



# Acoustic Illusion near Boundaries of Arbitrary Curved Geometry

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**We have proposed a scheme and presented the first experimental demonstration of acoustic illusion, by using anisotropic metamaterials to manipulate the acoustic field near boundaries of arbitrary curved geometry. Numerical simulations and experimental results show that in the presence of an illusion cloak, any object can be acoustically transformed into another object. The designed illusion cloak simply comprises positive-index anisotropic materials whose material parameters are non-singular, homogeneous and, moreover, independent of the properties of either the original object or the boundary.**

The coordinate-transformation-based technique of transformation acoustics allows unprecedented flexibility in manipulating acoustic waves with artificially structured metamaterials. Recent advances in acoustic metamaterials<sup>1–9</sup> have promised a way to realize unique material parameters unavailable in nature, giving the possibility of designing unconventional devices such as superlens, concentrators and invisibility cloaks. Among them the invisibility cloak that can create an “illusion” of the original space with the cloaked object concealed, may be one of the most analyzed and fascinating innovations<sup>10–18</sup>. A wide variety of approaches have been proposed which generally fall into two categories. One is hiding an object in a free-space<sup>12–20</sup>, for which the experimental demonstrations are very few since either inhomogeneous and very anisotropic parameters or a negative index material is required<sup>12–14</sup>. Up to now, most of the experimental breakthroughs belong to the other category, the so-called “carpet cloak” that can hide an object in space with a flat boundary<sup>21–23</sup>. Besides, the first demonstration of a macroscopic volumetric cloaking device operating at visible frequencies by using homogeneous anisotropic material is also reported in this category<sup>24</sup>. But acoustic cloaking schemes in more general cases have never been considered in which the object is located near a curved boundary rather than an ideal flat one.

Compared with cloaking an object by simply eliminating its acoustic scattering field, it is more challenging and intriguing to realize an “illusion cloak” for generating a general illusion such that a particular object appears to be like some other object of one’s choice<sup>25–27</sup>. Despite the growing interests in illusion cloaks, challenges still remain in experimentally achieving an effective control of scattering waves to create an illusion. In the previous designs, the constitutive parameters of illusion devices must either be double-negative<sup>25,28</sup> or have a complex spatial distribution<sup>26</sup>. Moreover, the parameters and their distributions should be closely related to the original object, which unavoidably results from the intrinsic transformations. As a result, the experimental realization of an illusion cloak using existing materials becomes extremely difficult, especially when the original object has a complicated configuration. Besides, the previous schemes to realize the illusion cloak are supposed to be in free-spaces, but camouflaging an object near boundaries of curved geometry (e.g., objects near the seafloor where the wave length is small compared to the size of the surface bumps) is more common in practice.

In this Letter, we have proposed and experimentally verified a new scheme to realize the acoustic illusion for an arbitrary object located near a concave surface in any shape. Inherently different from the previous designs, here we manipulate the scattering field of the object by utilizing the interesting features of anisotropic metamaterials instead of resorting to “complementary materials” which necessarily require negative-index materials. Then the resulting illusion cloak has a simple structure comprising anisotropic materials with positive index, for which the material parameters are non-singular, homogeneous and, moreover, independent of the properties of either the original object or the concave boundary. The first experimental demonstration of acoustic illusion is presented, characterized by the phenomenon that the scattering waves from the original object are transformed as if the waves are scattered from another “illusion object” which can be freely designed. In a special case where this



illusion object is chosen as a bulk of background medium, the illusion cloak becomes an invisibility cloak that can hide an arbitrary object near boundaries of curved geometry.

