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Research Article

Revealing the Transformation Invariance of Full-Parameter Omnidirectional Invisibility Cloaks

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Abstract — Searching for an optimal solution among many nonunique answers provided by transformation optics is critical for many branches of research, such as the burgeoning research on invisibility cloaks. The past decades have witnessed rapid development of transformation optics, and different kinds of invisibility cloaks have been designed and implemented. However, the available cloaks realized thus far have been mostly demonstrated with reduced parameters, which greatly impact the predefined cloaking performance. Here, we report a general design strategy to realize full-parameter omnidirectional cloaks that can hide arbitrarily shaped objects in free space. Our approach combines a singular transformation with transformation-invariant metamaterials. The cloaking device with extreme parameters is implemented using a metallic array structure. In the experiment, two cloak samples are designed and fabricated, one with nondiscrete cloaking regions and the other with separated hidden regions. Near-unit transmission of electromagnetic waves with arbitrary incident angles is experimentally demonstrated along with significantly suppressed scattering. Our work challenges the prevailing paradigms of invisibility cloaks and provides deep insight into how transformation optics could be harnessed to obtain easily-accessible metadevices.

Keywords — Transformation optics, Invisibility cloaks, Full-parameter, Omnidirectional.

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I. Introduction

Electromagnetic (EM) nonuniqueness is the universal phenomenon that more than one combination of geometrical structures and material configurations can generate the same or a high-fidelity EM response [1]. Despite the multiple solutions for a given EM response, searching for an easily-accessible solution is an endless goal [2]–[6]. For example, the ability to make an object invisible has been a topic of long-standing interest in both academia and industry due to its intriguing applications that have only been formulated in science fiction. From the physical point of view, an invisibility cloak is designed to suppress the scattering fields from a hidden object or reconstruct its scattered light such that this light is similar to that propagating in the pure surrounding background. A variety of cloaking methods have been proposed to reach this goal [7]–[19]. To the best of our knowledge, however, none of them can achieve ideal omnidirectional invisibility for light incident from any direction in practical experiments. For example, EM absorbers [7] can significantly suppress the scattering in the backward direction. As such, the target covered by the absorber is effectively invisible from a single base station radar device, as the echo signal from the target is suppressed. However, this approach becomes inefficient for bistatic detection, in which multiple base stations allow the detection of the scattering in the forward direction.

Recently, transformation optics (TO) and metamaterials have ignited unprecedented enthusiasm in realizing manmade cloaks that bring a new twist to conventional cloaking techniques [20]–[31]. The underlying mechanism stems from the form invariance of Maxwell's equations: a coordinate transformation does not change the form of Maxwell's equations and only changes the constitutive parameters and field values [32]–[35]. The TO-based cloak can smoothly guide the propagation of light around a hidden object, rendering the object invisible as if it is not there. Despite its remarkable property, the design of the TO cloak is a nonunique problem, e.g., similar cloaking effects can be achieved with an inhomogeneous transformation [36], [37], a linear transformation [38]–[40], scattering cancelation [41], [42], etc. Nonetheless, all of these transformations require extremely complex material parameters with anisotropy and inhomogeneity. In practical implementation, such complex material parameters are often realized in a reduced manner that deteriorates the cloaking performance [43]–[46]. Hence, the question of whether the complex material parameters of ideal full-parameter omnidirectional cloaks can be implemented with an easily acquired technology naturally arises.

Here, we revisit the theory of TO and show that the inherent transformation invariance facilitates the design of various full-parameter metadevices, such as invisibility cloaks. A facile yet viable concept is that an infinitesimal or infinity remains unchanged under any coordinate transformation. Specifically, the cloak is designed with a two-step transformation, i.e., a singular transformation and an invariant transformation. We show that the cloak parameters are independent of the shape of the hidden region, and a metallic channel array structure is subtly designed to fulfill the full-parameter requirement. As experimental proof, we consider two cloaking situations: multiple hidden objects and a single hidden object. Using direct field measurements, we map the magnetic field distributions and demonstrate significant suppression of scattering from the hidden object compared to the uncloaked case. Our work brings deep insight into how TO could enable a myriad of practically oriented applications and provide a new avenue for free-space omnidirectional invisibility cloaks that has never been experimentally realized.

