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Angular control of acoustic waves oblique incidence by phononic crystals based on Dirac cones at the Brillouin zone boundary

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ABSTRACT

This study investigated the angular control of incident acoustic waves for total transmission and reversed reflection using phononic crystals (PnCs). The Dirac point appears at the Brillouin zone boundary. The position of the Dirac point regularly changes with the length–width ratio of rubber rods, which makes the transmission angle adjustable. These structures could be applied to an acoustical 0 or π phase modulator by adjusting the number of layers of PnCs (even or odd). The angular control in the reflection domain can be achieved by adding a meta-surface at the boundary of the PnC.

1. Introduction

In recent years, the Dirac cone has been a hot research topic in many disciplines. Based on the degeneracy of Bloch eigenstates, types of liner dispersion relations are called Dirac-cone dispersion [1]. Recently, Dirac conical dispersions such as phononic crystals (PnCs) [2], photonic crystals (PtCs) [3,4] and metamaterials [5] were found in classical wave systems. The Dirac dispersion relations have two main types [6], a Dirac-like cone (located in the center of the Brillouin zone) [7,8], and a Dirac cone (appearing on the boundary of the Brillouin zone) [9,10]. The Dirac cone demonstrates many intriguing physical properties, including pseudo-diffusion transport [11,12], edge state [13], and Zitterbewegung oscillations [14,15]. The Dirac-like cone also has demonstrated some novel wave propagation behaviors like acoustic cloaking [8,16], tailoring of the wave front [17,18], and perfect lens [19], which are related to a zero effective refractive index (the effective mass density and the reciprocal of the effective bulk modulus equal to zero) [8,9,20–22]. These particular Dirac point properties were discovered by studying the vertical incident wave. The oblique incident wave also exhibits unique characteristics such as thane enhancement effect of the local field near the Dirac point in PtCs [23]. Recently, Xu et al. [24] investigated the angular selection for oblique incidence optical waves in both transmission and reflection by position-varying Dirac conical dispersion in PtCs. Their finding is useful for application in phase modulation of optical waves [24]. However, few publications focus on oblique incidence for PnCs with a Dirac cone.

In this paper, we demonstrate how to achieve angular control for oblique incident acoustic waves for both total transmission and reversed reflection in PnCs. The PnCs consist of rubber rods arranged in square lattice in water background. A Dirac point is found at the Brillouin zone boundary. By changing the length–width ratio of the rubber rods, the Dirac point is found to move along the *XM* direction, which makes the unity transmission angle selectable, not for normal incident wave, but for oblique incident wave. Different from Brewster's angle mechanism, the functionality of angular control does not rely on the refraction indices of the background medium. At the frequency of the Dirac point, the total transmission phenomenon is observed at a particular incident angle related to the Dirac point, irrespective of the thickness of the PnCs. However, the transmission will gradually become weak unto zero when deviating from particular angle as a result of the band gap. Interestingly, at that particular incident angle, the transmitted acoustic wave takes 0 or π phase shifting through even or odd number PnC layers. Unlike the PtC systems, the systems in this study merely require two components (rubber and water) to achieve phase shifting. Finally, by establishing a new acoustic

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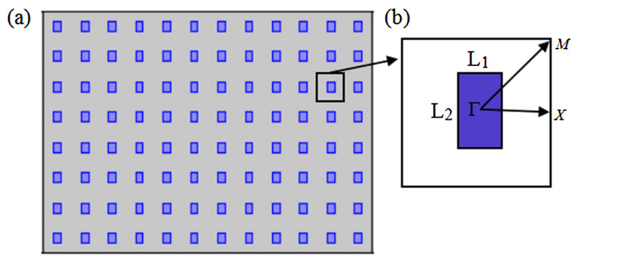

Fig. 1. (a) A two-dimensional PnC composed of rectangle rubber rods arranged as a square lattice in water. (b) The unit cell (width L_1 and length L_2) of the square lattice PnC.

meta-surface with a $\pi/2$ phase change on the surface of the PnC, angular selection can be achieved in the reflection domain.

2. Models and calculations

We designed a two-dimension (2D) PnC consisting of rectangular rubber rods arranged as a square lattice in water, as shown in Fig. 1(a). Fig. 1(b) shows the unit cell of the square lattice PnC, where L_1 and L_2 are the length and width of the rubber rods, respectively, and a is the lattice constant of PnC. The material parameters are set as below: the density is $\rho_r = 1300$ kg/m^3, the Lame constant is $\lambda_r = 2.08 \times 10^8$ N/m^2 and $\mu_r = 5.2 \times 10^7$ N/m^2 for rubber, the density is $\rho_0 = 1000$ kg/m^3 and the Lame constant is $\lambda_0 = 2.22 \times 10^9$ N/m^2 for water. Two different models are considered, model one and model two. For model one, $L_1 = L_2 = 0.38a$. For model two, $L_1 = 0.27a$, $L_2 = 0.52a$. We use the Finite Element Method (FEM) in COMSOL Multiphysics to calculate the dispersion relations, transmission sound field, and reflection sound field of model one and model two. We found that the shear wave velocity of the rubber does not affect the physical nature of our system.