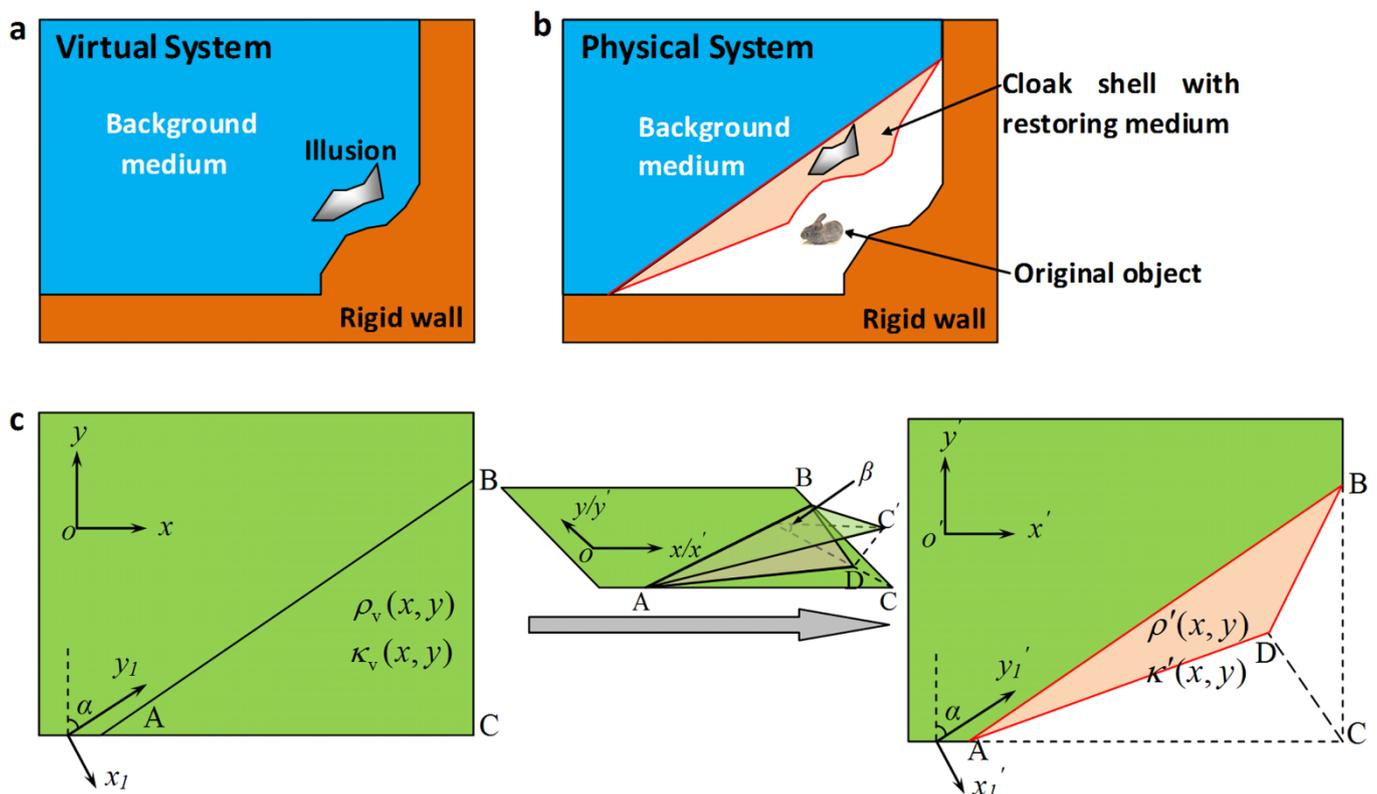
## Results

Figure 1 is a simple schematic diagram illustrating the design idea. In the physical space, a rabbit (the original object) lies near a curved boundary covered by an illusion cloak, as shown in Fig. 1(b). The whole system is perceived as a virtual system [Fig. 1(a)] where there is only a stone (the illusion). In other words, the illusion cloak makes the scattering fields in the real and illusion spaces to be identical. An illustration of the transformation is drawn in Fig. 1(c), where the space with an arbitrary concave boundary is drawn as the rectangle for a clear display. In virtual space ( $x$ - $y$  coordinates), the spatial distribution of mass density tensor and bulk modulus in the illusion area ABC is written as  $\rho_v(x,y)$  and  $\kappa_v(x,y)$  for a general case, which can be designed at will. It is shown that the illusion area ABC is folded for  $\beta$  degrees along the fold line AB into a higher dimension as ABC'. The region ABD is the projection of the triangle ABC' on the  $x$ - $y$  plane and can be regarded as the illusion cloak in physical space ( $x'$ - $y'$  coordinates). In such a way, the region ABC is squeezed as ABD, it is then apparent that the object inside the remaining region ACBD will not affect the reflection any longer.

