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Anomalous Beam Steering and Broadband Sound Absorption by Acoustic Metasurfaces with A Periodic Subwavelength Modulation

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ABSTRACT

Both periodic subwavelength structures and phase gradient metasurfaces have opened up new degrees of freedom to manipulate the acoustic waves respectively. In this paper, manipulation of elastic waves by phase gradient metasurfaces with periodic subwavelength modulation is studied. Anomalous sound reflection beam steering is observed, as well as significant sound absorption is achieved with deep subwavelength thickness in a broadband frequency range as damping is considered. The results extends the functionalities of acoustic metasurfaces and paves the way for the design of thin planar structures for broadband acoustic wave manipulation and extraordinary absorption.

Keywords: Acoustic metasurface, Periodic modulation, Absorption

1. INTRODUCTION

It is a significant topic to manipulate the propagation of sound at will. Such a design is available by employing acoustic metamaterials, where periodic modulation is applied by microstructures at a subwavelength scale. Numerous fascinating phenomena have been observed, including low-frequency band-gaps,[1,2] negative refractions,[3,4] subwavelength imagings[5,6] and cloakings.[7,8] And recent years have witnessed a great expansion of acoustic metamaterial functionality, among which metasurfaces have attracted significant attention owning to their compact planar subwavelength structure and unprecedented wave modulation capabilities. By introducing a phase gradient into ultrathin flat structures, the wavefronts of elastic waves can be molded into arbitrary shapes.[9, 10] A set of novel acoustic devices were proposed for their design flexibilities, including freely steering sound beam, [11, 12] converting propagating waves to surface waves,[13, 14] ultrathin planar lenses,[15, 16] acoustic diode,[17, 18] and vortex beam.[19]

In this paper, we introduce periodic subwavelength thin hard plates array into the phase gradient acoustic metasurface. Anomalous reflection wavefront manipulation and broadband sound absorption are observed as specially designed phase gradients is

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beyond the critical value that the incident propagating waves (PWs) would be converted into surface waves (SWs) along the interface. Although acoustic metasurfaces with periodic modulation were studied and wave-vector dependent Snell's law has been proposed to predict the behavior of outgoing PWs from higher order diffraction, [26-28] period that comparable with wavelength is necessary to achieve higher diffraction patterns. The anomalous PWs behavior as the period is shrunk to deep subwavelength dimensions have not been reported and discussed so far. In our microscopic description, new mechanism can be obtained by the joint action of periodic subwavelength constraints and phase gradient. This work indicates the combination of phase gradient and subwavelength periodic modulation can provide new approach for miniaturization of sound devices for wavefront manipulations and broadband acoustic absorbers.

2. MODELS

The schematic of an acoustic metasurface is illustrated in FIG. 1(a), with water (speed of sound c_0=1490 m/s; density ρ_0=1000 kg/m^3) as the background medium. The metasurface consists of periodically repeated rectangle cells with a width h_1. Each cell is filled with fluidlike material, the velocities in ith cell are c_i, the index i=1, 2..., n mark the cells from the upper to the lower. A thin hard plate (Young′s modulus E=330 GPa; density ρ=8750 kg/m^3; Poisson′s ratio σ =0.33) with a width h_2 is inserted between two adjacent cells. Thus the period is $L= h_1 + h_2$. We assume the right boundary of the acoustic metasurface is rigid and acoustic waves with a frequency f impinging on the metasurface from the left. the mass density in ith cell are $\rho_i=\rho_0\cdot c_0/c_i$, which can match the impedance between the metasurface and the background medium. Therefore, a incident wave can enter almost completely into the metasurface and reflected at the right boundary. The wavefronts inside different unit cells accumulate tunable phase delays $\phi_i=2d\cdot 2\pi f/c_i$, where d is the thickness of the metasurface. As the period L is much less than the wavelength of the incident wave, the phase delay variation along the surface can be described by phase gradient dϕ/dy.

