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Acoustic extraordinary refraction in layered sonic crystals with periodic slits

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ABSTRACT

In this paper, we present a study of acoustic wave propagation in layered sonic crystals (SCs) with periodic slits, and demonstrate the extraordinary acoustic refractions induced by acoustic backward and forward wave effects in SCs. By tuning the parameters of geometry structures and incident angles of acoustic waves, the positive, negative and zero acoustic refractions are demonstrated respectively. Taking advantage of the exotic acoustic refraction, we present the splitting of acoustic beams through the layered SCs, which is a new method to achieve acoustic beam splitting.

Introduction

In recent two decades, the acoustic artificial materials have attracted desirable attention due to their strong applications [1–4]. On the basis of sonic crystals (SCs), numerous applications and devices have been designed to achieve many abnormal acoustic phenomena and functions [5–8]. One of the most interesting and exotic phenomena and functions is acoustic negative refraction by flat sonic crystals [9–13]. Because of the extensive research interest and applications, the acoustic negative refraction based on sonic crystals has been comprehensively studied in these years [14–16], also incurred the research of acoustic zero refraction and positive refraction on the basis of sonic crystals [17,18]. The acoustic negative refraction of sonic crystals can be achieved both by the acoustic waves backward effect [8,15,16] and forward effect [4,9,14]. Recently, the layered metamaterial with periodic perforated plates has attracted much interesting due to its high anisotropy [16,19,20]. The acoustic negative refraction and focusing by forward and backward effects have been extensively studied based on the layered metamaterials [16], which are mainly restricted in relatively low frequency. In this paper, we study the acoustic refractions in a wide frequency range through the layered sonic crystals with periodic slitted plates. We demonstrate different acoustic refractions by tuning the parameters of the layered sonic crystals. Further, we study the beam splitting of acoustic waves through the sonic crystal by using the exotic refraction.

Results and discussion

The layered sonic crystal under study is schematically shown in Fig. 1, which consists of periodic steel plates with periodic slits immersed in water. The thickness of the plate is t, the width of the slits is d, the period of the plates is p_z (along z direction) and the period of the slits is p_x (along x direction). The material parameters are as follows: mass density $\rho = 7760\ \mathrm{kg/m^3}$, longitudinal acoustic velocity $c_p = 6010\ \mathrm{m/s}$ and transverse acoustic velocity $c_s = 3320\ \mathrm{m/s}$ for steel; mass density $\rho_0 = 1000\ \mathrm{kg/m^3}$, longitudinal acoustic $c_0 = 1490\ \mathrm{m/s}$ for water. Specifically, for simplifying the structure parameters in the study, we set the slits period $p_x = 1$ mm, the slits width $d = 0.5$ mm, and the plates thickness $t = 0.4$ mm. The period p_z for plates can be tuned to achieve different acoustic refractions induced by acoustic forward and backward wave effects, which will be analyzed in detail below. Throughout the study, we use the Finite Element based software COMSOL Multiphysics to perform the band structures, transmissions and filed distribution calculations.

Firstly, we investigate band structures of two SCs with different structure parameters structure $p_z/p_x = 1.88$ and $p_z/p_x = 1.10$ respectively, and the results are shown in Fig. 2. As is well known, the propagation of acoustic waves can be determined by the phase velocity ($\boldsymbol{v_p} = \omega\boldsymbol{k}/|\boldsymbol{k}|^2$) and the group velocity ($\boldsymbol{v_g} = \nabla_{\boldsymbol{k}}\omega$). We select the frequency of acoustic waves $f = 0.61(c_0/p_x)$ for example to demonstrate the forward and backward wave effects in the system, as shown in Fig. 2. For the system $p_z/p_x = 1.88$ [Fig. 2(a)], we can see that the wave vector along Γ–X_2 direction increases as the frequency increases near the frequency $f = 0.61(c_0/p_x)$ (see the third

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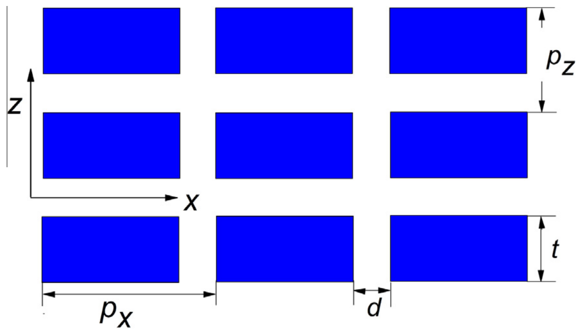

Fig. 1. Schematic demonstration for the layered sonic crystal with periodic slit plates.

band), which means that the gradient of equifrequency contour (EFC) in the band structure is away from the Γ point. Further, it indicates the $\boldsymbol{v_g}\cdot\boldsymbol{k} > 0$. Since the direction of group velocity is always forward (positive), thus based on the formula ($\boldsymbol{v_g}\cdot\boldsymbol{k} > 0$), the wave-vector direction is also forward (positive). Therefore, the propagating direction of group velocity and phase velocity of the acoustic waves in SC is the same, which is known as forward wave effect. However, for the system $p_z/p_x = 1.10$ [Fig. 2(b)], we can obtain another picture of acoustic wave propagation in the layered SC. We can see that the wave vector along Γ–X_2 direction decreases as the frequency increases near the frequency $f = 0.61$ (c_0/p_x) (see the second band), which means that the gradient of EFC in the band structure is pointing to Γ point, indicating the $\boldsymbol{v_g}\cdot\boldsymbol{k} < 0$. The group velocity direction and phase velocity direction are opposite, which causes a negative phase velocity for positive group velocity. This is the backward wave effect.