The specific transformation given by Fig. 1 has established a relationship between the physical and the virtual systems. By realizing the parameters of the illusion cloak accordingly, the scattering field generated by an arbitrary object placed inside the region ADBC will be transformed to be exactly the same as another object with any particular distribution of parameters, i.e.,  $\rho_v(x,y)$  and  $\kappa_v(x,y)$ . The anisotropic nature of the metamaterials composing the cloak shell will yield desired manipulation of the acoustic scattering field of the object if appropriately designed. The acoustic wave can be slowed down in certain directions by decreasing the effective sound velocity

of the metamaterial, and at the same time, the wave can be guided from one direction into another one with no reflection at the boundary between two different media. Particularly, it is noteworthy that the parameters of cloak shell only depend on the values of  $\rho_v(x,y)$ ,  $\kappa_v(x,y)$ ,  $\alpha$  and  $\beta$  (see the equations in Methods). This means the parameters of the cloak shell are completely independent of the original object or its acoustic environment, but only determined by how one folds the space and what kind of illusion will be created. Here the value of  $\beta$  should be less than  $0.5\pi$  to ensure that the mass density tensor is positive definite and no negative-index material is required. In general, the acoustic illusion is supposed to be single or multiple "illusion objects" distributed within the background medium in some particular manner. In such cases, the illusion cloak should be composed by embedding the "restoring media" into the cloaking media, and the restoring media creates the desired illusion effect<sup>25</sup>. The material parameters of the cloaking media are always homogeneous, as the parameters are  $\rho_v(x,y)=\rho_0$  and  $\kappa_v(x,y)=\kappa_0$  for the corresponding illusion object in the illusion space. The constitutive material parameters of the restoring media are non-singular, while their homogeneities depend on the properties of the illusion object. When the illusion object is chosen as homogeneous media, i.e.,  $\rho_v(x,y)=\rho_v$  and  $\kappa_v(x,y)=\kappa_v$ , the parameters of the restoring media should be homogeneous anisotropic as well. Therefore the materials parameters are independent of the geometries of boundaries and the original object. These features significantly simplify the design and fabrication of the proposed structure of illusion cloak. Acoustic field compression in the cloak region essentially makes the constitutive material anisotropic. Larger anisotropy corresponds to a smaller value of  $\cos \beta$ , which helps to reduce the thickness of the cloak shell.

In the current study, the background medium is chosen as air, and the values of  $\alpha$  and  $\beta$  are set to be  $\alpha=45^\circ$  and  $\beta=67^\circ$ , respectively. For simplicity without losing generality, the acoustic illusion here is



**Figure 1** | The virtual and physical systems with the corresponding coordinate transformation. (a) The virtual system. (b) The physical system. The orange regions represent the sound hard boundaries and the proposed invisibility cloak is placed within the regions surrounded by red lines. (c) Illustration of the transformation.  $\alpha$  is the rotation angle of the coordinate system and  $\beta$  is the angle between the plane ABC and ABC'.