II. Principle

Figure 1 illustrates a schematic of the two-step transformation. To show the generality of our approach for hiding arbitrary objects, we consider the region to be transformed to have the shape of a cloud (the outline is given in Figure 1(a)). The initial space is assumed to be vacuum. In the first step, the solid region within the outline is compressed into a small cloud (grey region II in Figure 1(b)), the constitutive parameters of which are given by $\varepsilon_b^u = \varepsilon_b^v = 1$ and $\mu_b^w = A^2$, where A is the compression ratio between the large and small clouds. To make the impedance of the small cloud match that of free space, an infinitely thin layer, marked by the outline of the large cloud, is stretched into a finite region (green region I) in Figure 1(b). Since the stretching factor is infinite, the constitutive parameters of green region I have singular values, $\varepsilon_a^u = \infty$, $\varepsilon_a^v = 0$, and $\mu_a^w = 0$. Similar to an optical null region (or near-zero-index materials) [47]–[50], green region I can concentrate the EM waves incident from all directions into the inner region without introducing any scattering at the outer boundary. The beauty of the singular values (i.e., infinite or zero) is that an arbitrary coordinate transformation applied to green region I will not change the principal values of its constitutive parameters and only rotate its optical axis. This property enables us to conceal an object of arbitrary shape in green region I by judiciously engineering the orientation of the optical axis. Hence, in the second step, we apply an invariant transformation to green region I and redirect its optical axis (according to the transformation) to guide light around the hidden region, the outline of which is an aircraft marked by the blue solid line in Figure 1(c). Figure 1(c) shows a ray trace diagram for when light illuminates the cloak designed above; i.e., light incident from a random direction is first guided around the aircraft, then concentrated into the small cloud, and finally returned to its original path after passing through the cloak. The details of the transformation are provided in Supplementary Note 1 of the Supporting Information.

III. Materials and Methods

The key to realizing this cloak lies in how to design a metamaterial that satisfies the full-parameter requirement for all regions, especially for region I, in which the parameters acquire both zero and infinite values. Utilizing one-dimensional metallic slit arrays, an equivalent optical null property can be achieved at the Fabry-Perot (FP) resonance frequency. However, this equivalence is valid only when the optical path length along the u direction is a multiple of the wavelength. Such a requirement is stringent and oftentimes complicates the practical implementation of the cloak. Tak-

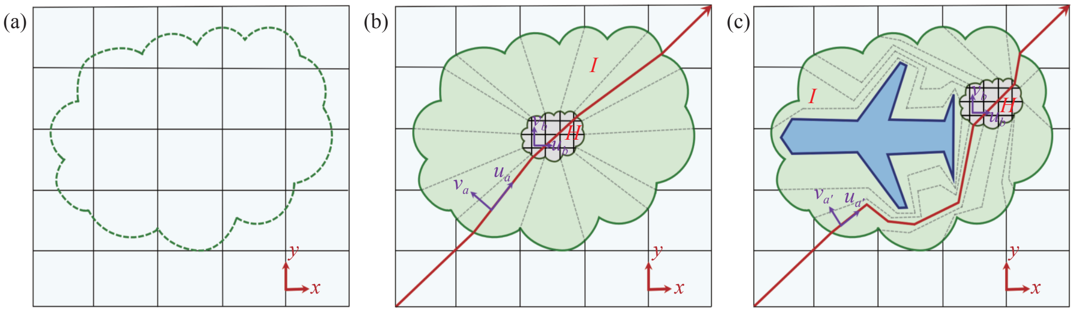

Figure 1 (a) Virtual space; (b) Singular transformation; (c) Ray diagram of light passing through the cloak.

ing Figure 1(c) as an example, the propagation lengths of EM waves in region I are nonuniform in different angular directions, making achieving FP resonance for all angles difficult. Although this problem can be solved by judiciously designing the propagation path and/or applying inhomogeneous dielectric padding in the slits, both procedures complicate the realization of the cloak if the hidden region takes an arbitrary shape.

