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Controllable transmission and total reflection through an impedance-matched acoustic metasurface

Jun Mei\(^1\) and Ying Wu\(^2\)

\(^1\) Department of Physics, South China University of Technology, Guangzhou 510640, People’s Republic of China
\(^2\) Division of Computer, Electrical and Mathematical Sciences and Engineering, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

E-mail: ying.wu@kaust.edu.sa

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Abstract

A general design paradigm for a novel type of acoustic metasurface is proposed by introducing periodically repeated supercells on a rigid thin plate, where each supercell contains multiple cut-through slits that are filled with materials possessing different refractive indices but the same impedance as that of the host medium. When the wavelength of the incident wave is smaller than the periodicity, the direction of the transmitted wave with nearly unity transmittance can be chosen by engineering the phase discontinuities along the transverse direction. When the wavelength is larger than the periodicity, even though the metasurface is impedance matched to the host medium, most of the incident energy is reflected back and the remaining portion is converted into a surface-bound mode. We show that both the transmitted wave control and the high reflection with the surface mode excitation can be interpreted by a unified analytic model based on mode-coupling theory. Our general design principle not only supplies the functionalities of reflection-type acoustic metasurfaces, but also exhibits unprecedented flexibility and efficiency in various domains of wave manipulation for possible applications in fields like refracting, collimating, focusing or absorbing wave energy.

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1. Introduction

Impedance is one of the most important physical quantities in the study of wave propagation, because it determines the scattering property of a wave when the wave comes across an interface. Consider a plane wave propagating in medium 1 normally incident onto an interface between medium 1 and medium 2. The reflection coefficient ($r$) is determined by $r = (Z_1 - Z_2)/(Z_1 + Z_2)$, where $Z_1$ and $Z_2$ are, respectively, the impedances of medium 1 and medium 2. Thus, it is apparent that if the impedances of the two media are matched ($Z_1 = Z_2$), all of the incident wave energy will transmit through the interface without reflection. In contrast, we show here that it is possible to achieve total reflection even though the impedances of two materials are matched. This counterintuitive phenomenon is attained by introducing a simple design of an acoustic metasurface with matched impedance to the host medium.

The metasurface, the planarized version of metamaterials, is an emerging concept that has attracted a great deal of attention in recent years [1-17]. One of the key features of metasurfaces is their subwavelength thickness, which greatly facilitates their fabrication and integration into small systems. The emergence of acoustic metasurfaces [18-21] therefore represents an important advance in the miniaturization of acoustic devices like lenses, waveguides, beam formers, etc. Several interesting studies on acoustic metasurfaces have been reported, including work on vibrational orientation engineering [18], reflected wavefront manipulation [19, 20], and high absorption [21]. In those studies, the main functionality of the acoustic metasurfaces lies in the manipulation of the reflected waves.

In this paper, we focus on establishing the functionality of an acoustic metasurface in the transmission domain. Such a metasurface has matched impedance to the host medium and a specially designed phase profile. Following a general design principle, we show that in the long wavelength region, it enables nearly total reflection of a normally incident plane wave accompanied by excitation of a surface-bound mode; in the short wavelength region, it renders opportunities to tailor the transmitted waves that can propagate along arbitrary directions with almost unity transmission. We systematically study these intriguing phenomena, using both full-wave simulations and theoretical analysis based on mode-coupling theory for acoustic waves [22-25]. The analytic model provides us clear guidance for the realization of desired functionalities. Potential uses in diverse applications like wave energy collimation, focusing, and enhanced absorption are envisaged.

