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Broadband asymmetric acoustic transmission through an acoustic prism

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ABSTRACT

Narrow bandwidth and complex structure are the main shortcomings of the existing asymmetric acoustic transmission devices. In this letter, a simple broadband asymmetric acoustic transmission device is proposed by using an acoustic prism filled with xenon gas. The sound pressure field distributions, the transmission spectra, and the prism angle effect are numerically investigated by using finite element method. The proposed device can always realize asymmetric acoustic transmission for the wave frequency larger than 480 Hz because the wave paths are not influenced by the wave frequencies. The asymmetric acoustic transmission is attributed to normal refraction and total reflection occur at different interfaces. Besides, relatively high transmission efficiency is realized due to the similar impedance between the acoustic prism and background. And the transmitted wave direction can be controlled freely by changing the prism angle. Our design provides a simple method to obtain broadband asymmetric acoustic transmission device and has potentials in many applications, such as noise control and medical ultrasound.

1. Introduction

The asymmetric acoustic transmission (AAT) devices can realize the asymmetric transmission of acoustic waves, and have attracted growing attentions due to its potential applications in various fields, such as noise control [1] and medical ultrasound [2].

Initially, the AAT devices were realized by breaking the time reversal symmetry based on nonlinear mechanism. Liang et al. [3–5] theoretically and experimentally investigated the asymmetric acoustic transmission in an AAT device consisting of a strongly nonlinear medium and a superlattice. However, the nonlinear system suffers from many disadvantages, such as frequency change, low conversion efficiency, and complex structure [6]. To overcome these obstacles, many researchers have devoted to designing linear AAT devices by breaking the spatial inversion symmetry and various structures are utilized, such as acoustic gratings [7–10], phononic crystals [11,12], and acoustic metasurfaces [13–16].

Although the existing AAT devices can realize asymmetric acoustic transmission, it is apparent that they have several common drawbacks which will restrict their potential applications. First, the AAT devices are valid only at a certain frequency or within some narrow frequency ranges. The AAT device proposed by Zhu et al. [17] can take effect only at the designed frequency, and that designed by Song et al. [18] is effective only within two frequency ranges. Second, the structures of these AAT devices are complicated. Li et al. [19] used gradient-index structure and Wang et al. [20] used acoustic metasurfaces to design AAT devices with broad bandwidth, but these models all have extremely complicated structures. Therefore, it is necessary to explore a new method to design AAT device with broad bandwidth and simple structure. In optical field, asymmetric transmission can be realized by prisms based on photonic crystals. Gundogdu et al. [21] demonstrated the asymmetric transmission in a single photonic crystal prism and a single solid uniform prism. Specially, the asymmetric transmission in homogeneous prism with relative permittivity larger than unity is attributed to refraction at the wedge in backward case and nearly total internal reflections at the wedge in forward case. Wang et al. [22] realized unidirectional light transmission by using a heterojunction structure composed of two square-lattice photonic crystals. Later, Oh et al. [23] investigated the one-sided elastic wave transmission by using an inverted bi-prism phononic crystal based on refraction and total reflection. Inspired by prisms used to realize asymmetric transmission, we propose an acoustic prism to

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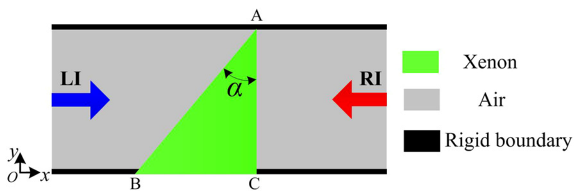

Fig. 1. Schematic view of the proposed AAT device composed of an acoustic prism. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

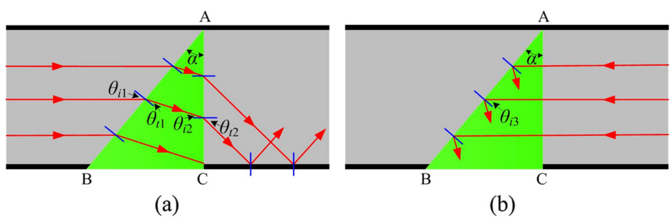

Fig. 2. Schematic views of the wave paths when the acoustic waves are incident from (a) left and (b) right. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

realize asymmetric acoustic transmission and our proposed mechanism derives from that proposed by Gundogdu.

In this paper, we design a simple AAT device by using an acoustic prism filled with xenon gas. The sound pressure field distributions, the transmission spectra, and the prism angle effect are numerically analyzed, and the simulations are performed by COMSOL Multiphysics software based on finite element method [24]. Compared with the previous AAT devices, the proposed AAT device is effective within a very broad frequency range, which is important in practical applications. The designed device has a simple structure and is easy to demonstrate experimentally. In particular, the proposed device has a wider frequency range than the design shown in reference [16], and the device is simpler than our group's previous design in reference [20]. Besides, relatively high transmission efficiency can be realized, and the directions of the transmitted waves can be controlled freely by changing the prism angle. Our mechanism provides a simple method to design broadband AAT devices and have potential applications in many fields, such as noise control and medical ultrasound.