To address this issue, we successfully design a metamaterial that makes the optical path lengths of light in region I uniform along all directions. Figure 2(a) displays the unit cell of the extreme metamaterial, i.e., a metallic slab corrugated with an air channel. Such an air channel supports the TE_{10} fundamental mode, whose effective relative permittivity is given by $\varepsilon_a^v = n_0^2 - c^2/(4f^2h^2)$, where n_0 is the refraction index of air, c is the speed of light in free space, f is the frequency, and h is the height of the air channel. Apparently, at the cutoff frequency $f = 5$ GHz, $\varepsilon_a^v = 0$. Additionally, the perfect electric conductor (PEC) walls prevent the propagation of EM waves along the v direction, giving rise to $\mu_a^w = 0$ and $\varepsilon_a^u = \infty$. As a result, this metallic channel array metamaterial exhibits the nihility property for tunnelling of EM waves from one side to the other along the u direction, irrespectively of the propagation path or optical path length. The material in region II exhibits a magnetic response along the w direction, which can be realized with a split-ring structure, as shown in Figure 2(b). The unit is composed of four split rings arranged in C4 symmetry on a printed circuit board (PCB). Detailed designs of the unit cell and the retrieval procedure of the effective parameters are provided in Supplementary Note 2 of the Supporting Information.

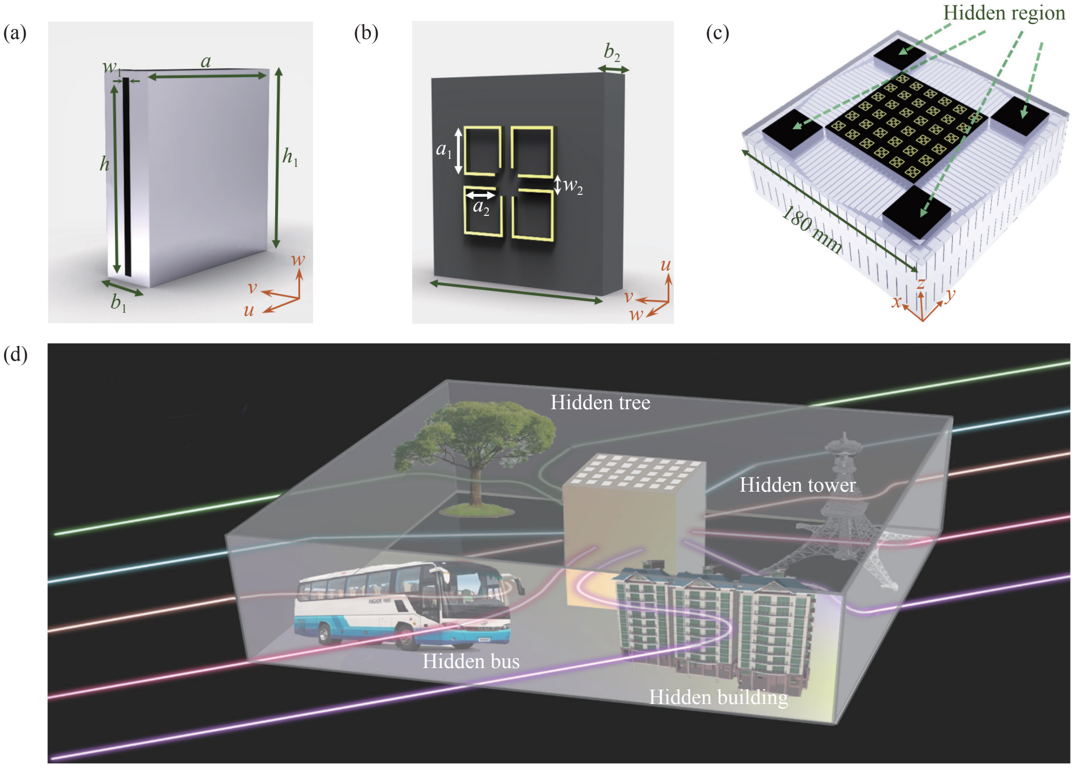

Figure 2 Realization of the omnidirectional metamaterial cloak. (a) Unit cell of the extreme metamaterial; (b) Unit cell of the nonextreme metamaterial; (c) Schematic of the designed cloak; (d) Illustrative scenario for the proposed cloak.

