PHONONIC CRYSTALS

by S. Yang, J.H. Page, Z. Liu, M.L. Cowan, C.T. Chan and P. Sheng

Recently, there has been a growing interest in studying acoustic and elastic waves in periodic composite materials [1-4]. Due to the periodicity of the structure, there can be ranges of frequency in which waves cannot propagate, giving rise to phononic band gaps. They are analogous to electronic band gaps in metals and photonic band gaps in photonic crystals. Thus such materials are called phononic 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, and the waves can have mixed longitudinal and transverse vector properties. These characteristics, coupled with the potential for developing accurate theoretical models, make phononic crystals promising systems for fundamental studies of wave properties in strongly scattering materials, including phenomena such as localization [5].

Tunneling is one of the most striking ideas in quantum mechanics. Recently, tunneling phenomena have been seen in photonic crystals [6-7]. The tunneling time is independent of sample thickness and the tunneling time of a photon is even less than the time it needs to travel in vacuum, i.e. it travels faster than the speed of light (superluminal phenomena) [6-9]. What happens in phononic crystals? As we all know, sound cannot travel if there is no medium and the sound velocity depends on the actual material. This makes the study of phonon tunneling even more intriguing.

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In this paper, we studied the transport of wave-packets through 3D phononic crystals using a pulsed ultrasound technique.

EXPERIMENTS

Our crystals consist of 0.800-mm-diameter tungsten carbide beads immersed in water. This choice of materials provides high scattering contrast in our ultrasonic experiments, due to the big differences in both density and velocity of the two components (for the tungsten carbide beads, the longitudinal and shear velocities are $v_L = 6.655$ km/s and $v_S = 3.23$ km/s, and the density is $\rho = 13.8 \times 10^3$ kg/m^3, while for water $v_L = 1.49$ km/s and $\rho = 1.0 \times 10^3$ kg/m^3). The beads are assembled in a face-centred-cubic (fcc) crystal structure, and arranged with the beads packed in triangular layers perpendicular to the body diagonal, or [111] direction.

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The sample was placed horizontally on top of a substrate, which was made sufficiently thick so that the multiple reflections in the substrate do not interfere with the sample signals. The transmitted waves through the sample were measured by placing the sample between two transducers and the whole system was immersed in a big water tank.

We also imaged the ultrasonic near-field amplitude patterns by replacing the receiving transducer with a very small, 0.2-mm-diameter hydrophone and scanning the hydrophone in an x-y grid across the surface.

RESULTS

Typical input and transmitted pulses through a phononic crystal consisting of 6 layers are shown in the following graph (Fig. 1). The transmitted pulse extends over a much longer time interval than the short input pulse, due to strong scattering in the crystal. Also the amplitude of the transmitted pulse is about 12 times smaller.

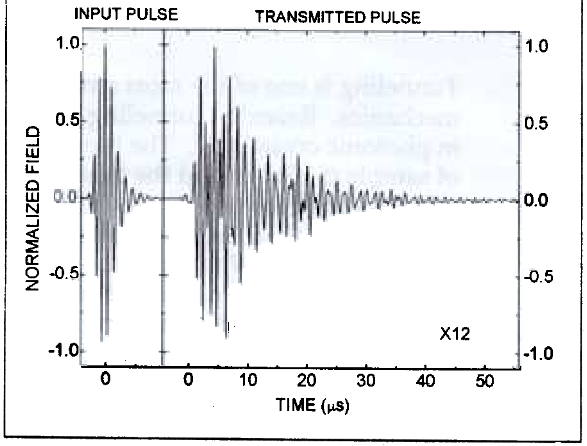

Fig. 1 **Transmitted ultrasonic pulse through a 6-layer sample compared with the input pulse.**

To measure the frequency dependence of the transmitted amplitude, we determine the transmission coefficient from the ratio of the amplitudes of the transmitted and input signals at each frequency using a Fourier transform technique. Fig. 2 compares our data with theoretical calculations using Multiple Scattering Theory [4]. Good agreement is observed. Between about 0.8 and 1.2 MHz, the transmission is very small along the [111] direction (from Γ to L), and the dip in the transmission becomes deeper as the sample gets thicker. The band structure in Fig. 2 also shows that there is a complete gap around 1.0 MHz for our system, which means waves near 1 MHz cannot travel *along any direction*. As a result, if there is a wave source inside the sample, the wave will be localized ("trapped") around the source. Yet, despite the breakdown of wave propagation in the gap, we can still measure a transmitted signal. How do the waves get through the crystal at these frequencies? Do they tunnel through? If they do, the group velocity v_g should increase with sample thickness, since the tunneling time is expected to be independent of the sample thickness and the group velocity is just the ratio of the sample thickness to the time. To answer this question, it is necessary to measure v_g.

To measure the group velocity, we digitally filter the pulses using a narrow Gaussian bandwidth (0.01 MHz). By measuring the time delay for a Gaussian pulse through the sample, we determine the group velocity.