In order to further understand the forward wave and backward wave effects described above, we calculate EFCs of the selected frequency for the two systems. The results are shown in Fig. 3 (a) and (c) respectively. As we mentioned above, the propagation of acoustic waves is determined by the phase velocity and group velocity. The phase velocity describes the evolution of equal-phase planes in a plane wave mode, and the group velocity describes the direction and speed of energy propagation. In the sonic crystal, the direction of phase velocity is the same as that of wave vector $\boldsymbol{k}$, while the direction of group velocity is normal to the EFC in wave-vector space. Generally speaking, Bloch modes in the SC can always be exited with acoustic plane waves incident from outside. In this process, the parallel component of the phase velocity is conserved across the interface following the Snell's law of refraction: $\boldsymbol{k_2}\cdot\sin\theta_i = \boldsymbol{k_1}\cdot\sin\theta_r$. Here, $\boldsymbol{k_2}$ is the refracted Bloch wave vector, $\boldsymbol{k_1}$ is the incident vector, θ_i is the angle of incidence, θ_r is the angle of refraction [21]. As shown in Fig. 3(a) and (c), for the incident waves with 30°, the blue circles are the EFC in water, and the red curves are the EFCs of the sonic crystal. $\boldsymbol{k_1}$ and $\boldsymbol{S_1}$ are the wave vector and group velocity of the incident waves respectively, which have the same direction. Based on the parallel-k-conservation rule, the $\boldsymbol{k_2}$ and $\boldsymbol{S_2}$ in Fig. 3 are the wave vector and group velocity of the refracted Bloch waves respectively. We can see that, for the system with $p_z/p_x = 1.88$, the directions for the phase velocity and group velocity go forward (forward wave effect). But for the system with $p_z/p_x = 1.10$, the group velocity goes forward, while the phase velocity goes backward (backward wave effect). Interestingly, these two refractions are both negative. In order to verify the analysis above, we calculate the field distributions for a Gaussian beam incident into the sonic crystals with the incident angle of 30°, and show them in Fig. 3(b) and (d) respectively. We can see that the propagations of the acoustic waves in the sonic crystals are negatively refracted, as expected.

In Fig. 3(a), we can observe that the EFC in the upper part with k_x ranging from 0 to $0.25(2\pi/p_x)$ is convex. Importantly, the tangent of this part EFC changes from k_x positive direction into k_x negative direction. Based on the analysis above, we can conjecture that for the incident waves with k_x ranging from 0 to 0.25, the acoustic refraction induced by the sonic crystal would change from positive refraction into negative refraction under the forward effect. In order to verify the conjecture, we calculate the pressure field distributions with different incident angles. For a smaller incident angle (23°), a positive refraction is observed in Fig. 4(a). Whereas we increase the incident angle to 27°, the refractive angle becomes very small and is almost close to zero [Fig. 4(b)]. Then, continuing to increase the incident angle, the negative refraction would be occurred, as discussed in Fig. 3(a). Similarly, we can observe that, for the system with $p_z/p_x = 1.10$ and the EFC with frequency 0.61 (c_0/p_x) [Fig. 3(b)], the lower part with k_x ranging from 0 to 0.25 is convex. The tangent changes from k_x positive direction into k_x negative direction. Therefore, for the incident angles increasing from 0, the refraction of sonic crystal will change from positive refraction to zero refraction, and then negative refraction under the backward effects. In Fig. 4(c) and (d), we calculate the field distributions for incident angle 23° and 26°. As expected, we can observe the positive, nearly zero. Again, for continuing to increase the incident angle, the negative refraction is occurred as shown in Fig. 3(b). When the incident angle continually increases to the angle that

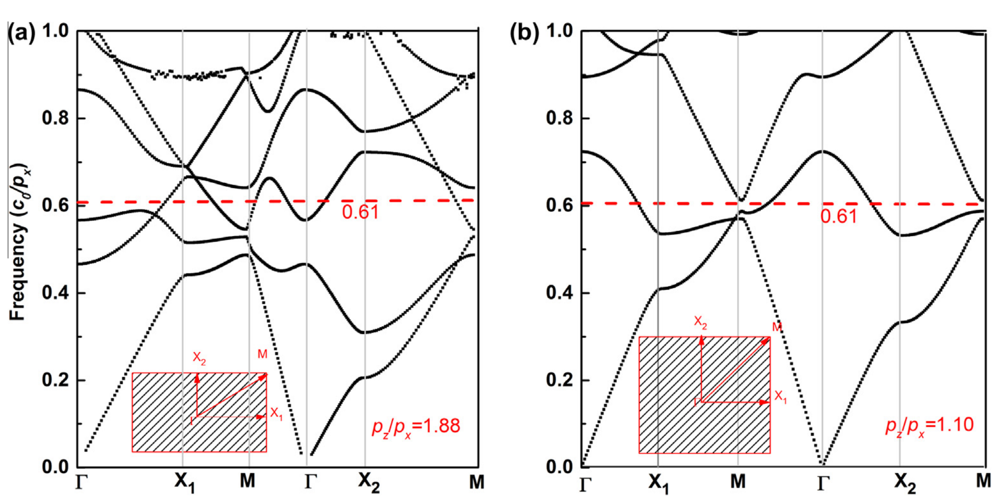

Fig. 2. Band structures for SCs with two parameter set: (a) $\{p_z, p_x\} = \{1.88, 1\}$, and (b) $\{p_z, p_x\} = \{1.10, 1\}$. The insets represent the first Brillouin zone.