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Broadband acoustic diode by using two structured impedance-matched acoustic metasurfaces

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An acoustic diode (AD) is proposed and designed based on a mechanism different from the previous designs by using two structured impedance-matched acoustic metasurfaces. This AD can realize unidirectional acoustic transmission within a broad band with high transmission efficiency due to the impedance-matching condition while allowing other entities such as objects or fluids to pass freely. What is more, the backtracking waves that come from the incoming waves can be efficiently prevented and cannot disturb the source. The acoustic pressure field distribution, intensity distribution, and transmission efficiency are calculated by using the finite element method. The simulation results agree well with the theoretical predictions. Our proposed mechanism can experimentally provide a simple approach to design an AD and have potential applications in various fields such as medical ultrasound and noise insulation. Published by AIP Publishing.
the beam is allowed to pass the MSCS with high transmission efficiency. Similarly, the lower part can also pass the MSCS. As a result, a plane wave of left incidence can pass the MSCS without any obstacles, which can be seen as the “positive incidence (PI).” Conversely, when a plane wave of right incidence passes the AMS, is divided into two parts with the refraction angle of 45° at 6860 Hz as indicated by the red arrows shown in Fig. 1(a), and reaches the top and bottom edges, the two parts of the beam are absorbed completely by the top and bottom absorptive boundaries, respectively. Hence, acoustic wave cannot pass the MSCS to the left, which can be regarded as the “negative incidence (NI).” The schematic of special acoustic performances of the proposed MSCS is shown in Fig. 1(b). For a rigid boundary, the incoming waves are reflected normally. However, for an absorptive boundary, the incoming waves are absorbed completely. For the AMS, the transmitted waves are manipulated at will, and the refraction angle is the arbitrary value (45° in this model). These structures lead to the AD effect of the MSCS.

We will design and realize the AMS with periodic cut-through slits in a thin plate. Two inert gases (argon and xenon) can be used to fill cut-through slits to realize the impedance-matched AMS as shown in Fig. 2(a). Here, the width of each slit is \( b = 8 \) mm, the thickness is \( h = 46 \) mm, and the separation between two neighboring slits is \( c = 0.8375 \) mm. It is necessary to point out that the different regions of argon and xenon can be separated by transparent thin polyethylene films. When a plane wave passes through one unit cell, the phase accumulation can be expressed as follows:

\[
\Phi = k_{\text{Arg}} h_{\text{Arg}} + k_{\text{Xen}} h_{\text{Xen}},
\]

(1)

where \( h_{\text{Arg}} \) and \( h_{\text{Xen}} \) are the heights of argon and xenon, respectively; \( k_{\text{Arg}} \) and \( k_{\text{Xen}} \) are their wavenumbers, respectively; and \( h_{\text{Arg}} + h_{\text{Xen}} = h \). The phase difference profile is

\[
\Delta \Phi(y) = \Phi(y) - \Phi(0),
\]

(2)

where \( \Phi(y) \) and \( \Phi(0) \) are the phases at the coordinate \( y \) and 0, respectively. We can choose different \( h_{\text{Arg}} \) and \( h_{\text{Xen}} \) to make the phase shifts from 0 to \( 2\pi \). The background medium...
is air. The calculated transmission ratio with different heights $h_{\text{Xen}}$ is very high as shown in Fig. 2(b) due to the impedance-matching condition. The sound velocities in air, argon, and xenon gases are $c_{\text{Air}} = 343 \text{ m/s}$, $c_{\text{Arg}} = 323 \text{ m/s}$, and $c_{\text{Xen}} = 169 \text{ m/s}$, respectively. Their corresponding acoustic impedances are $Z_{\text{Air}} = 442.5 \text{ Pa s/m}$, $Z_{\text{Arg}} = 576.2 \text{ Pa s/m}$, and $Z_{\text{Xen}} = 996.1 \text{ Pa s/m}$. It is obvious that the anomalous refraction will obey the generalized Snell’s law

$$\sin(\theta_i) - \sin(\theta_t) = (\lambda/2\pi n_i) (d\phi/dy),$$

(3)