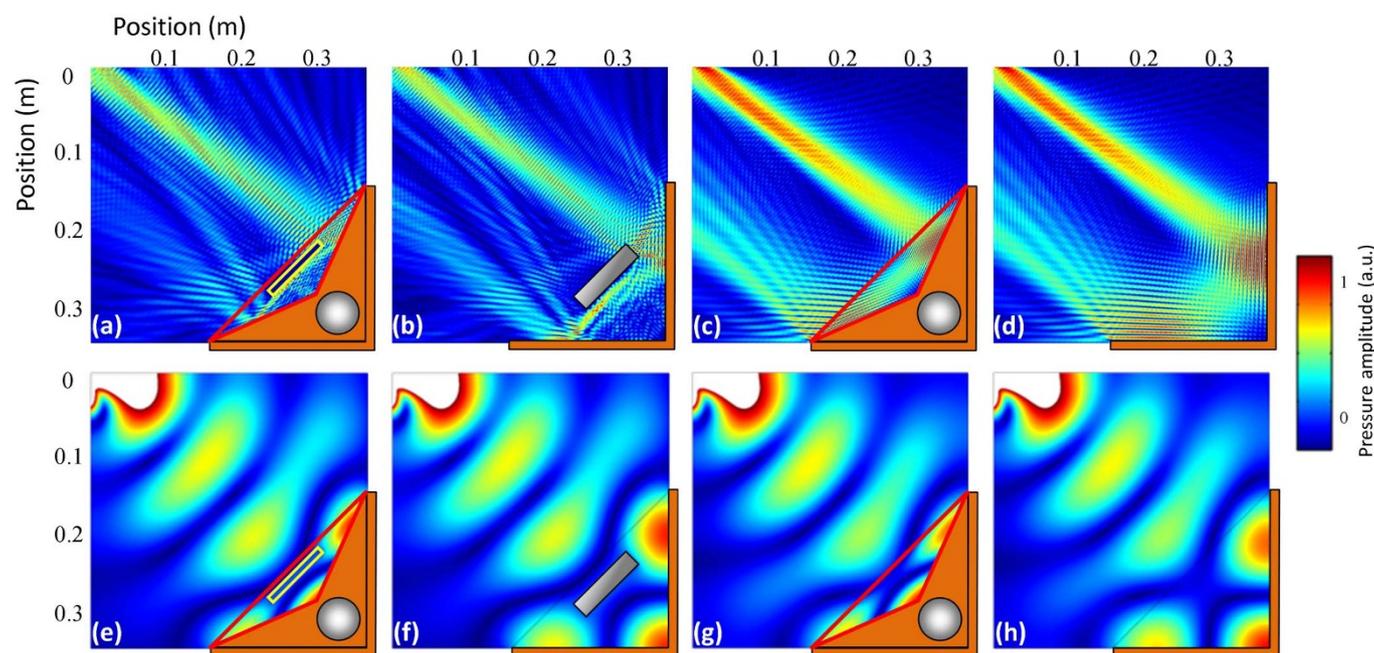


assumed to be a homogeneous object. Then the acoustic parameters in virtual space become two parts:  $\rho_0, \kappa_0$  of the background medium and  $\rho_i, \kappa_i$  of the illusion object, which can be obtained from transformation acoustics. Figures 2(a) and (b) numerically demonstrate the functionality of the illusion cloak, in which the scattering field of the aluminum cylinder (with a radius of 3.5 cm) near a typical rectangular corner is transformed into that of an aluminum right-rectangular prism (with a 2 cm  $\times$  9 cm cross-section). Figure 2(b) displays the scattering patterns of the prism under the excitation of the Gaussian beam (propagating at the angle of  $55^\circ$ ) of 42.5 kHz. In Fig. 2(a), the hybrid cloak is placed above the original object and the scattering pattern is altered in such a way that it is perceived as if there is only the prism. The hybrid cloak in Fig. 2(a) consists of two parts of homogeneous media. One part is the cloaking medium. The desired acoustic parameters can be diagonalized and enlarged with a same ratio<sup>22</sup> and become  $\rho_{11} = 7.71\rho_0$ ,  $\rho_{22} = 1.18\rho_0$ ,  $\kappa = 1.18\kappa_0$ . The rest part is the restoring medium which projects the image of the solid prism for the acoustic illusion. It is composed of an ordinary homogeneous medium of  $\rho' = 7.86\rho_i$  and  $\kappa' = 1.18\kappa_i$  in the global coordinates. Here,  $\rho_i$  and  $\kappa_i$  are much larger than that of air so the prism can be regarded as a rigid object for simplicity. When the illusion object is chosen as the background medium, the illusion cloak becomes an invisibility cloak. The performance of the invisibility cloak is shown in Figs. 2(c) and (d), where the acoustic field is notably different due to the lack of scattering effect of the rectangular prism. Figures 2(e)–2(h) show the corresponding results when the incident wave frequency is chosen as 1.7 kHz. It is observable that when the frequency is comparatively low, the acoustic scattering effect caused by the presence of the rectangular prism is weakened, and the difference between the acoustic fields shown in Figs. 2(e)–2(h) becomes not apparent. Nevertheless, careful scrutiny can reveal that the designed cloak is also capable of making the physical and the virtual spaces seem identical in such a case.

