Highly directional acoustic wave radiation based on asymmetrical two-dimensional phononic crystal resonant cavity

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The radiation properties of an asymmetrical two-dimensional phononic crystal resonant cavity with a point source inside are investigated experimentally. The resonant cavity is formed by two separated phononic crystals of different thickness, both of which consist of the same square array of steel rods in water. We observe highly directional acoustic wave radiation when a point acoustic source is put inside the cavity. The radiation field has a half-power beam width less than 6°. This design may serve as a highly directional acoustic source in applications. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2217923]

Since photonic crystals may control the propagation of electromagnetic waves in certain directions, they have attracted much attention in recent years.[1–13] Many interesting phenomena such as the enhancement and suppression of spontaneous emission,[1,2] the propagation of photons via hopping over coupled defects,[3,4] and the localization of donor and acceptor modes[5,6] have been suggested and observed. Parallel studies were soon extended to phononic crystals (PCs),[14–20] the elastic and acoustic analogs of photonic crystals. Because of the vectorial characters of elastic waves and the possible coupling between longitudinal and transverse modes, one expects richer physics in elastic waves propagating in PCs. Great progresses have been made in understanding the mechanism of wave propagation in PCs, such as the band gap formation, localized defect modes, acoustic wave tunneling, etc.

It has been demonstrated that a high directivity and radiation enhancement can be obtained by using the photonic crystal to modify the radiation of light source. There are two main approaches to obtain the high directivity by photonic crystals: one is to utilize high density of states at the band-edge frequency[21–23] and the other is to utilize the resonant defect state by introducing a planar defect (cavity) structure.[24,25] As high directivity has been realized by using photonic crystals,[22–25] which may be used for the achievement of new optical devices, it should be a useful practice as well to achieve a directional acoustic source (DAS), applied in novel acoustic devices by using phononic crystals, the elastic and acoustic analogs of photonic crystals. Recently, a highly directional acoustic source has been reported theoretically by making use of the coupling feature of the cavity resonant modes with a line source, placed inside a cavity formed by double two-dimensional (2D) phononic crystals.[26] But there is no experimental realization for such directional acoustic source yet. Here we experimentally demonstrate this highly directional acoustic source by placing a point acoustic source inside a 2D phononic crystal cavity.

The 2D PC that we use in our experiments is a 2D square array of steel rods immersed in water with axis along the z direction. The steel rods have a radius of 1.0 mm and the lattice constant is 1.3 mm. The planar cavity is formed by removing one layer of rods (the fifth layer) in an 11-layer PC sample, the remained structure, as schematically shown in Fig. 1, appears to consist of two uneven crystals, i.e., the front crystal of four layers (above) and the back crystal of six layers (below), which has a separation $d=a$, a being the lattice constant. The crystal length along the x direction, defined as the number of rods on each layer, is $L=60a$. Such an asymmetric design of the cavity, with the front crystal thin and the back crystal thick, serves to suppress the radiation along the backward direction, as considered in Ref. 26. If a symmetric cavity were used, two directional beams would emerge around both $+y$ and $-y$ directions.

Our experimental setup is based on the well known ultrasonic transmission technique. Figure 1 gives a schematic

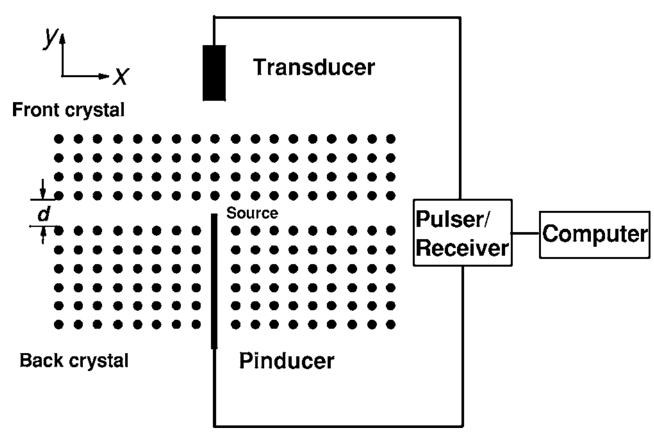

FIG. 1. Schematic representation of the sample and the experimental setup. The cavity consisting of four layers for front crystal and six layers for back crystal. The separation d of the two crystals, measuring the closest distance, being a, a is the lattice constant.

