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Redirection of sound waves using acoustic metasurface

Jiajun Zhao,[1,2] Baowen Li,[2,3,a)] Zhi Ning Chen,[1] and Cheng-Wei Qiu[1,a)]
[1]*Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576, Republic of Singapore*
[2]*Department of Physics and Centre for Computational Science and Engineering, National University of Singapore, Singapore 117546, Republic of Singapore*
[3]*Center for Phononics and Thermal Energy Science, School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*

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When acoustic waves are impinged on an impedance surface in fluids, it is challenging to alter the vibration of fluid particles since the vibrational direction of reflected waves shares the same plane of the incidence and the normal direction of the surface. We demonstrate a flat acoustic metasurface that generates an extraordinary reflection, and such metasurface can steer the vibration of the reflection out of the incident plane. Remarkably, the arbitrary direction of the extraordinary reflection can be predicted by a Green's function formulation, and our approach can completely convert the incident waves into the extraordinary reflection without parasitic ordinary reflection.
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When an acoustic wave with a certain frequency is excited in fluids, the fluid particles will experience a restoring force, hence oscillating back and forth monochromatically. The orientation of such longitudinal oscillation is the vibrational direction of a fluid particle. The vibration is undoubtedly an important characteristic of acoustic waves (like the polarization for electromagnetic waves). In electromagnetics, we can manipulate polarization by conventional methods such as dichroic crystals, optical gratings, or birefringence effects, etc.[1,2] In elastic waves, we can also reach the mode conversion because molecules in solids can support vibrations in various directions.[3,4]

However, when sounds propagate freely in fluids, few attempts were made so far toward tweaking the vibrational orientation, since the compressional mode inside the incident plane is considered to be the only possible case in acoustics. On the other hand, being enabled by the flexible dispersion of metamaterials, acoustic metamaterials can have solid-like transverse modes at density-near-zero[5] while conversely elastic metamaterials can have a fluid-like longitudinal mode when the elastic modulus goes negative[6] to allow polarization conversion. However, these metamaterials require resonating units, which have to be specially designed to balance possible loss. Nevertheless, if one can tweak the reflected sound out of the incident plane, the vibrational direction, though still longitudinal with respect to the reflected beam itself, can therefore be manipulated accordingly. In other words, we can yield perpendicular vibration components in reflection with respect to the incident vibration, and control the spatial angle of such out-of-incident-plane vibration.

In this connection, we propose a scheme by designing an acoustic flat metasurface reflector to manipulate the vibrational orientations generated by sound in fluids. Metasurfaces have drawn much attention recently in electromagnetics, such as frequency selective polarizers,[7] the waveform conversion,[8] wavefront-engineering flat lens,[9] and polarization converter.[10] The concept of acoustic metasurfaces has not been well investigated before, owing to the intrinsic nature of compressional modes and limited choices of natural materials. In this connection, this paper addressed a flat metasurface to manipulate the extraordinary out-of-incident-plane reflection and vibration in acoustics, validated by the theoretical modeling and the numerical experiment.

In this paper, we theoretically demonstrate that in fluids, extraordinarily reflected sound waves can be achieved along a three-dimensional spatial angle out of the incident plane by manipulating the impedance distribution of a flat metasurface reflector. In particular, the arbitrary manipulation can be unanimously predicted and concluded by our three-dimensional impedance-governed generalized Snell's law of reflection (3D IGSL), which is rigorously derived from Green's functions and integral equations. Consequently, the vibrations of the extraordinary reflection and the incidence will form a spatial angle in between, rather than sitting in one plane. Such inhomogeneous flat metasurface can be effectuated by means of impedance discontinuity, and further implemented by tube arrays with properly designed lengths. Finite-element-simulation results agree with the theoretical prediction by 3D IGSL.