As an experimental demonstration, we fabricate a square cloak to validate its performance in an anechoic chamber. A schematic of the cloak is shown in Figure 2(c). The cloak shell with metallic channel arrays is fabricated using a 3D printing method, while the inner core is filled with split-ring units. These metallic channel arrays depicted in Figure 2(c) can guide EM waves from the outer space to the inner core while circulating them around the four hidden regions at the corners. Notably, this design eliminates the stringent requirement on the optical path lengths of the metallic channels, thereby greatly simplifying the practical implementation of the cloak. Figure 2(d) presents an illustrative scenario for the proposed cloak, and the hidden region is flexible since the path can be freely chosen.

IV. Results

An experiment is performed to measure the $H(z)$-field distributions around the cloak in the anechoic chamber. Figure 3(a) depicts the details of the metallic channel arrays, and the parameter distribution of the cloak is shown in Supplementary Note 3. Figure 3(b) presents a schematic of the measurement system. A C-band (4–6 GHz) horn antenna, located 200 cm from the cloak, is used as the source. A loop antenna with a radius of 10 mm is used as the receiver. Both the transmitting and receiving antennas are connected to a vector network analyzer (VNA) to obtain the amplitude and phase of the measured $H(z)$-field. The loop antenna is attached to a mechanical arm of the 3D measurement platform, which freely moves the antenna in the xoy plane to detect the magnetic field point-by-point. The scanning area is 800 mm × 800 mm with a resolution of 4 mm.