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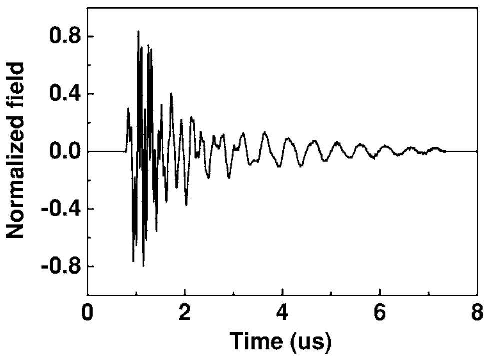

FIG. 2. The pulse signal of the pinducer.

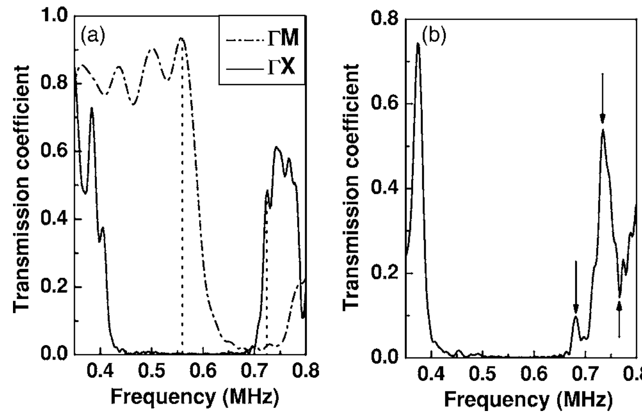

FIG. 4. The amplitude transmission coefficients for (a) the ten-layer PC system without cavity and (b) the PC system with cavity, as shown in Fig. 1. The two vertical dashed lines in (a) delimit the full band gap, and a resonant transmission peak appears in the band gap for the system with cavity, see (b).

diagram of the experimental setup, showing the position of the phononic crystal with respect to the pinducer (served as a point source) and the detecting transducer. The diameter of the pinducer is 1.5 mm and the central frequency of it is about 5 MHz. Figure 2 gives the pulse signal of the pinducer. The entire assembly was immersed in water. A pulser/receiver generator (Panametrics model 5900PR) produces a short duration pulse. The pulses transmitted through the sample were detected by an immersion transducer, which has a central frequency of 1 MHz and a diameter of 12.5 mm. Although it is quantitatively not very accurate to use a 12.5 mm transducer to measure the field distribution, which actually gives the average of the field on the transducer surface, however, the measurement in this way does not overestimate the directivity of the radiation field distribution or the angular distribution of the radiation. The pulses were then transformed into the frequency domain using a fast-Fourier transformed (FFT) technique, allowing the wave amplitude for each frequency component to be plotted as a function of position in the detecting plane.

The frequency of resonant cavity state can be determined by measuring the transmission coefficient of the perfect phononic crystal without cavity and the phononic crystal with cavity, respectively. When measuring the transmission coefficient, we use two planar immersion transducers with the central frequency of 0.5 MHz as the generating transducer and receiving transducer. Figures 3(a) and 3(b) give the pulse signal and the frequency spectrum of the transducers. To ensure a good approximation to a plane wave incident normally onto the PC slabs, the generating transducer is placed at a comparatively far distance away from the sample. The input pulse is determined by measuring the pulse transmitted through water alone, without sample in place. We determine the transmission coefficient from the amplitudes of the transmitted and input signals at each frequency using a Fourier transform technique: $|T(f)|=A_{\mathrm{trans}}(f)/A_{\mathrm{in}}(f)$. Figure 4(a) gives the transmission coefficient of the ten-layer perfect phononic crystal without cavity, which exhibits a full band gap with frequency from 0.57 to 0.72 MHz. Figure 4(b) shows the transmission coefficient of the sample with cavity, as shown in Fig. 1. As observed, there is a narrow resonant peak appearing at the frequency of 0.68 MHz inside the full band gap, resulting from the coupling of the incident plane waves with the cavity state of the double PC cavity. At the resonance frequency, the vibration of pressure field is strongly localized inside the defect with a form of standing wave and exponentially attenuates into the double PC slabs on both sides. An acoustic source put inside the defect can strongly couple with the resonant defect state and give rise to highly directional radiation, as predicted by theory.[26] Here below, we present the experimental demonstration for this effect.

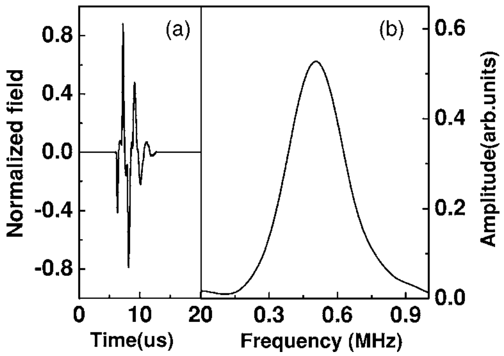

FIG. 3. The pulse signal and the frequency spectrum of the transducer used in the transmission coefficient measurement. (a) pulse signal and (b) frequency spectrum.