2. Acoustic metasurface

2.1. Design and characteristics

The schematic of the acoustic metasurface is illustrated in figure 1(a). It is immersed in air and is formed by introducing periodically repeated supercells on a rigid thin plate with thickness $h$. Each supercell contains $m$ cut-through slits. The width of each slit is $w$ and the separation between two neighboring slits is $p$. Thus, the period of one supercell is $d = m(w + p)$. We use
the index $i = 1, 2, ..., m$ to mark the slits in one supercell from the left to the right. The $i$th slit is filled with a material that has refractive index $n_i = 1 + (i - 1)\lambda_0/mh$ (such an index profile is required by the functionalities of the metasurface, as will be explained in details in section 2.2) and impedance $Z_i = Z_0$, where $Z_0$ and $\lambda_0$ are, respectively, the impedance and wavelength of air. We would like to emphasize three important features of such a system. First, the impedance of the material inside each slit is matched to that of air, which can enhance wave transmission and suppress reflection. Second, the difference in the refractive indices of neighboring slits is a constant, indicating that the phase difference between the ‘acoustic paths’ in adjacent slits is a constant, which is crucial to generate a continuous pattern of the wavefront for the transmitted wave. Third, the filling materials in the slits are dispersive and should be adapted to the working

Figure 1. (a) A schematic of one supercell of the acoustic metasurface. (b) The calculated transmittance at different wavelengths. (c)–(e) The pressure field patterns when a plane wave is normally impinging on the metasurface from the bottom at wavelengths $\lambda_0 = 0.6d$, $0.7d$, and $0.8d$, which correspond to points A, B, and C in figure 1(b), respectively.
frequency. However, in reality, it is challenging to satisfy all the conditions over the whole frequency range. From an experimental point of view, the functionality of a real acoustic metasurface is usually optimized for a particular working frequency (or within a specified narrowband frequency range) and may still work for certain bandwidth with relatively good performance. Thus, we want to emphasize that the proposed structure is a general design paradigm of a novel type of acoustic metasurface. The examples presented in the following context indeed show that the same design principle can be successfully applied to different frequency regions, and some interesting phenomena are found. Throughout this paper, we focus on the situation where the thickness of the rigid plate is less than the wavelength in air \( h < \lambda_0 \). In this sense, we can treat the thin plate as an acoustic ‘metasurface’.

A simple design of a metasurface is considered here in the following proof-of-principle demonstration, where each supercell comprises four slits \((m = 4)\) and each slit’s width and height are \( w = 0.2d \) and \( h = 0.5d \), respectively. We assume that a plane acoustic wave is normally impinging on the metasurface from the bottom, and we calculate the wave energy transmittance spectrum by full-wave simulation based on finite-element method (COMSOL Multiphysics), which is plotted in figure 1(b). We observe that the transmittance almost maintains unity in the short wavelength region where \( \lambda < d \), but it exhibits a steep drop from 98\% to 1.6\% when \( \lambda_0 \) is increased to \( d \), showing a step-function-like profile. When \( \lambda_0 \) is further increased, the transmittance remains nearly zero. It is worth noting that although the transmittance varies dramatically across the whole spectrum range of figure 1(b), the impedance of the metasurface does not change; it is always matched to that of the host medium. In what follows, we investigate the transmission behaviors in different frequency regions and explore their corresponding physical mechanisms.

### 2.2. Performance and functionalities

In the short wavelength region where \( \lambda_0 < d \), the pressure field patterns for a normally incident plane wave with \( \lambda_0 = 0.6d \), \( 0.7d \) and \( 0.8d \) are shown in figures 1(c)–(e), respectively. We observe that the transmitted waves bend in different directions from the original direction of the incident wave. The high transmission efficiency (>98\%) is achievable because of the relatively large width of the slits and, more importantly, the matched impedance between the slit-filling materials and air. The arbitrary direction of the transmitted wave is obtained from our special design of the metasurface. As mentioned above, each slit of the metasurface (e.g., the \( i \)th slit) is filled with materials having different wave velocities \( c_i = c_0/m_i \). Thus, the wavefronts inside different slits accumulate different phase changes \( \Phi_i \) when they pass through the thin plate. For example, the first slit in the supercell is filled with air, i.e., the background medium, whose relative refractive index is \( n_1 = 1 \). Therefore, the corresponding phase change is given by \( \Phi_1 = \omega h / c_0 \). Considering that \( \Phi_i = \omega n_i / c_0 = \Phi_1 + 2\pi (i - 1)/m \ \ (i = 2, 3, \ldots m) \), the phase difference between the ‘acoustic paths’ in neighboring slits is a constant and is given by \( \Delta \Phi = \Phi_{i+1} - \Phi_i = 2\pi/m \). Thus, the phase change between the \( i \)th slits of the neighboring supercells is always \( 2\pi \), which is required to maintain a continuous and smooth wavefront pattern of the transmitted wave. Since \( \Delta \Phi \) is a constant and the distance between the centers of the neighboring slits is also fixed, we can use a constant transverse phase gradient, \( d\Phi/dx = 2\pi/d \), to describe the phase changes along the \( x \)-direction on the upper surface of the thin plate. Such a transverse phase gradient gives rise to oblique transmitted waves due to the generalized Snell’s law of refraction [1]:
\[ k_0 \left[ \sin(\theta_i) - \sin(\theta_t) \right] = \frac{\partial \Phi}{\partial x}, \tag{1} \]