2. Model and design

The broadband AAT device is designed by using an acoustic prism filled with xenon gas, the schematic view of the proposed AAT device is shown in Fig. 1. The acoustic prism is a structure with right triangle section (labeled with "ABC") and the prism angle is α. As the acoustic prism is filled with xenon gas and immersed in air, separation method is taken to prevent the mutual gas diffusion. The different regions of xenon and air can be separated by using polyethylene films (thin enough to be regarded as transparent to acoustic waves) in the experiment, which have been used successfully in the previous experiment [5]. The acoustic prism can modulate the directions of the transmitted waves freely according to the classical Snell's law. The rigid boundaries shown in Fig. 1 can completely reflect the incoming waves. To simplify the wave paths, boundary BC is set as absorptive boundary to completely absorb the incoming waves. And the absorptive boundary can be realized by metamaterials or traditional materials, such as spongy, porous or fiber materials. Besides, the blue and red arrows indicate the incident wave directions of left incidence (LI) and right incidence (RI), respectively. When the plane waves are incident from left and right, the wave paths denoted by red arrow lines are shown in Fig. 2(a) and (b), respectively. As shown in Fig. 2(a), the plane wave of LI impinges on the interface AB obliquely and normal refraction occurs at interfaces AB and AC. The wave passes through the acoustic prism and then impinges on the rigid boundaries, so the plane wave of LI can pass through the proposed device, which can be identified as "positive direction". However, in Fig. 2(b), the plane wave of RI impinges on interface AC normally and passes the interface horizontally. Then total reflection occurs at interface AB because the incident angle θ_{i3} is larger than the critical angle. Therefore, the plane wave of RI cannot pass through the proposed device, which can be identified as "negative direction". As a result, the proposed device can realize asymmetric acoustic transmission when normal refraction and total reflection occur at different interfaces.

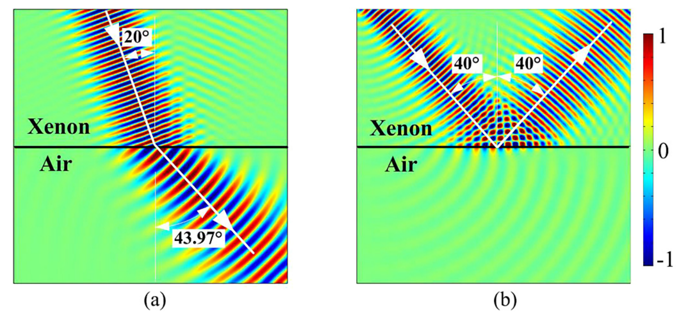

Fig. 3. Sound pressure field distributions when a Gaussian beam of 8 kHz is incident from xenon gas to air with incident angle (a) 20° and (b) 40°. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

It's necessary to point out that the prism angle α need to be designed carefully in order to achieve asymmetric acoustic transmission. The sound velocities in xenon and air are $c_X = 169$ m/s, $c_A = 343$ m/s, respectively. The acoustic impedances of xenon and air are $Z_X = 996.1$ Pa · s/m, $Z_A = 442.5$ Pa · s/m, respectively [25]. The refractive indexes of xenon gas and air are $n_X = 2.03$, $n_A = 1$, respectively. When the acoustic wave impinges on the interface between two gases with different refractive index, refraction will occur and obey the classical Snell's law [26]:

$$\sin(\theta_i) \cdot n_i = \sin(\theta_t) \cdot n_t, \tag{1}$$

where θ_i and θ_t are the incident angle and refraction angle, respectively. n_i and n_t are the refractive index of incident medium and transmitted medium, respectively.

When the acoustic wave impinges on the interface between xenon gas and air, there are two cases. When the acoustic wave is incident from air into xenon gas, the normal refraction can always occur and the refraction angle is smaller than the incident angle. Conversely, when the acoustic wave is incident from xenon gas into air, the refraction angle is larger than the incident angle and the critical angle for total reflection is $\theta_c = \sin^{-1}(c_X/c_A) = 29.5°$. When a Gaussian beam of 8 kHz is incident from xenon gas to air with different incident angles, the sound pressure field distributions are shown in Fig. 3. If the incident angle ($\theta_i = 20°$) is smaller than the critical angle θ_c, the normal refraction occurs, as shown in Fig. 3(a). But if the incident angle ($\theta_i = 40°$) is larger than the critical angle θ_c, the total reflection occurs, as shown in Fig. 3(b).

According to the different performances at the interfaces between xenon gas and air, we design this kind of AAT device. For LI case, the incident angle at interface AB is $\theta_{i1} = \alpha$, the refraction angle at interface AB is $\theta_{t1} = \sin^{-1}(\sin(\theta_{i1}) \cdot n_A/n_X)$, the incident angle at interface AC is $\theta_{i2} = \alpha - \theta_{t1}$, the refraction angle at interface AC is $\theta_{t2} = \sin^{-1}(\sin(\theta_{i2}) \cdot n_X/n_A)$. According to the designed wave path of LI case that normal refraction occurs at interface AC, the incident angle at interface AC needs to satisfy $\theta_{i2} < \theta_c$, that is $\alpha < 53°$. For RI case, the incident angle at interface AB is $\theta_{i3} = \alpha$.