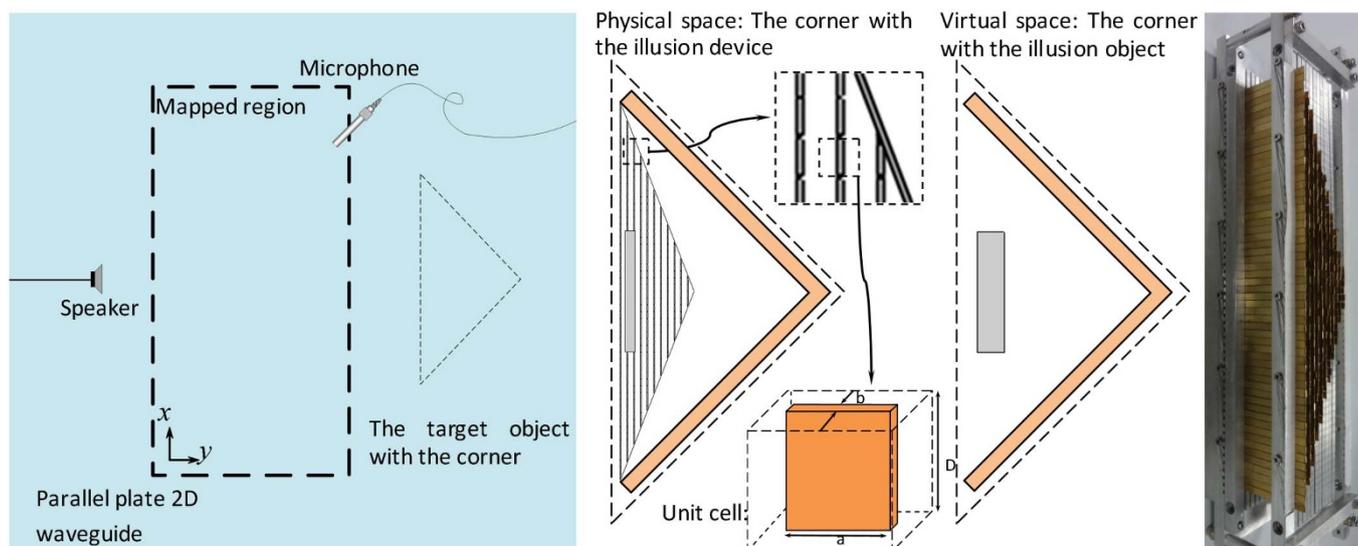
Although the proposed scheme applies to concave curved boundaries with arbitrary shapes, in the experiments we confine ourselves in the typical case of a rectangular corner with sound hard boundary

that can be easily fabricated with high precision, for improving the agreement between the theoretical predictions and the experimental results. The experiment is carried out inside the two-dimensional (2D) parallel plate waveguide standing 3 cm high, the setups and acoustic field mapping area are illustrated in Fig. 3. Considering the difficulty in fabricating the cloak devices with subwavelength structure at high frequency region, the measurement is carried out under a relatively low driving frequency of 1.7 kHz to guarantee the precision of the structural parameters of sample. The anisotropic parameters of the cloaking media are simply realized by arranging a square lattice of thin slabs periodically in air with the structural parameters properly designed<sup>2</sup>. The narrow slit between the slabs can considerably slow down the wave along the direction perpendicular to the slab, but do not reflect the wave as the slabs are so thin that the acoustic impedance along the direction parallel to the slabs does not change much from that of the air. We choose the cell size as  $D = 5$  mm so that the effective acoustic parameters of the structure is obtained as  $\rho_{11}^{\text{eff}} = 7.86\rho_0$ ,  $\rho_{22}^{\text{eff}} = 1.18\rho_0$ ,  $\kappa^{\text{eff}} = 1.18\kappa_0$  at 1.7 kHz. In the experiment, the illusion object is also chosen as the right-rectangular prism, and the illusion device is thus fabricated by inserting the restoring media into the cloaking media as shown in the right part of Fig. 3.

For a particular object, its ability to scatter incident acoustic wave will definitely be weakened as the incident wavelength increases, provided no resonance effect gets involved. This means that the difference between the acoustic scattering fields generated by objects with different shapes is relatively weaker at low frequency region. Under such circumstances, a simple inspection on the acoustic scattering field will fail in serving as an effective and straightforward way to identify the shape of scatterer, especially in experiments. As there exist some seeming similarities between the scattering fields generated by cloaked and uncloaked objects at low frequency region, and for unambiguously evaluating the performance of the designed cloaks, we used the parameter of field disparity (FD) defined as  $\text{FD} = |p(x, y) - p_{\text{illusion}}(x, y)|$ , where  $p(x, y)$  is the sound pressure amplitude measured at  $(x, y)$  in the mapping region when a particular



