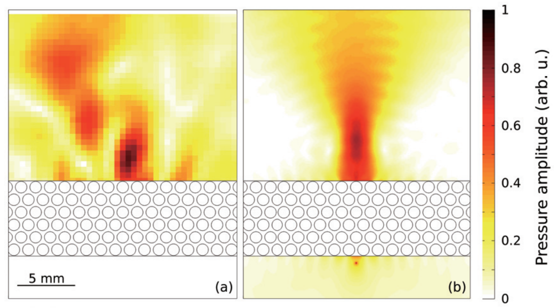

Fig. 5 Pressure field maps: a) experiment, b) simulation. The source in b) was 200 times brighter than shown.

velocity $v_g > v_p$ [1], confirming the existence of a band gap around 450 kHz.

Experimental and simulated pressure field maps, when a point source was placed near the input face of the sample, are presented in **Fig. 5**. The simulation was performed at the index matching frequency of 514 kHz, while the experimental data are shown at 540 kHz. Both experiment and simulation show a clear focus although experimental image is somewhat distorted. The resolution of the images according to the Rayleigh criterion is 0.85λ for the experimental data and 0.8λ for the simulations, indicating that lateral resolution is larger than diffraction limit (λ/2).

4. Conclusion

The focusing of ultrasonic waves by a solid 2D crystal made of stainless steel rods in a PDMS matrix was investigated. The interesting effect of bubble defects in the matrix on the transmission was modeled successfully using finite element simulations. Despite large losses, focusing still can be observed. In order to obtain super resolution, future work will focus on improving the quality of the crystals and reducing the losses.

Acknowledgment

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