where \( \theta_i(\theta_t) \) is the angle of incidence (refraction), and \( k_0 = 2\pi/\lambda_0 \) is the wavenumber in the background (air). According to equation (1), the refraction angle is given by \( \sin(\theta_t) = \lambda_0/d \) when the plane wave is normally incident on the metasurface as discussed earlier. In figures 1(c)–(e), we draw the refraction angles predicted by the formula \( \theta_t = \arcsin(\lambda_0/d) \) over the full-wave simulation patterns, and excellent agreement between the predictions and the field patterns is observed.

The formula \( \theta_t = \arcsin(\lambda_0/d) \) also predicts that the refraction angle, \( \theta_t \), will increase if \( \lambda_0 \) increases, as long as \( \lambda_0 \) does not exceed \( d \). Such monotonic behavior of \( \theta_t \) as a function of \( \lambda_0 \) has already been verified by the results shown in figures 1(c)–(e). This means that the metasurface is capable of tuning the directions of the transmitted waves at different frequencies. This functionality of controlling and molding transmitted acoustic waves over a large angular domain with high efficiency, together with the recent reported results on manipulating reflected waves [18–20], enables the possibility of full control of acoustic waves using metasurfaces on a planar subwavelength platform. Here, we point out that in order to maintain a relatively smooth wavefront for the transmitted wave, \( \lambda_0 \) should cover at least two slits.

When \( \lambda_0 \) is increased to \( d \), as shown in figure 1(b), the transmittance drops from 98\% to 1.6\%. The pressure field pattern at \( \lambda_0 = d \) is plotted in figure 2(a), in which we see, remarkably, that the refraction angle is 90° and the transmitted wave behaves like a plane wave propagating along the surface of the thin plate, i.e., the \( x \)-direction, even though the incident wave is propagating in the \( y \)-direction. The 90° refraction angle can be predicted by equation (1). If the wavelength, \( \lambda_0 \), is further increased to be larger than \( d \), interesting phenomena appear. As shown in figure 2(b), the pressure field pattern for the case of \( \lambda_0 = 1.6d \) exhibits two features: most of the incident wave is reflected back, and the transmitted wave, which accounts for only a
small portion of the total energy, is confined on the surface of the metasurface with a wavelength/transverse periodicity of $d$.

2.3. A unified analytic model

The generalized Snell’s law can predict the propagating directions of the transmitted waves in the short wavelength region ($\lambda_0 \leq d$). But it cannot give quantitative information on the transmittance and it cannot explain the total reflection accompanied with the confined surface mode either. In the following, we develop a unified analytic model based on mode-coupling theory [22–25] to study the physical origins of the intriguing transmission and reflection properties over the whole wavelength regime covering all the cases of $\lambda_0 < d$, $\lambda_0 = d$, and $\lambda_0 > d$.