**Figure 2 | Numerical demonstrations showing the effectiveness of the designed devices.** Acoustic pressure fields (a) in physical spaces (an aluminum cylinder covered by the illusion device), (b) in virtual spaces (only the inhomogeneous illusion object placed in the corner), (c) in physical spaces (an aluminum cylinder covered by the illusion device), (d) in virtual spaces (only background medium with the corner), (e)–(h) the corresponding results for 1.7 kHz. The orange regions represent the sound hard boundaries and the proposed illusion cloak is placed within the regions surrounded by red lines. The restoring media is highlighted by yellow lines.



**Figure 3 | Schematic illustration of the experimental setup.** Two-dimensional parallel plate waveguide used to map the acoustic field near the cloak. The mapped region is indicated together with the sound source. The unit cell of the cloaking media is presented with the measured samples, with  $a = 4.8$  mm,  $b = 0.8$  mm,  $D = 5$  mm. And the photo of the prototype of cloak is also shown in the right.

target is placed near the rectangular corner, and  $p_{\text{illusion}}(x,y)$  is the sound pressure amplitude measured at  $(x,y)$  when the desired illusion object is placed near the rectangular corner. It is obvious that FD gives a quantitative estimation on the similarity between the scattering fields of the target object and the illusion object. When FD vanishes, the scattering fields of the two objects are identical, i.e., each of these two objects can be acoustically perceived as the other one. Figure 4 illustrates the comparison of the measured FD for two cases where the target object is chosen as the original object alone [Fig. 4(a)] and the original object covered with the illusion cloak [Fig. 4(b)] respectively, and also the corresponding numerical simulations [Figs. 4(c) and (d)]. A good agreement is observed between the numerical prediction and the experimental result. It is apparent that the acoustic scattering field generated by the original object alone is significantly different from that of the illusion object, as shown by the large fluctuations in Figs. 4(a) and (c). Contrarily, both the numerical and experimental results of the FDs are negligible [see Figs. 4(b) and (d)] when covered with the illusion cloak, indicating that the existence of the illusion cloak makes the original object to be acoustically perceived as the illusion object. When the illusion object is chosen as air, the device performs well as an invisibility cloak, which is indicated by the phenomenon that FD in Fig. 4(e) is nonzero as the target object is the original object, while FD in Fig. 4(f) tends to zero as the target object is the original object with the cloak. Figs. 4(g) and (h) are the corresponding numerical results.

The sound source is chosen as a 3 cm-diameter sound speaker in the experiments to approximately generate a sound field of an ideal omnidirectional sound source in the 2D waveguide. Although this approach is reasonable when the frequency is only 1.7 kHz, but will generate some disparities between the experimental result and the ideal case in the near field by careful comparison. Besides, a complete sound absorption at the outside boundaries of the 2D parallel plate waveguide cannot be attained at low frequency region. These factors will not affect the performance of the illusion device but will make the field patterns of the experimental and numerical results not identical, as observed from Fig. 4.

