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The Anomalous Reflection of Acoustic Waves Based on Metasurface

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***Abstract*—Metasurfaces with sub-wavelength thickness and planar profile have exhibited novel waves manipulating properties that could not be realized by traditional materials. Here we present an acoustic metasurface (AMS) model composed of double-split hollow sphere (DSHS) resonator arrays with the functionality of modulating reflected wavefronts at will. By tailoring the split-hole diameter of DSHS, the AMS can be designed to cover 2π phase shifts with the step of π/4. The acoustic wave perpendicularly and obliquely incident on the AMS can be reflected at any angle. These anomalous manipulations of the reflected wave's direction are simulated to fulfill the generalized Snell's Law by projecting suitable phase gradient. Such AMS provide another path to acoustic application such as acoustic imaging, cloaking, beams steering devices.**

Keywords: acoustic metasurface, double-split hollow sphere (DSHS), phase gradient, anomalous reflection

I. INTRODUCTION

In recent years, the anomalous manipulation of the classical waves (such as Electromagnetic (EM) waves and acoustic waves) has attracted researcher's attention. The artificial metamateiral is a good candidate to manipulate electromagnetic (EM) or acoustic waves. It has been reported that the EM metamaterials exhibit some unique effects for classical waves, such as negative refraction, extraordinary transmission, sub-wavelength imaging, cloaking, inverse Doppler and so on [1-11]. Later, in EM region, a kind of ultrathin metasurface with phase discontinuities is proposed to modulate wavefronts of EM waves at will, which satisfies the generalized Snell law of reflection and refraction. This kind of device with the advantage of subwavelength thickness and low loss can easily achieve the anomalous manipulation of classical waves which may be very difficult to the traditional metamaterial. As the natural materials have the limited phase change, the artificial resonant structures of EM metamaterials, like "V"-antenna, "H"-structure, and split resonant rings (SRRs) [12-16], are applied to design the EM metasurface with subwavelength scale thickness, which have the phase discontinuities with the phase shifts covering 2π span. By tailoring a suitable phase gradient, some kinds of unique EM wavefront control phenomenon, for instance, anomalous reflection and refraction, propagated waves converting to surface waves, ultrathin planar metalens, axicons, and polarization manipulation [16-22] can be theoretically and experimentally achieved with high efficiency.

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Acoustic wave is another kind of classical wave which follows the normal Snell's Law. If the generalized Snell law of metasurface can be realized in acoustics region, it will have deep influence on the acoustic application and the design of sub-wavelength acoustic devices. However, due to an inherent distinction between EM waves and acoustic waves, it is very difficult to realize the acoustic metasurface (AMS). Considering the fact that natural material only provides a limit phase shift, researchers should appeal to the artificial structure of acoustic metamaterials (AMM). The first experimental acoustic metasurface was presented by hybrid resonance of membrane structure with total absorption based on the impedance-matched concept [23], but the arbitrary manipulation of the acoustic waves is a challenge by this method. So the AMS with phase discontinuities is still a main path to controlling the acoustic waves. By means of the structure of coiling-up space from AMM, the AM can be realized to anomalously manipulate reflected acoustic waves in theory and simulation [24]. And then experiments are presented to realize the wavefronts modulation, including anomalous reflection and refraction, planar acoustic axicon and lens [25, 26]. So far, all the structures of the AMs are limited by the coiling-up space with double-negative parameters. We will pursue to another suitable model that will be probably in experiment utilized to fabricate the AMS with phase gradient.

In this work, we present another acoustic resonant structure of double-split hollow spheres (DSHSs) to design AMS, which have the properties of discontinuous phase shifts ranging from 0 to 2π with step of π/4 capable of general modulation of the reflected wavefronts. It is demonstrated that the acoustic waves incident on the AMS will obey the generalized Snell's law ($n_i k(\sin(\theta_r)-\sin(\theta_i))=\xi$, $\xi=\frac{d\Phi}{dx}$), including anomalous reflection and negative reflection. When acoustic waves are perpendicularly incident on the AMS, it will be obliquely reflected at any angle by tuning the phase gradient of DSHS "reflectarrays". For the obliquely incident waves on the AMS, the waves may be reflected in negative direction.