We divide the entire domain into three regions, as shown in figure 2(b). In Region I, a plane wave with wave-vector $k_0$ is incident along the $y$-direction and part of it is reflected back. Because of the periodic structure on the metasurface, we can express the pressure field in this region as

$$ p^I = \sum_n \left( \delta_{n,0} e^{ik_0 y} + r_n e^{-ik_0 y} \right) e^{iG_n y}, $$

where $\delta_{n,0}$ is the Kronecker delta, $k_{y,n} = \sqrt{k_0^2 - G_n^2}$ is the $y$-component of wave-vector $\vec{k}$ of the $n$th-order diffracted wave, with $G_n = 2\pi n/d$ being the reciprocal vector, and $r_n$ denotes the normalized pressure amplitude of the $n$th reflected–diffracted wave. In Region III, the wave field consists of transmitted waves only, so that

$$ p^III = \sum_n \left( t_n e^{ik_{y,n}} \right) e^{iG_n y}, $$

where $t_n$ denotes the normalized pressure amplitude of the $n$th transmitted–diffracted wave. The metasurface is marked as Region II. Since the width of each slit, $w$, is much smaller than the wavelength, we approximate the wave propagation inside the slits by retaining only one waveguide mode. In this way, the pressure field inside the $i$th slit can be written as

$$ p^I = a_i e^{ik_i y} + b_i e^{-ik_i y}, $$

where $k_i = k_0/n_i$ is the wave-vector for the acoustic waves inside the $i$th slit. By requiring continuity of $v_y$ and pressure at the two interfaces of the thin plate over the slit region, and making $v_y$ vanish elsewhere on the interfaces, we obtain the following equations for the solution of the wave energy transmittance and reflectance:

$$ 1 + n_i + \left( n_i e^{iG_{1i} + r_{-1} e^{iG_{-1i}}} \right) \sin \left( \frac{G_{1i} w}{2} \right) = a_i + b_i, \quad (i = 1, 2, 3, 4), \quad (2.1) $$

$$ t_0 + \left( t_1 e^{iG_{1i}} + t_{-1} e^{iG_{-1i}} \right) \sin \left( \frac{G_{1i} w}{2} \right) = a_i e^{ik_i} + b_i e^{-ik_i} \quad (i = 1, 2, 3, 4), \quad (2.2) $$

$$ (1 - r_0) \frac{k_0 d}{\rho_0} = \sum_{i=1}^4 \frac{k_i w (a_i - b_i)}{\rho_i}, \quad (2.3) $$

$$ t_0 \frac{k_0 d}{\rho_0} = \sum_{i=1}^4 \frac{k_i w (a_i e^{ik_i} - b_i e^{-ik_i})}{\rho_i}, \quad (2.4) $$

$$ -r_{\pm 1} \frac{k_{y,\pm 1} d}{\rho_0} = \sum_{i=1}^4 \frac{k_i w (a_i - b_i) e^{-iG_{\pm 1i}}}{\rho_i} \sin \left( \frac{G_{1i} w}{2} \right), \quad (2.5) $$
∑ρρ = −α ± ± = −− ±][(t)kd kw a b Gw ee e sinc 2 , (2.f)

where αi denotes the position of the center of the ith slit and ρ = Zci ii is the mass density of the respective material. The predictions of transmitted waves by mode-coupling theory are shown in figures 3(a)–(c) for λ0 = 0.6d, d, and 1.6d, respectively. They agree well with their corresponding numerical simulated patterns, i.e., figures 1(c), 2(a), and (b), respectively, without adjusting any parameter. We note that to obtain the results shown in figure 3, we only need to use the first-order diffraction waves (|n| ≤ 1) in Regions I and III, and contributions from other higher-order diffraction waves are negligible. Thus, only three reflection/transmission coefficients (n0±1 and t0±1) need to be solved in equation (2), which significantly reduces the complexity of the problem.