## Discussion

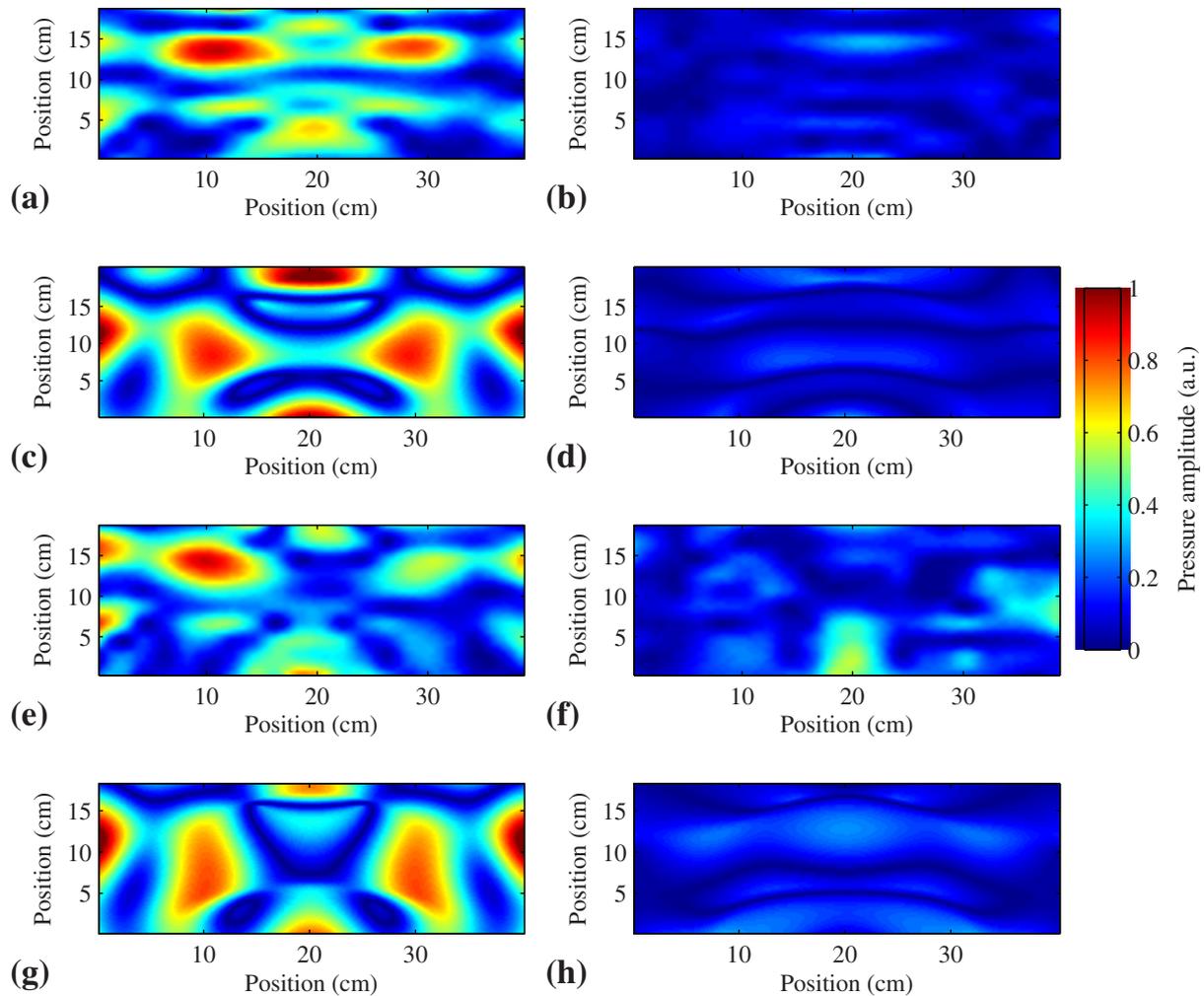
The scheme of illusion cloak should be valid when the boundary is in a different shape and the illusion object is inhomogeneous. Besides, in the experiment, the performance of the proposed structure is

exemplified only for a particular value of driving frequency at low frequency region, just for the purpose of facilitating the sample fabrication as well as guaranteeing the measurement precision. We must stress that, however, our strategy should be able to work within a broad band, in respect of the fact that no resonant element gets involved. The only restriction on the effectiveness of the design is the validation of the effective medium approximation, which requires the sizes of an individual cell unit in the cloak to be sufficiently small as compared with the wavelength. For instance, in the current work the cell size is up to one-fortieth of the wavelength in air but only one-tenth of the wavelength in the metamaterial in the  $y$  direction. If the driving frequency is largely increased, the acoustic wave will begin to interact with the structure and dispersion effect emerges. In such a case, the effective parameters will deviate from the expected values and the performance of the illusion device will be impaired. Further decreasing the cell size with advanced fabrication technology will help to promote the upper limit of the operating bandwidth of the device.

In summary, we have proposed and experimentally verified a new scheme to realize the acoustic illusions of hiding and camouflaging near a non-planar surface. The numerical and experimental results demonstrate that an arbitrary object can be perfectly hidden or acoustically transformed into another one of our choice, by manipulating the acoustic wave with anisotropic acoustic metamaterials. The cloaking medium consists of anisotropic materials with homogeneous positive parameters. Moreover, the parameters of the cloak shell are completely independent of the properties of either the original object or cloaked region. These features, which are made possible by implementing particular anisotropic metamaterials to manipulate the acoustic wave, should significantly facilitate practical applications of the designed structure. And this unique manipulation should also benefit the developments of waveguide, concentrating and imaging devices<sup>29</sup>.