The coordinate is illustrated in Fig. 1, where the flat metasurface reflector is placed at $z = 0$ plane, i.e., x-y plane. In water (speed of sound $c_0 = 1500\,\mathrm{m/s}$; density $\rho_0 = 1\,\mathrm{kg/m^3}$), an acoustic plane wave p_i from the space $z > 0$ is impinged upon the flat surface $z = 0$ with unit amplitude and the frequency $\omega = 300\,\mathrm{K\,rad/s}$. Figs. 1(a)–1(d) are the simulated acoustic fields in the upper space $z > 0$, which are the projections upon the plane perpendicular to z axis. For the incident field in Fig. 1(a), one can notice that the vibrational direction of fluid particles (orange double-headed arrow) excited by the incidence forms the incident plane (yellow dashed line) with z axis. As shown in Fig. 1(b) for the reflected field, if the impedance reflector is homogeneous, the particle vibration excited by the ordinary reflection p_{ro} (orange double-headed arrow)

[a)]Authors to whom correspondence should be addressed. Electronic addresses: eleqc@nus.edu.sg and phylibw@nus.edu.sg.

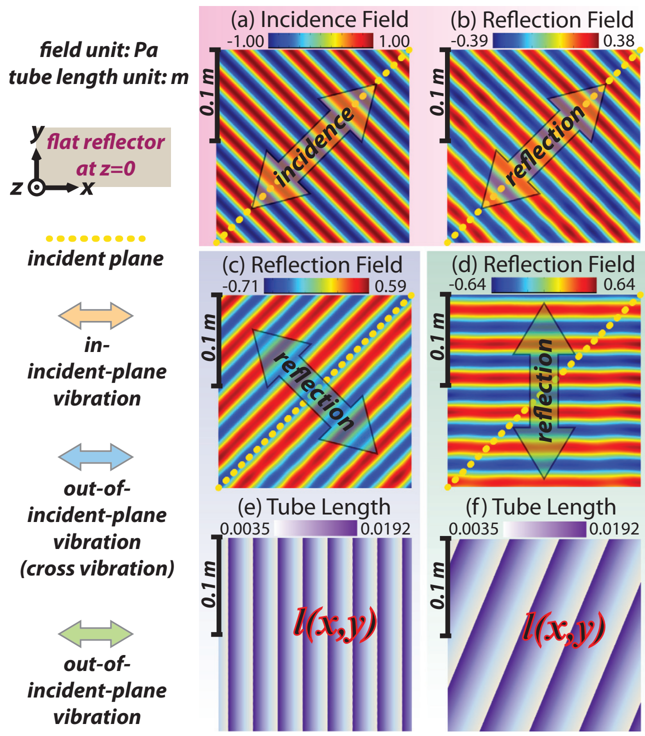

FIG. 1. (a) Observing along $-\mathbf{z}$, a plane wave is propagating toward the metasurface at $z = 0$. The vibration of fluid particles excited by the incidence (orange double-headed arrow) is within the incidence plane (yellow dashed line). (b) The ordinary reflection generated by a homogeneous flat reflector excites the in-incident-plane particle vibration. (c) Observing along $-\mathbf{z}$, the flat metasurface reflector excites the out-of-incident-plane cross vibration of fluid particles (blue double-headed arrow). (d) Another metasurface reflector excites the extraordinary vibration of fluid particles (green double-headed arrow). (e) and (f) The realization schematics of the metasurface, and the tube lengths corresponding to (c) and (d), respectively, are exhibited in (e) and (f).