In the long wavelength region where λ0 > d, we have large n0 and t±1, while other terms (t0 and r±1) are almost zero. In this case, λ0 = 1.6d. By solving equation (2), we obtain the values of the reflection/transmission coefficients as follows: n0 = 0.928 + i × 0.372, t0 = (4.032 + i × 2.514) × 10−16, r±1 = (-0.733 + i × 1.231) × 10−16, r−1 = (-3.891 - i × 2.600) × 10−16, t+1 = -1.053 - i × 0.076, t−1 = -1.006 - i × 0.321. Using these values, we calculated the field distributions and plot it in figure 3(c). Large n0 and almost zero t0 account for the high reflection and low transmission in the far field. High t±1 means that the first-order transmitted–diffracted waves with horizontal wave vector ±2π/d are dominant in Region III. However, these waves are evanescent along the vertical direction (i.e., the y-direction) because k±1 = \sqrt{k_0^2 - (2π/d)^2} are purely imaginary. Hence, they do not contribute to the far-field transmission. They interfere with each other and lead to the surface-bound mode shown in figure 3(c). Thus, the total reflection of an impedance-matched metasurface is the result of the vanishing zero-order transmitted waves and the occurrence of the surface-bound mode originates from the interference between the +1 and −1 orders of evanescent transmitted waves, as revealed by mode-coupling theory.

In the short wavelength region where λ0 < d, we have large t1, nonzero but small enough t−1 and n0, and other terms (t0 and r±1) that are almost zero. Since n0 is small in magnitude, e.g.,
$|n_1|^2 < 0.12$ for $\lambda_0 = 0.6d$, the reflection is weak and most of the incident wave energy can transmit through the thin plate with high efficiency, which is a desired property in realizing a transmission-type metasurface. On the other hand, since $k_y, \pm l = \sqrt{k_0^2 - (2\pi/d)^2}$ are real numbers in this case, both the $t_1$ and $t_{-1}$ terms represent propagating waves in Region III. Considering that the transmission coefficients, $t_1$ and $-t_{-1}$, are substantially different in their magnitudes $t_1 > |t_{-1}|$, the interference effect of these two waves is dominated by $t_1 e^{ik_{x,1}x}$ and leads to an oblique transmitted wave with the refraction angle given by

$$\theta = \arctan \left( \frac{G_1}{k_0} \right) = \arcsin \left( \frac{G_1}{k_0} \right) = \arcsin \left( \frac{\lambda_0}{d} \right),$$

which is consistent with the generalized Snell’s law discussed earlier. Therefore, the interference effect between two asymmetrical propagating diffraction orders is the underlying physics for the bending of the transmitted waves as shown in figure 3(a).

At the critical point where $\lambda_0 = d$, we have large $n_0$ and $t_{\pm 1}$. Again, there exists nonzero reflection. Since $k_y, \pm l = \sqrt{k_0^2 - (2\pi/d)^2} = 0$ in this case, in Region III we obtain an $x$-direction propagating mode with wavevector $k_x = G_{\pm 1} = \pm 2\pi/d$, from which we can tell that the transmitted wave should have the same spatial period as the supercell and that the refractive angle equals 90°, which are indeed demonstrated in figure 3(b).

### 2.4. Realization of the metasurface

Here we propose a simple method to realize the acoustic metasurface by using existing natural materials, with an example shown in figure 4. Basically, we use the composites of two noble gases, i.e., argon and xenon, to realize the refractive index $n_i$ and impedance $Z_i$. The reasons for us to choose these two gases are stated as follows. First, both of them are odorless gases with very low chemical reactivity. Therefore, it is safe to use them in the experiments. Second, the sound speeds in argon and xenon gases are $c_{\text{Arg}} = 323 \text{ m s}^{-1}$ and $c_{\text{Xen}} = 169 \text{ m s}^{-1}$, respectively, both of which are smaller than the sound speed in air. Their acoustic impedances are $Z_{\text{Arg}} = 576.2 \text{ Pa s m}^{-1}$ and $Z_{\text{Xen}} = 996.1 \text{ Pa s m}^{-1}$. Such a combination of material parameters enables us to design the metasurface with desired properties. We will show in detail that by placing the composite gases (consisting of argon and xenon with specified filling ratios) in the second, third and fourth slits of the supercell, it is possible to satisfy the required phase difference condition between neighboring slits as well as the impedance-matching condition.