Fig. 2(a) shows the dispersion relations of the two models, where the blue and red hollow circles represent model one and model two, respectively. All results are plotted in terms of the dimensionless frequency $\omega_a/2\pi\nu_0$, ν_0 is the sound velocity of the background medium. For both models, the fourth and fifth bands cross at the XM direction, forming the Dirac point. Interestingly, their corresponding frequencies are close to the same value [$\omega_A = 0.7671(2\pi\nu_0/a)$, $\omega_B = 0.7677(2\pi\nu_0/a)$, so $\omega_A \approx \omega_B$]. It implies that at the frequency of Dirac point, acoustic unity transmission angle can be controlled by selecting the size of the rubber rods. Figs. 2(b) and 2(c) demonstrate the pressure field distribution of the doubly degenerate eigenstates at the Dirac point for model one. Obviously, one of the doubly degenerate eigenstates is the dipolar mode shown in Fig. 2(b), and the other is the quadrupole mode showed in Fig. 2(c). The deep red and blue represent the positive and negative maximum values of the pressure sound field, respectively. So the linear dispersion relation shown in Fig. 2(a) is caused by the interaction between the dipole mode and the quadrupole mode.

3. Results and discussion

3.1. Total transmission properties for the oblique incident

At the frequency of Dirac point, these structures exhibit a very interesting feature of acoustic control with angle selection. We consider the finite phononic crystal sandwiched by one type of medium. The illustration of the acoustic wave incident is shown in Fig. 3(a). Regions I and III are consistent with the material of the background medium (water), Region II represents a PnC. L is the layer of the PnC, θ is angle of sound incidence on PnC. The upper and lower boundaries are set as Floquet periodic conditions. The incident acoustic wave transmits from region I into

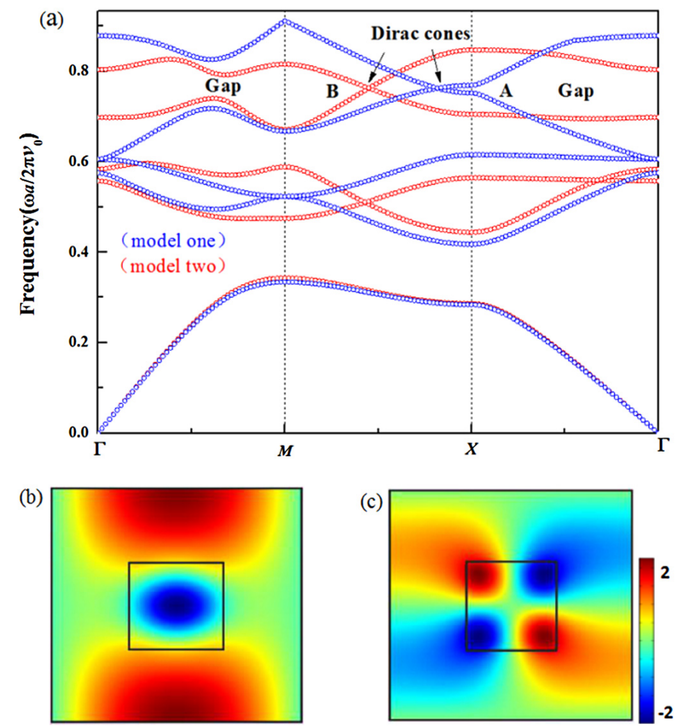

Fig. 2. The dispersion relations of two models and the pressure field distribution of Bloch eigenstates of model one. (a) The dispersion relations of model one (blue hollow circles) and model two (red hollow circles). A and B are the Dirac cones in model one and model two, respectively. There is a doubly degenerate state at the Dirac point for model one. (b) Dipole mode and (c) Quadrupole mode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

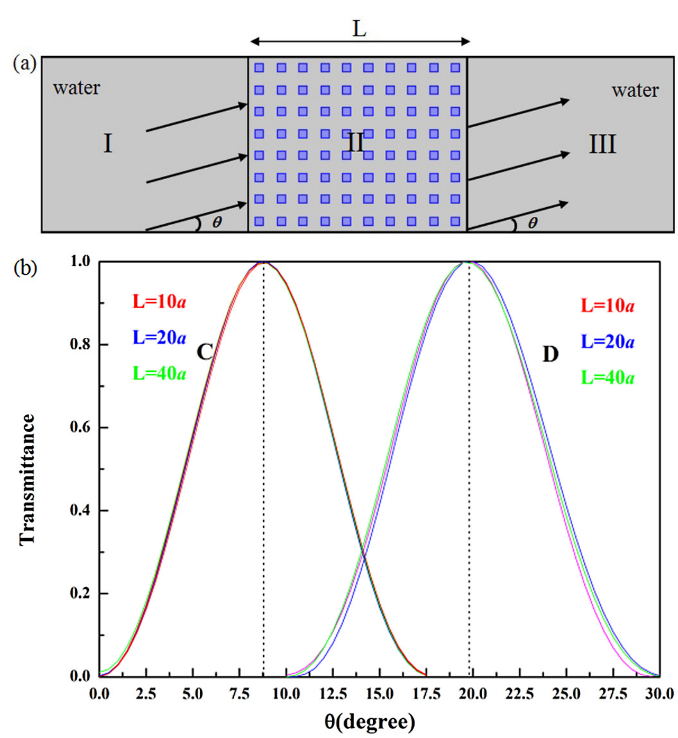

Fig. 3. (a) Illustration of angular control of sound waves incident on PnC. (b) The transmission spectrum for model one and model two with different layers. The solid line C corresponds to model one at Dirac point frequency $\omega_A = 0.7671(2\pi\nu_0/a)$. The solid line D corresponds to model two at Dirac point frequency $\omega_B = 0.7677(2\pi\nu_0/a)$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)