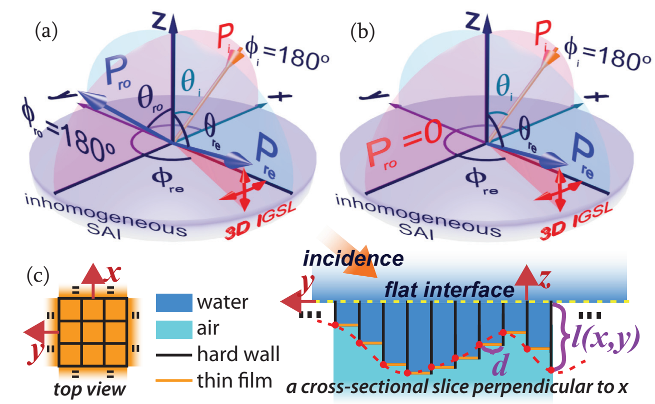

FIG. 2. (a) For a flat metasurface reflector with an inhomogeneous 2D SAI, the directions of p_{ro}, i.e., θ_{ro} and ϕ_{ro}, are not influenced, while p_{re} occurs simultaneously with the direction θ_{re} and ϕ_{re} controlled by 3D IGSL. (b) If a heterogeneous SAI is properly designed upon the reflector, p_{ro} will become null. (c) Realization schematics by tube arrays, comprising the reflector (yellow dashed line).

will be co-planar with the incident vibration, as expected intuitively. In order to steer the acoustic vibrations freely, a metasurface reflector composed of the inhomogeneous specific acoustic impedance SAI, which can be realized by different layouts of tube resonators with designed lengths, is implemented in Figs. 1(c) and 1(d), while the same incidence in Fig. 1(a) is used. The incident plane (yellow dashed line) is identical throughout all cases in Figs. 1(a)–1(d). It can be seen from the reflected fields in Figs. 1(c) and 1(d) that the particle vibration excited by the reflection (blue double-headed arrow) deviates away from the incident plane by employing the inhomogeneous impedance surface. Observing along $-\mathbf{z}$, we manipulate the x-y plane projection of the vibration (excited by reflection) perpendicular to the incident plane as shown in Fig. 1(c), as named *cross vibration*. Another example is shown in Fig. 1(d), where the out-of-incident-plane vibrational orientation (green double-headed arrow) is steered robustly by the flat metasurface at $z = 0$. The corresponding reflected acoustic field at $z > 0$ projected in the x-y plane is shown in Fig. 1(d), verifying the robust and precise manipulation of the out-of-incident-plane vibrational orientations of fluid particles.

In order to provide a theoretical and systematic framework for precisely manipulating the vibrational orientation in fluids, we thereby establish 3D IGSL. Here, we consider the reflection by a flat acoustic metasurface at $z = 0$, and formulate the modified Snell's law in acoustics for inhomogeneous two-dimensional SAI.[11] More specifically, the inhomogeneous SAI will give rise to the out-of-incident-plane vibration excited by the extraordinary reflection p_{re} (uniquely controlled by 3D IGSL) as well as the in-incident-plane vibration excited by an ordinary reflection p_{ro}, as shown in Fig. 2(a). Interestingly, it is found that the metasurface at $z = 0$ designed according to 3D IGSL cannot alter the direction of p_{ro} excited by the metasurface reflector, but can "turn off" p_{ro} as shown in Fig. 2(b). In other words, our design can create the steerable p_{re} as well as the switchable p_{ro}. This is unique for our acoustic metasurface while it is generally difficult to eliminate the parasitic ordinary refraction or reflection for electromagnetic metasurfaces.[12] p_{re} can be in principle steered along arbitrary directions by the metasurface, simultaneously with p_{ro} eliminated, resulting in the corresponding manipulation of cross vibration in the absence of the ordinary in-plane vibration. Therefore, 3D IGSL describes the generalized reflection law regarding the inhomogeneous SAI metasurface and provides a clear-cut way for manipulating p_{re} and its vibration along arbitrary spatial angles.

Here, we will focus on the theoretical formulation. As depicted in Figs. 2(a) and 2(b), p_i, θ_i (the angle between the orange line and $\mathbf{z}$), and ϕ_i (the angle between $\mathbf{x}$ and the x-y-plane projection of the orange vector) stand for the incident plane wave, the incident polar angle, and the azimuthal angle, respectively. The similar notations are adopted for p_{ro} and p_{re}.