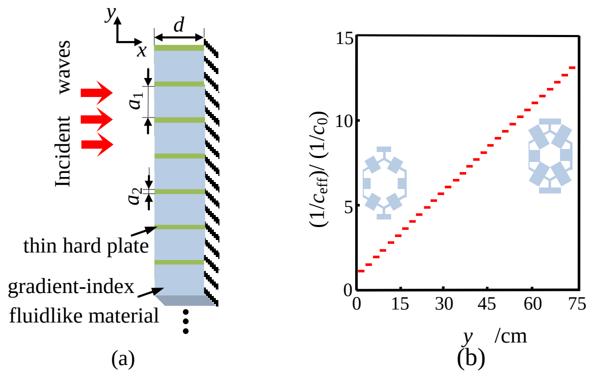

Figure 1. (a) Schematic of acoustic metasurface with periodic subwavelength array of thin solid plates. (b) The variation of material parameters in different units.

The wavefronts of the outgoing PWs can be manipulated by dϕ/dy, the fundamental governing mechanism behind metasurfaces is described by the generalized Snell's law. We assume the velocities of the fluidlike material in ith cell are $c_i= c_0/(1+q\cdot (i\text{-}1))$, which can be adjusted by changing q. For two adjacent cells numbered as i and i +1, the phase difference is $\Delta\phi =2d\cdot q\cdot k_0$, where $k_0 =2\pi f / c_0$. As well as L_2 is much smaller than L and has little influence on the phase gradient, the phase gradient dϕ/dy have the form $(2d/L) \cdot q\cdot k_0$. In this case, Thirty different units denoted B_1 to B_{30} are designed to construct the proposed metasurface. L and d are selected as L=20mm and d =25mm.

3. RESULTS AND DISCUSSIONS

3.1 Performances and functionalities

The wave propagation behavior inside the metasurface is investigated using full-wave simulation based on FEM (COMSOL Multiphysics). we carried out a series of numerical simulations at different frequencies as a Gaussian acoustic beam incident vertically and phase gradient $d\phi/dy = 1.1k_0$. FIG. 1(b) shows the reciprocal of the velocity distributions of the metasurface. Due to the generalized Snell's law, the reflection angle can be calculated by[20]

$$\theta_r = \arcsin\left(\frac{1}{k_0}\frac{d\phi(y)}{dy}\right) \quad (2)$$

Where θ_r is the reflection angle, $d\phi(y)/dy$ is the phase gradient in the y-direction. From the view of Eq (1), the phase gradient $d\phi/dy$ has a critical value for the reflection angle θ_r=90°. When $d\phi/dy$ is larger than the critical value, the absolute value in the right of equal-sign will larger than 1 and θ_r will become a complex number. It means the reflective waves will disappear and the incident PWs will be converted into SWs propagating along the interface. But in our case, as periodic thin hard plates are introduced, the propagation of the SWs will be restricted.

FIG. 2(a)-2(f) illustrate the results while the frequencies increase from 11000Hz to 17000Hz (Normalized frequency $k_0L/2\pi$=0.15 to 0.23). Anomalous reflected PWs can be observed in the broadband range, and the direction exhibits abrupt change. Vertical reflection can be observed at 0.152 and 0.181, respectively. The reflection angles change from close to 90°to 0° while the frequencies increase from $k_0L/2\pi$=0.152 to $k_0L/2\pi$=0.181. And the same process can be also found as the frequencies increase from 0.182 to 0.22. The wavefront of the reflected waves has only little distortions in all cases, just like the waves reflected from a uniform plate. It means the periodic subwavelength modulation can significantly change the acoustic properties of the metasurfaces.