where $\theta_i$ is the incident angle, $\theta_t$ is the refraction angle, $\lambda$ is the wavelength, $n_i$ is the refractive index, and $d\phi/dy$ is the phase gradient in the $y$-axis. When the frequency of the incoming wave is 6860 Hz (just a sample value) and the anomalous refraction angle is 45°, the phase gradient should be 0.0889 rad/mm. The eight different heights of $h_{\text{Xen}}$ are 46 mm, 39.5 mm, 33.1 mm, 26.6 mm, 20.2 mm, 13.7 mm, 7.2 mm, and 0.8 mm, respectively, which can realize discrete phase shifts from 0 to $2\pi$ with a step of $\pi/4$ as shown in Fig. 2(c). The width of AMS arrays composed of six supercells is $a = 424.2 \text{ mm}$ in the MSCS.

Our simulations were performed by commercial software COMSOL Multiphysics based on FEM. When a Gaussian beam impinging normally upon the AMS with finite length $\sim 10 \lambda$ at 6000 Hz (a) is shown for $f = 6000 \text{ Hz}$ with a theoretical refracted angle of 54.0°, (b) is shown for $f = 6860 \text{ Hz}$ with a theoretical refracted angle of 45.0° and (c) is shown for $f = 8000 \text{ Hz}$ with a theoretical refracted angle of 37.3°, respectively. The simulation results demonstrate that the anomalous refraction can be realized by the AMS, which play an important role in the MSCS to realize the AD effect. This AMS consists of 15 supercells in this simulation.

In order to demonstrate the AD effect of our designed MSCS, we use numerical simulation results to illustrate the distributions of the acoustic pressure field $p$ and the intensity field $|p|^2$ at 6860 Hz (the corresponding wavelength $\lambda = 50 \text{ mm}$) for both PI and NI cases, respectively. The simulation results are shown in Fig. 4, where (a) and (c) are the acoustic pressure field distributions at 6860 Hz for PI and NI cases, respectively; and (b) and (d) are the spatial intensity distributions at 6860 Hz for PI and NI cases, respectively. For the PI case, a plane wave of left incidence passes our designed transmitted AMS and is divided into two parts. Both of them impinge on the rigid boundary with normal reflection as shown in Figs. 4(a) and 4(b). Therefore, this wave can pass the MSCS with high transmission efficiency due to the impedance-matching condition. However, for the NI case, a plane wave of right incidence passes the AMS, is divided into two parts with the refraction angle of 45.0°, and reaches the top and bottom edges, respectively. The two parts of the beam are absorbed completely by the top and bottom absorptive boundaries, respectively, as shown in Figs. 4(c) and 4(d). Hence, this wave cannot pass the MSCS. The simulation results agree well with theoretical predictions, which demonstrate that the MSCS can realize unidirectional acoustic transmission with high efficiency.

In order to verify the broadband performance of the MSCS, the transmission coefficient for PI and NI cases are calculated for comparison from 5000 Hz to 12000 Hz as indicated in Fig. 5. The results indicate that the MSCS can realize the AD effect within a remarkable broad bandwidth.
approximately from 5100 Hz to 8400 Hz, for which the transmission coefficient for the PI case is more than 80% and the transmission coefficient for the NI case is less than 15%. As a result, the AD effect can be obtained in the MSCS with high efficiency.

In summary, we have proposed a MSCS capable of realizing the AD effect while allowing other entities to pass freely by using the AMS with the advantage of high transmission efficiency, broad operation bandwidth, and thin thickness. We first introduced the AD and then designed the transmitted AMS composed of two inert gases (argon and xenon). According to the generalized Snell’s law, the anomalous refraction can be realized by this AMS, which play an important role in the MSCS to realize the AD effect. The distributions of acoustic pressure field and the intensity field have proved that the MSCS can realize unidirectional acoustic transmission, which agrees well with the theoretical predictions. Note that the backtracking waves can be efficiently prevented and cannot disturb the source. What is more, the transmission coefficients for PI and NI cases are calculated for comparison. The results indicate that the MSCS can realize the AD effect within a remarkable broad bandwidth approximately from 5100 Hz to 8400 Hz. Our mechanism can experimentally provide a simple approach to design an AD and have potential applications in various fields such as medical ultrasound and noise insulation.

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