We measured the far-field amplitude distribution for the PC cavity system at the cavity resonant frequency of 0.68 MHz, as shown in Fig. 5. We found that the acoustic field rapidly attenuates outside the cavity structure along the x direction, which means that the energy can hardly radiate along this direction. However, there exists a very strong radiation in the front of the double cavity within a very narrow angular range in the $+y$ direction. The results are in excellent agreement with the prediction by calculation in Ref. 26. The high directivity comes from the coupling of cavity state with the y plane wave component of radiation source.

To further demonstrate the angular distribution of power emitted from the source embedded inside the PC cavity, we measured the intensity distribution of power versus the angle for the resonant frequency in the gap (0.68 MHz) and another two frequencies nearby but in the passband (0.74 and 0.76 MHz) which are denoted by arrows in Fig. 4(b) at the far field about $115a$ from the acoustic point source. The measured results are presented in Fig. 6, which clearly show that the radiation is almost wholly confined within the narrow angular regions along the $+y$ direction at 0.68 MHz, but obviously broadened in angular distribution for frequencies outside the band gap. The half-power angular widths can be

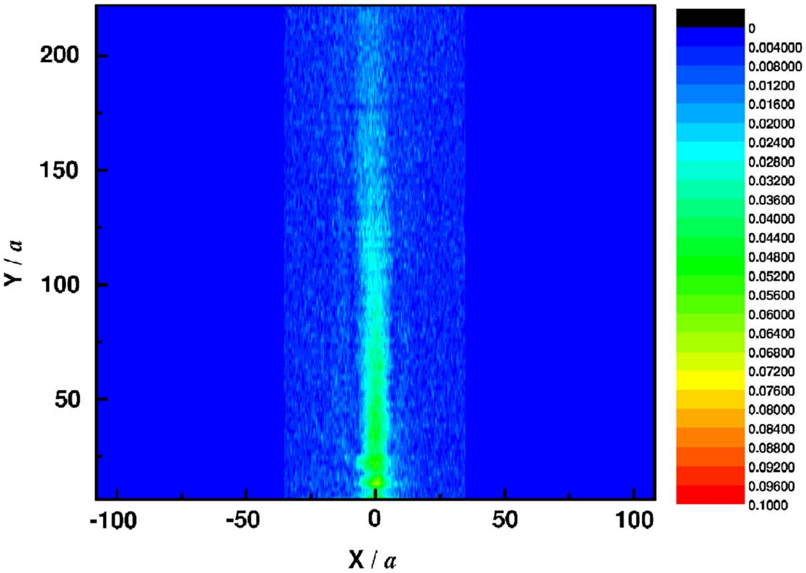

FIG. 5. (Color online) Measured amplitude field distribution of the PC system.

easily estimated as 5.8°, which further demonstrates that a very high directional acoustic source can be obtained by utilizing the resonant cavity state.

In conclusion, introducing planar cavity in a phononic crystal allows resonant cavity state created within the full band gap. This kind of state can strongly couple with the acoustic source put inside the cavity and give rise to highly directional radiation. For a cavity structure formed by two phononic crystal slabs of different thickness, the point source placed inside the cavity radiates the energy through the thinner phononic crystal and along the surface normal direction of cavity surface within very narrow angular regions. Radiation field with half-power beam width of less than 6° is obtained.

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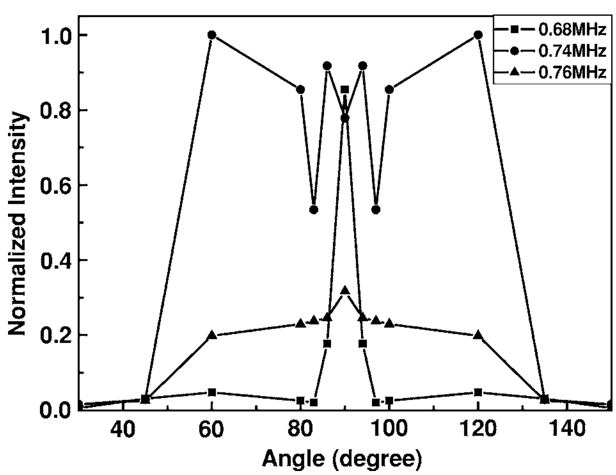

FIG. 6. Measured far-field radiation patterns for various frequencies vs angle.

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