We use $k_{\text{Arg}}$ and $k_{\text{Xen}}$ to denote the wave-vectors in argon and xenon, respectively, and $h_{\text{Arg}}$ and $h_{\text{Xen}}$ to denote their corresponding heights. The phase accumulation in the $i$th slit is expressed as: $\Phi_i = k_{\text{Arg}} h_{\text{Arg}} + k_{\text{Xen}} h_{\text{Xen}}$. According to the phase gradient condition stated in section 2.2, it should satisfy $\Phi_i = k_{\text{Arg}} h_{\text{Arg}} + k_{\text{Xen}} h_{\text{Xen}} = \Phi_1 + (i-1)\pi/2 = k_0 h + (i-1)\pi/2$. The geometric size requires that the total thickness of the two gases equal to that of the thin plate, i.e., $h_{\text{Arg}} + h_{\text{Xen}} = h$. By solving these two equations, we get the roots of $h_{\text{Arg}}$ and $h_{\text{Xen}}$ for the $i$th slit ($i=2, 3, 4$). The spatial distributions of argon and xenon are precisely demonstrated in figure 4(a), when the working wavelength is $\lambda_0 = 0.6d$. Once $h_{\text{Arg}}$ and $h_{\text{Xen}}$ as well as the structure of the composite are fixed, the input impedance of the composite gas in the $i$th slit is also uniquely determined, which ultimately determine the wave energy transmittance for a normally incident plane wave. It is well known that if the input impedance is perfectly matched to air (background medium), 100% transmittance of wave energy is achieved. When the input impedance slightly
deviates from that of air, we can still obtain high transmittance. In figure 4(a), we plot the wave energy transmittance computed for each single slit ($i = 1, 2, 3, 4$) separately, from which we observe pretty high (>95%) transmittance for any one of them, implying the input impedance is indeed matched to air. In figure 4(b), we plot the pressure field distribution when a plane wave is normally impinging on the metasurface at wavelengths $\lambda_0 = 0.6d$.

Thus, with this simple example, we indeed show that the phase change condition and the impedance-matching condition can be simultaneously obtained by using real structures and materials. In the experiment, the different regions of air, argon, and xenon can be separated by using polyethylene films (thin enough to be regarded as transparent to acoustic waves), as had been successfully used in previous experiment [26]. Finally, we want to point out that it is not a trivial task to achieve desired phase change and matched impedance simultaneously if we simply mix these two gases. In our design, we employ the concept of layered media, which fortunately offers us great flexibility in tuning the input impedance while preserves the required phase change.

We would like to point out that at current level of design and fabrication of acoustic metamaterials, in addition to the simple method proposed above, there are other options/methods that can be used to realize the acoustic metasurface, although these alternatives are more complex and require further studies. Take the metasurface shown in figures 1(c)–(e) as an
example, each slit has a width of \( w = 0.2d \) and a height of \( h = 0.5d \). For the wavelength range considered in this work, \( \lambda_0 \in [0.6d–1.6d] \), the maximum refractive index \( n_{i,\text{max}} \) is given by \( n_{i,\text{max}} = 1 + 3\lambda_0/4h \in [1.9–3.4] \). Such values of refractive index and the required matched impedance to the host medium are attainable, at least in principle, because they have been previously reported in experimental works by using either simple-structured solid scatters with rectangular or cross shape \([27, 28]\), or by using labyrinthine or space-coiling metamaterials with tapered channels and apertures that having significantly improved and broadband impedance matching \([29]\), or a genetic-algorithm-optimized \([30–32]\) acoustic structure which ideally possesses a maximized refractive index, minimized acoustic impedance mismatch with host medium, and minimized frequency dependence \([32]\).

3. Conclusions

To conclude, we propose a general design paradigm for a novel type of acoustic metasurface by introducing periodic cut-through slits in a rigid thin plate and imparting the desired phase change over the surface of the plate. We demonstrate that the wave manipulating properties of the metasurface have unprecedented flexibility. The metasurface can bend normally incident plane waves into desired directions with high transmittance, or it can totally reflect the incident wave even though the impedance is matched to the host medium. When total reflection occurs, a surface-bound mode is excited. The physical origins of these fascinating effects can be interpreted by a unified analytic model based on mode-coupling theory. Our findings not only supply the functionalities of the reflection-type acoustic metasurfaces, but also have potential applications in fields like focusing, localization, and enhanced absorption of wave energy.

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