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II. Results and Discussion

From our earlier work, the DSHS and its prior structure of split hollow sphere (SHS) are artificial acoustic resonators which have realized negative-modulus AMM [27-31] near the resonant frequency due to its acoustic local resonance and can easily be coupled with other structure in experimental environment [30-31]. As an acoustic Helmholtz resonator, Split hollow sphere (SHS) has been proved to be suitable to fabricate AMS [32]. Because the DSHS is another kind of Helmholtz resonator with symmetry structure and has similar properties as the SHS, it can also be used to design AMS. When there is an acoustic wave incident on a DSHS structure, a lot of energy will be stored in the cavity and released from the split holes in two directions. If the stored energy in the cavity and released energy from the penetrated holes match well with each other, a strong resonance will appear in the structure at a certain frequency related with the geometry size, which is similar as the L-C resonance in EM region. According to the lumped circuit model, the DSHS is analogous to an inductor-capacitor-inductor circuit as shown in Fig. 1(a). The hollow sphere acts as an acoustic capacitor with the capacitance of $C_a = V/(\rho_0 c_0^2)$ and the two split holes acts as acoustic inductors with the inductances of $L_1 = \rho_0 t / S_1$ and $L_2 = \rho_0 t / S_2$, respectively, where V is the volume of hollow sphere, ρ_0 is the density of air, c_0 is the sound speed in air. The cross section sizes of the two split holes are the same ($S_1 = S_2 = \pi d^2/4$) because of the identical holes' diameter. Therefore, the resonant frequency of the DSHS is expressed as $f = 1/(2\pi\sqrt{(L_1+L_2)C_a})$ from the resonant model. This relationship between geometry size of DSHS and resonant frequency is the foundation on the design of AMS.

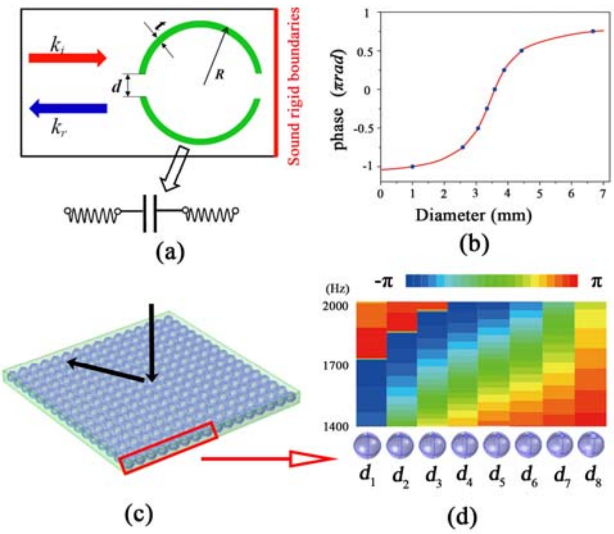

Fig. 1 (Color online) (a) The cross-section view of one DSHS with periodic boundary condition in the simulated environment. (b) The reflected phase versus split-hole diameters of DSHS at 1700 Hz and the selected sizes of DSHSs with the phase step of π/4 are shown in blue round dot (c) The designated AMS composed of periodic reflectarrays with eight kinds of DSHSs. (d) The calculated reflected phase shifts of the eight unit cells of DSHSs at the frequency ranged from 1400 to 2000 Hz.

Our simulations are conducted by COMSOL Multiphysics software based on a finite element method (FEM). The cross-section view of one DSHS in the simulated environment is shown in Fig. 1(a). The side faces are set as periodic boundaries. The left face is radiation boundary with 1-Pa planar acoustic waves, which are normally incident on the surface of DSHS structure. The right transmitted face is set as rigid boundary condition ensuring no transmitted waves. As a necessary condition to realize an AMS, the reflected amplitude of each unit cells should reach near 1 at our discussed frequency band. However, if the transmitted boundary is not rigid, the reflected amplitude is very high near the resonant frequency and very low away from the resonant frequency [27], which will be unable to realize anomalous reflection [7].