## Methods

The device is designed according to transformation acoustics<sup>19</sup>, the relationship of material parameters between virtual and physical systems can be written as  $\rho'^{-1} = \mathbf{H}\rho^{-1}\mathbf{H}^T / \det(\mathbf{H})$ , and  $\kappa'_1 = \det(\mathbf{H}) \times \kappa_1$ , in which  $\mathbf{H}$  is the Jacobian defined as  $\mathbf{H} = \text{diag}\{\partial x'_1 / \partial x_1, \partial y'_1 / \partial y_1\}$ . The required parameters in the global physical coordinates  $(x',y')$  are obtained to facilitate the following numerical simulations. Hence, the parameters are  $\rho'^{-1} = \mathbf{R}\rho^{-1}\mathbf{R}^T / \det(\mathbf{R})$  and  $\kappa' = \det(\mathbf{R}) \times \kappa_1$ , where  $\mathbf{R}$  is the rotation matrix defined as  $\mathbf{R} = [\cos \alpha, \sin \alpha; -\sin \alpha, \cos \alpha]$ . For folding the area



**Figure 4 | Experimental results.** Experimental results for the illusion cloak with its corresponding numerical result. The field of FD when the target is chosen as (a) the original object without the illusion cloak placed in the corner, and (b) the original object with the illusion cloak placed in the corner. (c), (d) Corresponding numerical results. (e)–(h) Corresponding experimental and numerical results for the invisibility cloak.

ABC, the mapping between the physical region ABD and the virtual one ABC is specified by  $x'_1 = x_1 \cos \beta$  and  $y'_1 = y_1$ . Then the parameters of the cloak are

$$\rho'(x,y) = \begin{pmatrix} \cos^2 \alpha \cos \beta + \frac{\sin^2 \alpha}{\cos \beta} & \frac{\sin \alpha \cos \alpha \sin^2 \beta}{\cos \beta} \\ \frac{\sin \alpha \cos \alpha \sin^2 \beta}{\cos \beta} & \frac{\cos^2 \alpha}{\cos \beta} + \sin^2 \alpha \cos \beta \end{pmatrix} \rho_v(x,y);$$

$$\kappa'(x,y) = \kappa_v(x,y) \cos \beta.$$

The numerical simulation in Fig. 4 is performed with acoustic module of COMSOL Multiphysics® (the commercial software package based on finite-element method). The sound source is idealized as a 2.5 cm line source and the parameters of the ideal sound absorption material are adopted as the PML layer for absorbing the sound waves at the boundary. All the other structural and geometrical parameters of the 2D model are in accord with that shown in Fig. 3. The experiment is carried out inside the 2D parallel plate waveguide standing 3 cm high, the setups and acoustic field mapping area is illustrated in Fig. 3. All the structures, whose cross section is shown in Fig. 3, fill the entire height of the wave guide. A 3 cm-diameter sound speaker is used to excite the waveguide with a sinusoidal signal. Considering the difficulty in fabricating the cloak devices with subwavelength structure at high frequency region, the measurement is carried out under a relatively low driving frequency of 1.7 kHz to guarantee the precision of the structural parameters of sample. The sound pressure is measured by a 1 cm diameter microphone (Brüel & Kjær 4191). The microphone is plugged into the upper plate of the waveguide and can move with the plate in steps in the mapping region above the waveguide. The recording and analysis equipment contain a Brüel & Kjær PULSE 3160-A-042 multichannel analyzer and a desktop computer with Brüel & Kjær PULSE software LabShop version 13.5.10.

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## Author contributions

W.W.K., X.F.Z., R.Q.L. and X.Y.Z. conducted the theoretical simulations and experiments. J.Y. and H.D.W. fabricated the device. W.W.K. and B.L. interpreted the data. W.W.K., B.L. and R.Q.L. constructed the experimental set-up. J.C.C. and B.L. conceived and supervised the study. W.W.K., B.L. and J.C.C. wrote the paper.

## Additional information

**Competing financial interests:** The authors declare no competing financial interests.

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