The inhomogeneous 2D SAI Z_n of the flat metasurface at $z = 0$ is the extension of the one-dimensional SAI which only creates the in-incident-plane vibration and redirection in acoustics.[13] For simplicity in modeling, we consider

$$Z_n(x, y, \omega) = A\left[1 - i\tan\frac{\psi(x, y)}{2}\right], \tag{1}$$

where A is an arbitrary real constant and $\psi(x, y)$ represents the spatially varying component only existing at the imaginary part. Note that $\psi(x, y)$ in Eq. (1) has already taken into account the circular frequency.

We assume p_i in the upper space satisfies

$$p_i(x,y,z,\omega) = p_{i0}(\omega)\exp[ik_0(x\sin\theta_i\cos\phi_i + y\sin\theta_i\sin\phi_i - z\cos\theta_i)], \quad (2)$$

where k_0 stands for the wave number in free space and p_{i0} for the amplitude of the incidence. It is found that p_{ro} excited by the reflector at $z=0$ with Z_n satisfies[13]

$$p_{ro}(x,y,z,\omega) = p_{i0}(\omega)\frac{2A\cos\theta_i - \rho_0 c_0}{2A\cos\theta_i + \rho_0 c_0}\exp[ik_0(x\sin\theta_{ro}\cos\phi_{ro} + y\sin\theta_{ro}\sin\phi_{ro} + z\cos\theta_{ro})], \quad (3)$$

where ρ_0, c_0 are the density and the speed of sound in the upper space $z>0$ in Figs. 2(a) and 2(b), $\theta_{ro}=\theta_i$ and $\phi_{ro}=\phi_i$. p_{ro} is attributed to the reflection by the properly-averaged value of the inhomogeneous 2D SAI Eq. (1), while the variance of the 2D SAI is the cause of p_{re}.[13] Here, by virtue of Green's functions,[13,14] p_{re} in the upper space, serving as the result of the 2D SAI variation, can be expressed as an integral equation

$$p_{re}(x,y,z,\omega) = ik_0\frac{\rho_0 c_0}{2A}\times\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{i\psi(x_0,y_0)}[p_i(x_0,y_0,0,\omega) + p_{ro}(x_0,y_0,0,\omega) + p_{re}(x_0,y_0,0,\omega)]G(x,y,z,\omega;x_0,y_0,0)dx_0\,dy_0, \quad (4)$$

where G stands for the Green's function accommodating the boundary condition. In the far field approximation,[15] G can be derived explicitly

$$G(\mathbf{r},\omega;\mathbf{r}_0) = \frac{\exp(ik_0|\mathbf{r}|)}{4\pi|\mathbf{r}|}\exp[-ik_0(x_0\sin\theta_{re}\cos\phi_{re} + y_0\sin\theta_{re}\sin\phi_{re})] \times\left[\exp(-ik_0z_0\cos\theta_{re}) + \frac{2A\cos\theta^* - \rho_0c_0}{2A\cos\theta^* + \rho_0c_0}\exp(ik_0z_0\cos\theta_{re})\right], \quad (5)$$

where $\mathbf{r}=(x,y,z)$, $\mathbf{r}_0=(x_0,y_0,z_0)$, and θ^*, a constant, describes the effective incident angle with respect to the Green's function Eq. (5).[13,16] Inserting Eq. (5) into Eq. (4) and using Born approximation,[17] we are able to determine p_{re}, which includes the following term:

$$p_{re} \propto \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{i\psi(x,y)}\exp[ik_0x(\sin\theta_i\cos\phi_i - \sin\theta_{re}\cos\phi_{re}) + ik_0y(\sin\theta_i\sin\phi_i - \sin\theta_{re}\sin\phi_{re})]dxdy. \quad (6)$$

Note that for the trivial case when $\psi(x,y)=0$, Eq. (6) is non-zero which implies that p_{re} propagates along the same direction as p_{ro}. That is to say, if the flat metasurface is of uniform SAI which only generates the common reflection, the contribution of Eq. (6) should also be taken into account besides Eq. (3). In addition, we find that Eq. (6) is a two-dimensional Dirac Delta function when $\psi(x,y)$ is a linear function with respect to x and y, which imposes the directivity of p_{re} to be

$$\Psi(\theta_{re},\phi_{re}) \propto \delta[k_0x(\sin\theta_i\cos\phi_i - \sin\theta_{re}\cos\phi_{re}) + k_0y(\sin\theta_i\sin\phi_i - \sin\theta_{re}\sin\phi_{re}) + \psi(x,y)]. \quad (7)$$