The radius of the DSHS is constantly selected as R=12.5 mm and the sphere shell's thickness is t=0.5 mm. By simultaneously tailoring the diameter of double-split-hole from 0 to 7 mm. one can obtain the corresponding reflection amplitude and phase. The simulations show that the reflection amplitudes of different DSHSs structure are all near 1 and the phase shifts cover 2π range near each resonant frequency. The simulated phase versus diameter of the double-spilt holes at the frequency of 1700 Hz is shown in Fig. 1(b), which demonstrates that the phase shifts of reflected waves cover 2π range. The diameter of eight DSHSs with the phase shift of π/4 are selected as round dot in Fig. 1(b), which means d_1=1 mm, d_2=2.58 mm, d_3=3.06 mm, d_4=3.34 mm, d_5=3.58 mm, d_6=3.88 mm, d_7=4.43 mm and d_8=6.75 mm. In the simulation, the eight acoustic atoms of DSHSs are arrayed as a reflectarray (it could also be understood as a molecule) and then the reflectarrays are periodically arranged as AMS shown in Fig. 1(c). To further illustrate the property of the eight DSHS, we present the comparison of the reflected phase at the frequency range of 1400-2000 Hz plotted in Fig. 1(d). Obviously, the phase changes from –π to π at 1700 Hz covered 2π range. In the simulation, the AMS is placed in the free space of air. The four side faces of AMS are set as periodic boundary conditions. A 1-Pa plane harmonic acoustic wave is perpendicularly incident on the AMS via a radiation boundary condition at the input boundary and a rigid boundary condition is applied to output boundary face. For a better monitor to the reflected wavefronts, the reflected space is designed much larger than the thickness of AMS. The two adjacent side-faces are meshed as free triangular, and then the meshing of each face is copied to the opposite face. The entire simulated domain is meshed by the tetrahedron based on the face meshing and the user predefined size is set as "Finer", implying that the maximum element size is 66 mm, the minimum element size is 4.8 mm and the maximum element growth rate is 1.4. The solvers are chosen as "spools."

Theoretically, the anomalous manipulation of acoustic waves by AMS exhibits at a fixed frequency, which seriously hinders the development of its acoustic application. We should discuss the behavior of AMS at a broadband frequency. The AMS with phase gradient of π/120 (rad/mm) is selected as a research object. It is known that the perpendicularly incident waves on the AMS will be obliquely reflected at the designed frequency of 1700 Hz shown in Fig. 2(b). We also simulate acoustic pressure field distribution on other band near 1700 Hz as shown in Figs.2(c)-(d). From the distribution of reflected wavefronts, it is obviously demonstrated that the oblique reflection also exists at the frequencies of 1600 Hz, and 2000 Hz with different reflection angles of 65° and 45°, which agree well with the calculation by generalized Snell's law with the angles of 62.3° and 45°, respectively). In Fig. 3(e), when the frequency is lower than 1600 Hz, the acoustic waves will be perpendicularly reflected at 1500 Hz, which satisfies the traditional Snell Law. If the frequency of incident waves is 2100 Hz (higher than 2000 Hz), the reflected wavefronts will be thrown into confusion and not regular meaning the strong scattering as shown in Fig. 3(f). Therefore, the AMS can realize anomalous reflection at a broadband frequency range of 1600~2000 Hz with the bandwidth of 400 Hz. It can also be seen from Fig. 1(d) that the discontinuous phase can be existed in the frequency range of 1600~2000 Hz. Furthermore, it is noted in Fig. 3 that the acoustic energy will get lower and the shapes of reflected wavefronts become more irregular as the frequency is far away from the center frequency of 1700 Hz. According to the physical mechanism of the AMS, the energy in the cavities of the DSHSs becomes weaker and the local resonance will not be strong enough to contribute more energy to the anomalous reflected waves. These results further prove that the local resonance of DSHS contributes to the anomalous manipulation of the AMS.

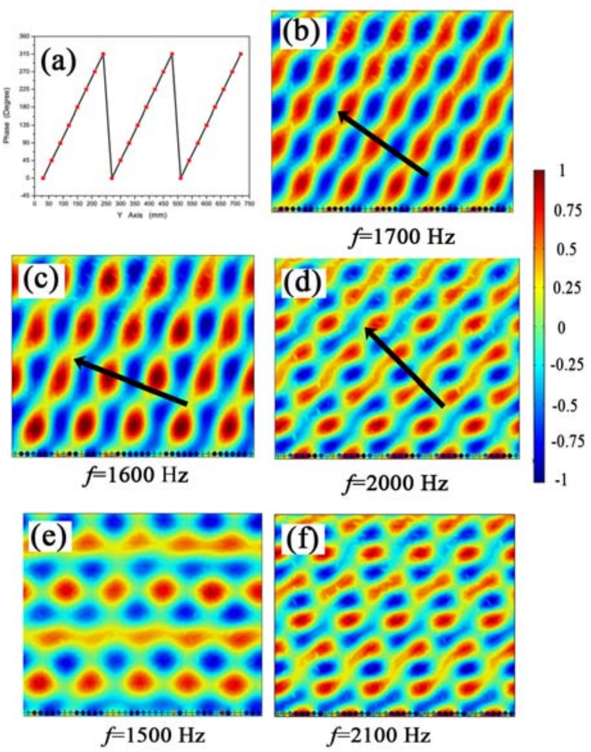

Fig. 3 (a) The broadband anomalous reflection of the AMS designed with the phase gradient of π/120 (rad/mm). (b) The calculated reflected acoustic pressure field distribution at 1600 Hz with 65° Reflection, (c) 1700 Hz with 56° reflection and (d) 2000 Hz with 45° reflection. (e) The field distribution of normal reflection at the frequency of 1500 Hz. (f) The field distribution of acoustic scattering at 2100 Hz.