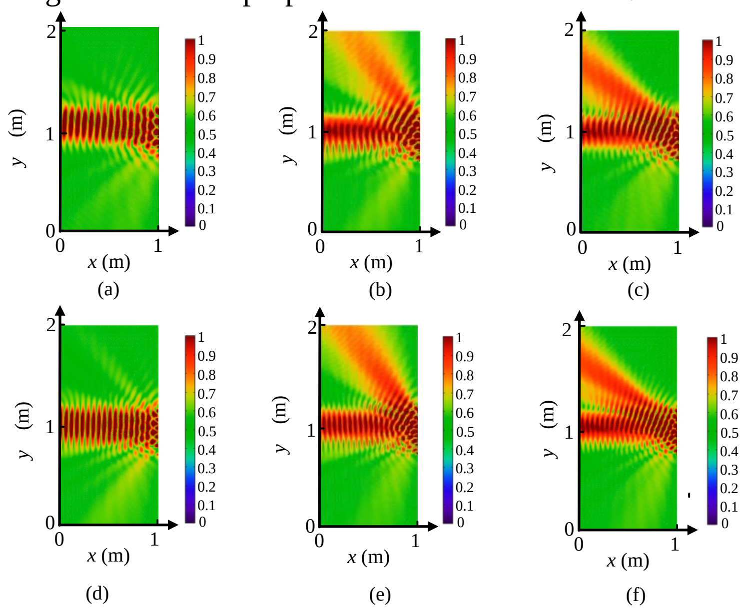

Figure 2. The pressure field patterns for the metasurface with periodic subwavelength thin hard plates as $d\phi/dy = 1.1k_0$ at normalized frequencies (a) 0.152, (b) 0.156, (c) 0.164, (d) 0.181, (e) 0.189, (f) 0.199

The governing mechanism behind the metasurfaces can be analysised by vector diffraction theory[21, 22]. In our model, the propagation of the wave along the *x* direction is constrained by the phase gradient as dϕ/d*y*>k_0. And the propagation along the *y* direction is constrained by the periodic thin hard plates at the same time. Then the wave should be reflected front and back in each slit (just as shown in Fig. 3 (a)). We introduce such multiple reflection course into the diffraction theory, can obtain the expression:

$$\sin\theta_r = \frac{1}{k_0} m \frac{d\phi(y)}{dy} - n\frac{\lambda_0}{L} \tag{7}$$

Where λ_0 is the wavelength of incident wave in water, *n* is the order of diffraction associated with the periodic grating, *m* is the number of reflections.

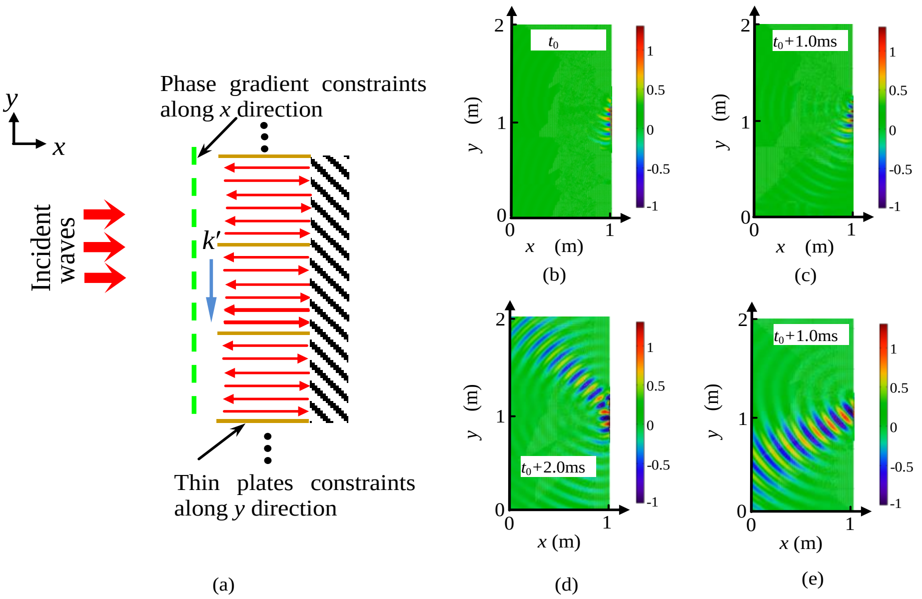

Figure 3. Schematics of the local multiple reflections process for phase gradient acoustic metasurface with periodic modulation and the transient simulations of scattered field at different times..

To verify the theoretical analysis, transient simulations are carried out on the proposed metasurface. FIG. 3(b) is the scattered field when the incident wavefront first hits the metasurface at 11800 Hz with dϕ/dy = 1.1 k_0, similar field distribution can be achieved for the metasurface with dϕ/dy = 0.5 k_0 at the same time. FIG. 3(c) and 5(d) are the scattered fields of the metasurface with dϕ/dy = 1.1 k_0 at different times, as well as FIG. 3(e) is the scattered field of the metasurface with dϕ/dy = 0.5k_0 at 11800 Hz as the outgoing propagating wave is formatted. It is shown that for the metasurface with dϕ/d*y* = 0.5k_0, the outgoing propagating wave goes across the simulation space in 1.1ms. But for the metasurface with dϕ/dy = 1.1k_0, 2.2ms is needed for the outgoing propagating wave to go across the simulation space, which means the formation time of the latter is much longer than the former. It leads us to conclude that the outgoing propagating wave from the metasurface with dϕ/d*y* = 1.1k_0 gets local multiple reflections.