Therefore, the spatial directivity of p_{re} only makes sense when

$$\begin{cases} \sin\theta_{re}\cos\phi_{re} - \sin\theta_i\cos\phi_i = \dfrac{1}{k_0}\dfrac{\partial\psi(x,y)}{\partial x} \\ \sin\theta_{re}\sin\phi_{re} - \sin\theta_i\sin\phi_i = \dfrac{1}{k_0}\dfrac{\partial\psi(x,y)}{\partial y}, \end{cases} \quad (8)$$

where ψ is a linear function with respect to x and y. Equation (8) unveils the relation between the incident direction and the direction of p_{re}, i.e., 3D IGSL, which is regarded as the generalized law for acoustic metasurface reflection. We note that if the metasurface is thin and allows transmission, Eq. (8) is the generalized law of refraction for the metasurface as well, revealing the generality of our approach. It is noteworthy that if ψ is a constant for a uniform 2D SAI, Eq. (8) will be reduced to the usual Snell's law. 3D IGSL serves the manipulation of the vibration of fluid particles excited by p_{re}, theoretically via tuning the parameter ψ of the inhomogeneous SAI flat reflector, with no influence on the direction of p_{ro}, as illustrated in Fig. 2(a).

Other advantage of our Green's function formulation also gives p_{ro} amplitude as[13]

$$r_{ro} = p_{i0}(\omega)\times(2A\cos\theta_i - \rho_0c_0)/(2A\cos\theta_i + \rho_0c_0). \quad (9)$$

Usually, both p_{ro} and p_{re} coexist, but 3D IGSL only tunes θ_{re} and ϕ_{re}. In order to obtain purely cross vibration excited by p_{re} with full control, we need to eliminate p_{ro}. By particularly controlling the value of A in Eq. (1), we manage to "switch off" p_{ro}, as illustrated in Fig. 2(b). Based on Eq. (9), if $A=(\rho_0c_0)/(2\cos\theta_i)$, p_{ro} will be eliminated, while the 2D SAI becomes

$$Z_n(x,y,\omega) = \frac{\rho_0c_0}{2\cos\theta_i}\left[1 - i\tan\frac{\psi(x,y)}{2}\right]. \quad (10)$$

Thus, it is discovered that metasurface cannot affect the direction of p_{ro} but just keep or eliminate p_{ro}.

Equally important is the plausible realization schematic of the inhomogeneous SAI in Eq. (1), by discretizing the impedance. As depicted in Fig. 2(c), all hard-sidewall tubes are assembled and juxtaposed perpendicular to the flat interface, illustrated in the top view. Each tube, serving as one discrete 2D SAI pixel of the flat metasurface reflector, has a square cross section whose width is d, with four surrounding hard sidewalls (black). In the view of a cross-sectional slice in Fig. 2(c), one end of each tube constitutes the flat interface of the metasurface at $z = 0$ (yellow dashed line), and the other end contacts with air (light blue). The space $z > 0$ and the interior are filled with water (dark blue), without separation. The water-air interface separated by a thin film (orange) is regarded as the pressure-release termination of each tube.