From the formula of the generalized Snell's Law, it is of significance that the gradient phase plays a key role on manipulating the direction of acoustic wavefronts. Firstly, we simulated a sample with the phase gradient $\xi = 0$ as shown in Fig. 3(a). From the distribution of reflected wavefronts, the acoustic waves are normal reflected, which follows the traditional Snell law. We also discuss the AMS samples with three kinds of spacing distances, 30 mm, 60 mm, and 90 mm, meaning the phase gradient of ξ is π/120, π/240 and π/360 (rad/mm), respectively. When an acoustic wave is normally incident on the AMS, the calculated reflected field distributions are shown in Figs. 3(b)-(d). It is clearly seen that the reflected waves are not perpendicular to the AMS, which do not fulfill the traditional Snell's law. It is also demonstrated that the normal incident waves on the three AMS obliquely reflect in different direction. According to the generalized Snell's law, the reflection angles of the three AMSs should be 56.4°, 24.6° and 16.1°, respectively. From the reflected wavefronts of FEM data shown in Figs. 3(b)-(d), the reflection angles are respectively calculated as 58°, 24° and 15°, which are in good qualitative agreement with theoretical analysis. Let us pay attention to the energy distribution in the AMS, it is noted that the acoustic pressure in the cavity of each DSHS is stronger than that of free space and exhibits negative value, which means local resonance and out-of-phase response in the DSHS. As ξ becomes larger, the absolute value of negative pressure in the cavity of DSHS will be smaller, which means a weaker resonance in the DSHS. Meanwhile, the energy of the anomalous reflection will be lower. It is illustrated that the local resonance of DSHS has a great contribution to the anomalous reflection of the AMS, which is similar with EM plasmonic resonance (the physical mechanism of EM metasurface). These results illustrate that the acoustic resonator of DSHS with symmetry structure and negative modulus is another feasible choice to design AMS in practice.

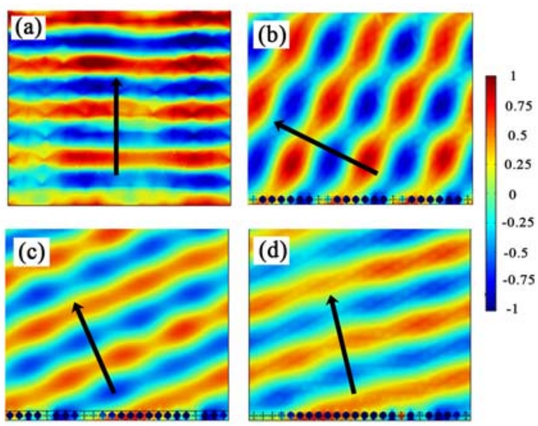

Fig. 2 (a) The reflected acoustic field distribution of normal material with the phase gradient of $\xi = 0$. (b), (c), (d) represent the reflected acoustic field distribution of designed AMSs with three kinds of phase gradient of $\xi = \pi / 120$, $\xi = \pi / 240$ and $\xi = \pi / 360$, respectively.

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III. Conclusion

In conclusion, we have demonstrated a planar sub-wavelength AMS that realizes the arbitrary modulation of the reflected modulation. The AMS is constructed by periodic reflectarray with eight kinds of DSHS, which put up spatially varying phase response covered 2π range with the step of π/4. It is simulated that an acoustic plane wave perpendicularly incident on the AMS can obliquely reflect at different angles according to the designed phase gradient, which fulfills the generalized Snell's law. The simulation also shows that the anomalous reflection of considered AMS is not only suitable for a fixed frequency, but also realized in broadband frequency region with the bandwidth of 400 Hz. When acoustic waves are obliquely incident on the AMS, the reflected waves lie in the same side of normal with the incident waves, which presents a negative reflection. The simple fabrication of the proposed AMS provides another method to realize the arbitrary manipulation of acoustic waves in experiment. With our presented ultrathin AMSs, we can expect great promises for acoustic application such as medical imaging, cloaking of the warship and beams steering devices.

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