In Fig. 3 we plot the group velocity at 0.945 MHz, which lies inside the gap, versus the sample thickness. This figure

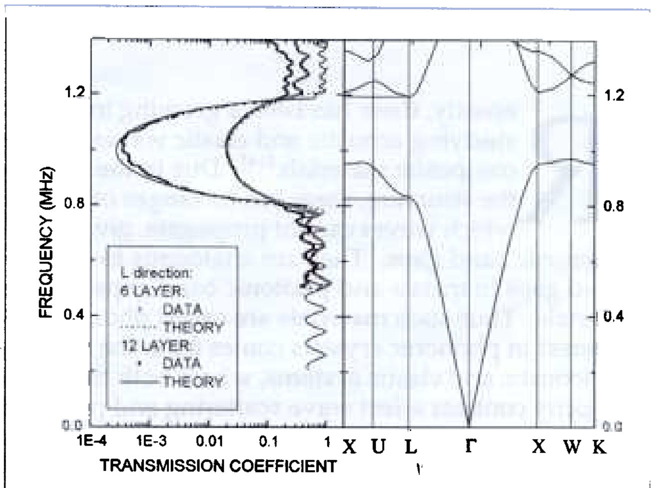

Fig. 2 **Left panel, the theoretical and experimental frequency dependence of the amplitude transmission coefficient for 6 layer and 12 layer samples respectively; right panel, the band-structure for our crystals.**

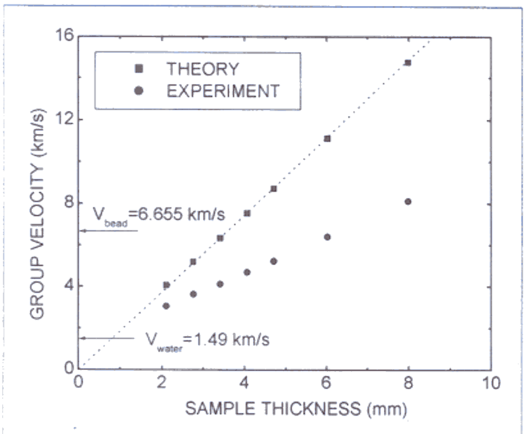

Fig. 3 The group velocity at 0.945 MHz versus sample thickness. The arrows indicate the longitudinal velocity in tungsten carbide and water respectively.

shows clearly that the group velocity in the gap increases with the sample thickness. Both experimental and theoretical values can be bigger than the longitudinal velocity in either component. These results demonstrate convincingly that tunneling is involved, since normally the velocity is independent of the distance travelled. The experimental values in the gap are smaller than the theoretical prediction, due to absorption in real samples that is not included in the theory.

By measuring the transmitted field across the surface of a phononic crystal, we found that the wave amplitude just above the surface is not uniform, but varies in periodic patterns which reveal the underlying structure of the crystal. Our experimental results are in good agreement with the theory. This suggests that analysis of such near-field diffraction patterns could be used to determine crystal structures. We also detected a line defect in one of our crystals, which suggests another potential application - the detection of defects in real crystals, which are usually not perfect and whose properties may be strongly influenced by defects. Such measurements cannot be performed on photonic crystals, as the wavelength of light is much smaller. Thus studying such field patterns for phononic crystals may provide a powerful new approach for learning about wave scattering and propagation inside periodic composite materials.

CONCLUSIONS

In this paper, we presented both theoretical and experimental results for the transport of ultrasound waves through fcc phononic crystals consisting of tungsten-carbide beads in water. We found that there is a complete band gap in this system. Inside the gap, the group velocity increases with the sample thickness, which suggests that tunneling is involved. Our data are explained by Multiple Scattering Theory which gives good overall agreement with the experiments.

Currently, we are working on solid 3-D phononic crystals in which we expect to observe even faster group velocities inside the phononic band gap. These solid crystals are also better suited for developing potential applications of phononic crystals, such as ultrasound filters, sound mirrors, and novel devices that exploit the anomalous refractive index and focusing properties of phononic crystals (e.g. "superlenses" and "superprisms").

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REFERENCES

1. Mârtinez-Sala *et al.*, *Nature*, **379**, 241 (1995).
2. Montero de Espinosa *et al.*, *Phy. Rev. Lett.*, **80**, 1208 (1998)
3. Kafesaki and Economou, *Phy. Rev. B* **60**, 11993 (1999).
4. Liu *et al.*, *Phy. Rev. B* **62**, 2446 (2000).
5. M. Torres *et al.*, *Phy. Rev. Lett.*, **82**, 3054 (1999).
6. A. M. Steinberg *et al.*, *Phy. Rev. Lett.*, **71**, 708 (1993).
7. M. Mojahedi *et al.*, *Phy. Rev. E* **62**, 5758 (2000).
8. T.E. Hartman *J. Appl. Phys.*, **33**, 3427 (1962).
9. R. Landauer *Nature*, **341**, 567 (1989).