In order to realize the 2D SAI metasurface's inhomogeneity by impedance discretization, $d < 2\pi/k_0$ is required to eliminate higher diffraction orders. The SAI of each tube at the opening facing $z > 0$ can be calculated[11]

$$Z_t(x, y, \omega) \approx \frac{\rho_0 c_0 k_0{}^2 d^2}{2\pi} - i\rho_0 c_0 \tan[k_0 l(x, y) + k_0 \Delta l], \quad (11)$$

where $l(x, y)$ is the spatial distribution of the length of each tube and $\Delta l \approx 0.6133d/\sqrt{\pi}$ is the effective end correction. By comparison between Eqs. (1) and (11), it is required that $A = \rho_0 c_0 k_0{}^2 d^2/(2\pi)$ and $A \tan[\psi(x, y)/2] = \rho_0 c_0 \tan[k_0 l(x, y) + k_0 \Delta l]$, leading to the value of the spacing d for discretization and the dependence between $l(x, y)$ and $\psi(x, y)$

$$d = \sqrt{(2\pi A)/(\rho_0 c_0 k_0{}^2)}$$
$$l(x, y) = \frac{1}{k_0} \arctan\left[\frac{k_0{}^2 d^2}{2\pi} \tan\frac{\psi(x, y)}{2}\right] + \frac{n\pi}{k_0} - \Delta l, \quad (12)$$

where the arbitrary integer n is required to be set suitably to make l a positive value. Thus, the change of ψ at the flat-metasurface reflector, representing the manipulation of fluid-particle vibrations through the control of p_{re}, is now interpreted by the change of l (red dashed line in Fig. 2(c)), demonstrating one straightforward realization scheme based on impedance discontinuity. In principle, tubes can be regarded as Helmholtz resonators, and the complex SAI at each pixel can thus be realized by a suitable arrangement of resonators.

The simulation results verify the robustness in the manipulation of fluid-particle vibrations according to our 3D IGSL. We first consider the ideal case without using the tube-array configuration, by selecting water as the background media and $\psi(x, y) = -100\sqrt{3}y$ at the SAI metasurface in Eq. (10). The incident plane ultrasound with $\omega = 300$ Krad/s, $\theta_i = 18°$, and $\varphi_i = 180°$ is impinged upon the metasurface at $z = 0$. The spatial angles for p_{re}, i.e., θ_{re}, and φ_{re}, are theoretically found to be 66.9° and 250.4° by 3D IGSL in Eq. (8), respectively. The simulation in Fig. 3(b) validates our theory, where p_{ro} disappears thoroughly owing to the specific design of the coefficient according to Eq. (10). The cut slice at $\varphi_{re} = 250.4°$ in Fig. 3(b) clearly shows that p_{re} is propagating towards the predicted direction without any disturbance. In other words, we realize this out-of-incident-plane reflection, and simultaneously achieve the full manipulation of its fluid-particle vibration.

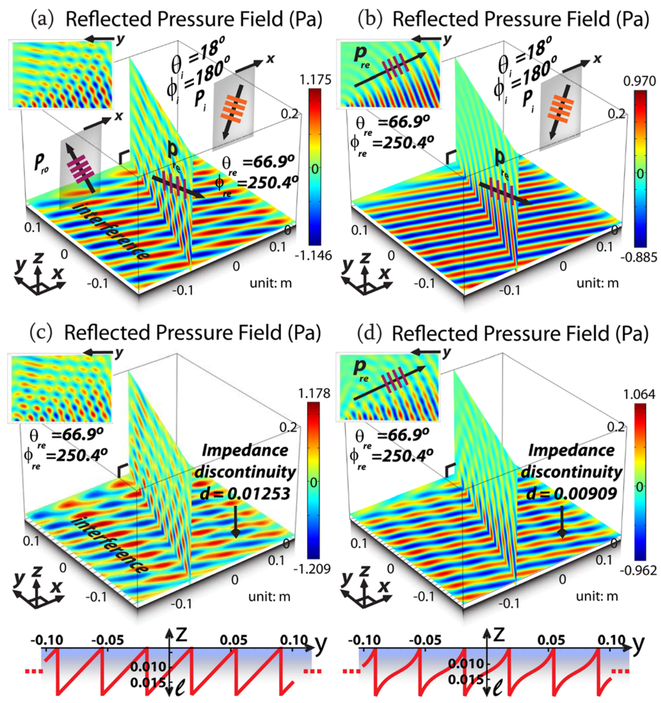

FIG. 3. (a) The acoustically flat-metasurface reflector with an inhomogeneous SAI excites both p_{ro} and p_{re} when an arbitrary A is chosen in Eq. (1). The fluctuation of the interference verifies our theory. (b) A particular SAI is suggested according to Eq. (10) so that only the pure out-of-incident-plane vibration is excited by p_{re} with an expected direction. (c) and (d) Simulation results based on the realization of tube arrays with relations $l(x, y)$ enclosed below, corresponding to the cases (a) and (b), respectively.