3.2 Effects of the material damping

The influence of damping do not be considered in the above analysis models. For the notably long time delay of the multiple reflection, it can be considered that the incident wave can be significantly attenuated even if the intrinsic absorption rate in the metasurface is minimal, which is a long desired feature for acoustic devices. Here we introduce viscous damping to the fluid like material in the metasurface by 2% imaginary modulus. FIG. 5(a), 7(b) and 7(c) are the field distributions with the same damping as dϕ/dy= 1.1k_0 at k_0L =0.156, 0.164 and 0.199. Compared with the corresponding results without damping in FIG. 2(b), 2(c) and 2(f), sharp attenuation of the reflected PWs can be observed. As a comparation, FIG. 2(d) and 7(e) are the pressure field distributions of the metasurfaces with and without damping at normalized frequency $k_0L/2\pi$ = 0.155 as dϕ/dy = 0.5k_0, obvious reflected PWs can be observed in both cases. It indicates poor damping effect without the multiple reflection. FIG. 7(f) shows the variation of the sound attenuation coefficient with frequency of the metasurfaces both with dϕ/dy= 0.5k_0 and dϕ/dy= 1.1k_0. Significant sound absorption can be obtained in a wide frequency range in the case of dϕ/dy= 1.1k_0.

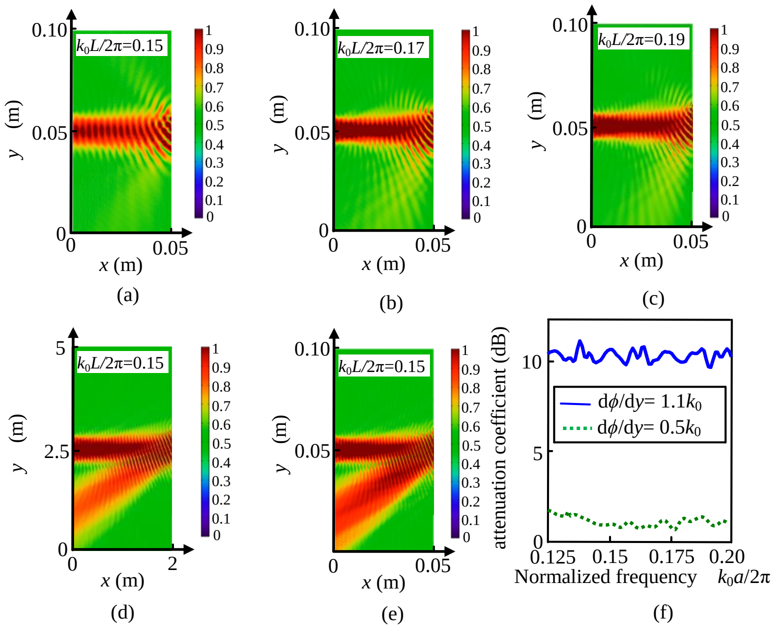

Figure 4. (a)- (b) Pressure field distributions of lossy and lossless metasurface with periodic modulation as phase gradient dϕ/dy= 0.5 k_0. (c)- (e) Pressure field distributions of lossy metasurface with periodic modulation as phase gradient dϕ/dy= 1.1k_0. (f) The variation of insertion loss of reflected wave with frequency as phase gradient dϕ/dy= 0.5 k_0 and dϕ/dy= 1.1 k_0.

The results confirm that the multiple reflections by the interplay of subwavelength periodic modulation and phase gradient can markedly increases the time and distance that waves travel inside the unit cells while the geometric dimensions of the structure are not increase. Thus, absorption performance of damping can be strongly enhanced. Because resonant structures are not involved, it is useful to obtain a broadband and thin-layer absorption performance.

4. CONCLUSIONS

In summary, we have demonstrated that the phase gradient metasurface with a subwavelength periodic thin hard plates array can cause anomalous reflection PWs at a large frequency range, as well as broadband significant sound absorptions can be achieved with a thin layer structure as the damping is introduced. Consider the joint effect of phase gradient and periodic constraint, an analytic expression has been derived to describe the anomalous wave behaviors. It is hoped that this study could provide guidance to recent activities of steering sound by acoustic metasurfaces.

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