In particular, in Fig. 3(a), the same parameters are kept except for another selection for A, whose value is arbitrarily taken to be $\rho_0 c_0$. It clearly shows that p_{ro} coexists and interferes with p_{re}, but p_{re} still keeps the same direction ($\theta_{re} = 66.9°$ and $\varphi_{re} = 250.4°$), verifying our theoretical prediction. Although such *double reflections* are predictable well by our theory, p_{ro} will disturb the manipulated out-of-incident-plane fluid-particle vibration excited by p_{re} in Fig. 3(a). Therefore, we generally "switch off" p_{ro} and make the out-of-incident-plane vibration excited by p_{re} "pure," as demonstrated in Fig. 3(b).

Next, we consider the realization when the metasurface reflector with realistic impedance discretization is applied, in order to reproduce Figs. 3(a) and 3(b). In the reflected-field simulation of Figs. 3(c) and 3(d), $d = 0.01253$ and $d = 0.00909$ are selected, respectively, according to Eq. (12), and their corresponding distributions of $l(x, y)$ are enclosed. (In these two cases there is no variation of l along **x**.) Fig. 3(c) shows strong interference between p_{re} and p_{ro}, while Fig. 3(d) shows the nearly undisturbed p_{re}, coinciding with Figs. 3(a) and 3(b), respectively, verifying our proposed realization using the layout of tube arrays.

Recalling the given example in Fig. 1, we set the oblique incident angles as $\theta_i = 60°$ and $\varphi_i = 225°$. The flat acoustic metasurface with $\psi(x, y) = 100\sqrt{6}x$ in Eq. (10) is placed as the reflector at $z = 0$, whose tube-length distribution $l(x, y)$ is illustrated in Fig. 1(e) according to Eq. (12). Through 3D IGSL in Eq. (8), we manage to make p_{re} arise with the direction $\theta_{re} = 60°$ and $\varphi_{re} = -45°$, and simultaneously make p_{ro} eliminated, corresponding to the simulation of the reflected field in Fig. 1(c). The perpendicular intersection between the incident plane and the x-y-plane projection of the particle vibrations in Fig. 1(c) exhibits the so-called cross vibration of fluid particles excited by reflection, leading to this intriguing "tweak" of vibrational orientations in fluids. Fig. 1(d) is another example to verify the robustness of our theory. The flat metasurface reflector with $\psi(x,y) = 50\sqrt{6}x - 100\sqrt{3}y + 50\sqrt{6}y$ in Eq. (10) is selected and the corresponding $l(x,y)$ is illustrated in Fig. 1(f). Similarly, by the prediction from 3D IGSL, p_{re} occurs to the direction $\theta_{re} = 60^\circ$ and $\varphi_{re} = 270^\circ$ with the suppression of p_{ro}, whose field projection at the plane perpendicular to $\mathbf{z}$ is Fig. 1(d).

In summary, we propose an acoustic flat metasurface reflector to manipulate vibrational orientations of fluid particles in acoustics, and show that a complete conversion between two perpendicular vibrations by deviating the extraordinary reflection p_{re} out of the incident plane. It is found that the control of the metasurface's parameter can keep p_{re} only, while suppressing the ordinary reflection. We also theoretically unveil the generalized rule of 3D IGSL with respect to the specific acoustic impedance. The out-of-incident-plane fluid-particle vibration and the arbitrary degree of freedom in directional manipulation are numerically implemented using the designed layout of tube arrays.

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