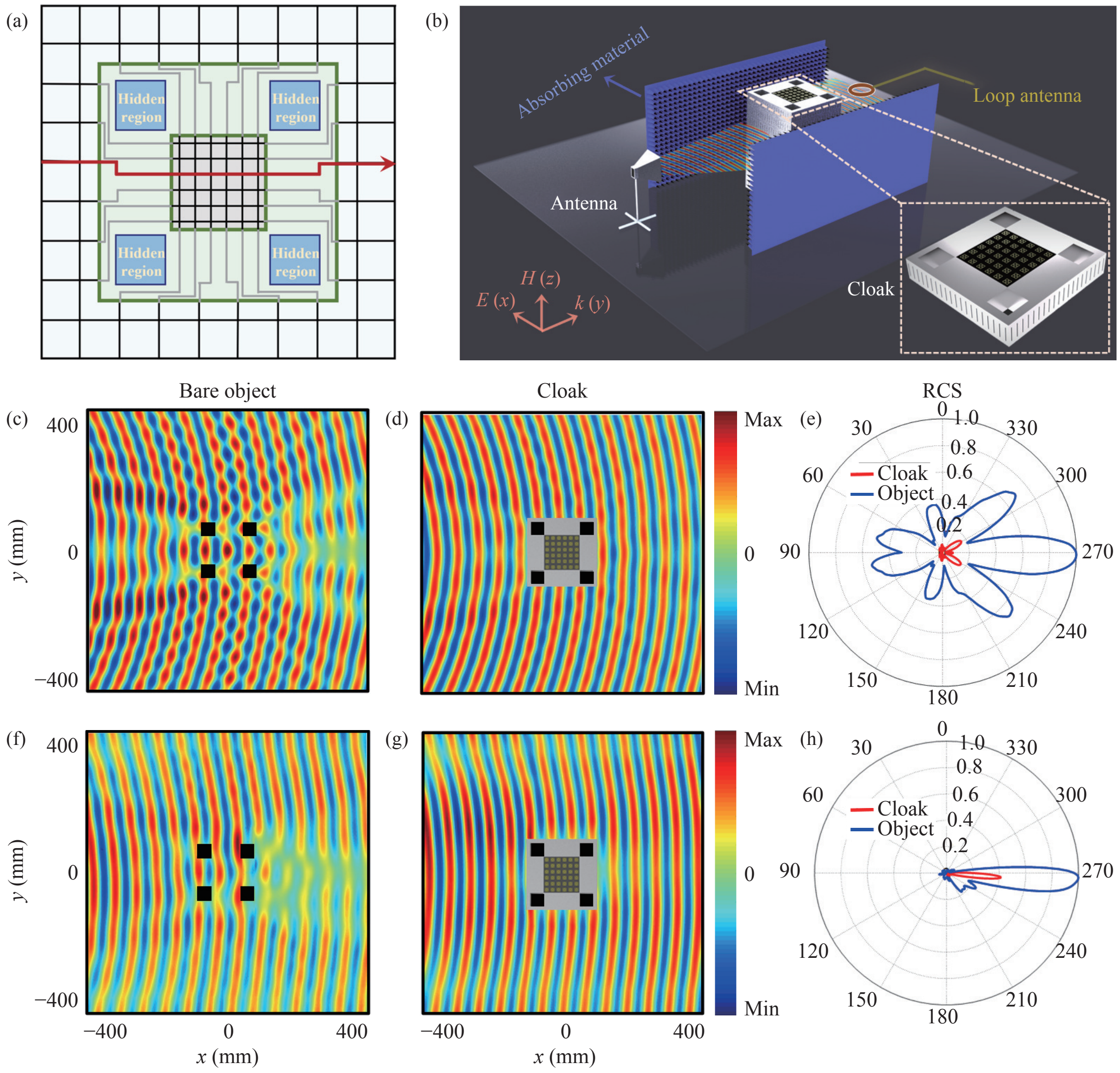

Figure 3 (a) Distribution of the air gaps inside the metal; (b) Experimental setup; (c)–(d): Simulated distributions at 5 GHz for the bare object (c) and the cloaked object (d) under normal incidence from the left; (e) RCS result of the simulation; (f)–(g): Experimental magnetic field distributions for the bare object (f) and the cloaked object (g) under normal incidence; (h) RCS result of the experiment.

For comparison, we plot the simulated magnetic field distributions at 5 GHz for the bare object (Figure 3(c)) and cloaked object (Figure 3(d)) for normal incidence from the left. The corresponding radar cross-section (RCS) is calculated, as shown in Figure 3(e). The four metal squares strongly scatter the incident wave, and the designed cloak eliminates the scattering.

In the experiments, the working frequency of the metamaterial cloak is optimized to be 5 GHz. Figure 3(f) and Figure 3(g) show the measured results for normal incidence. Figure 3(f) shows that when EM waves impinge on the bare object in free space, a shadow forms behind the object, whereas the scattering is significantly suppressed when the object is covered with the cloak, as shown in Figure 3(g), and both the phase and amplitude of the EM waves are successfully reconstructed. To quantitatively demonstrate the cloaking performance, we also determine the differential RCS, defined as $\sigma_{\text{cloakde/bare}} = 2\pi\rho|H_y^{c/b} - H_y^g|^2$, where H_y^c, H_y^b, and H_y^g are the magnetic fields measured for the cloaked object, bare object, and pure background cases, respectively. Here, ρ is 2 m to fulfill the far-field requirement. Figure 3(h) demonstrates that the differential RCS of the cloaked object is significantly suppressed, with a reduction in the total RCS of more than 80%.

Furthermore, to show the ability of the cloak to hide arbitrary objects, another cloak sample is fabricated with a single hidden region at the center. Figure 4(a) displays a schematic of the fabricated cloak, where the right panel shows the details of the metallic channel arrays. Figures

4(b), (c) and (d) show the simulated results. We also measure the magnetic field distributions and RCS for normal incidence at the angle of 0° (Figures 4(e), (f) and (g)). The optimum working frequency of the metamaterial cloak slightly shifts from 5 GHz to 5.05 GHz in this case. Similarly, the cloak well suppresses the scattering from the bare object, as demonstrated by the restored phase and amplitude of the EM waves behind the cloak. To show the omnidirectional ability of the cloak, the field distributions for incident angles of 22° and 45° are also measured; please refer to Supplementary Note 4 and Supplementary Note 5 for more information.

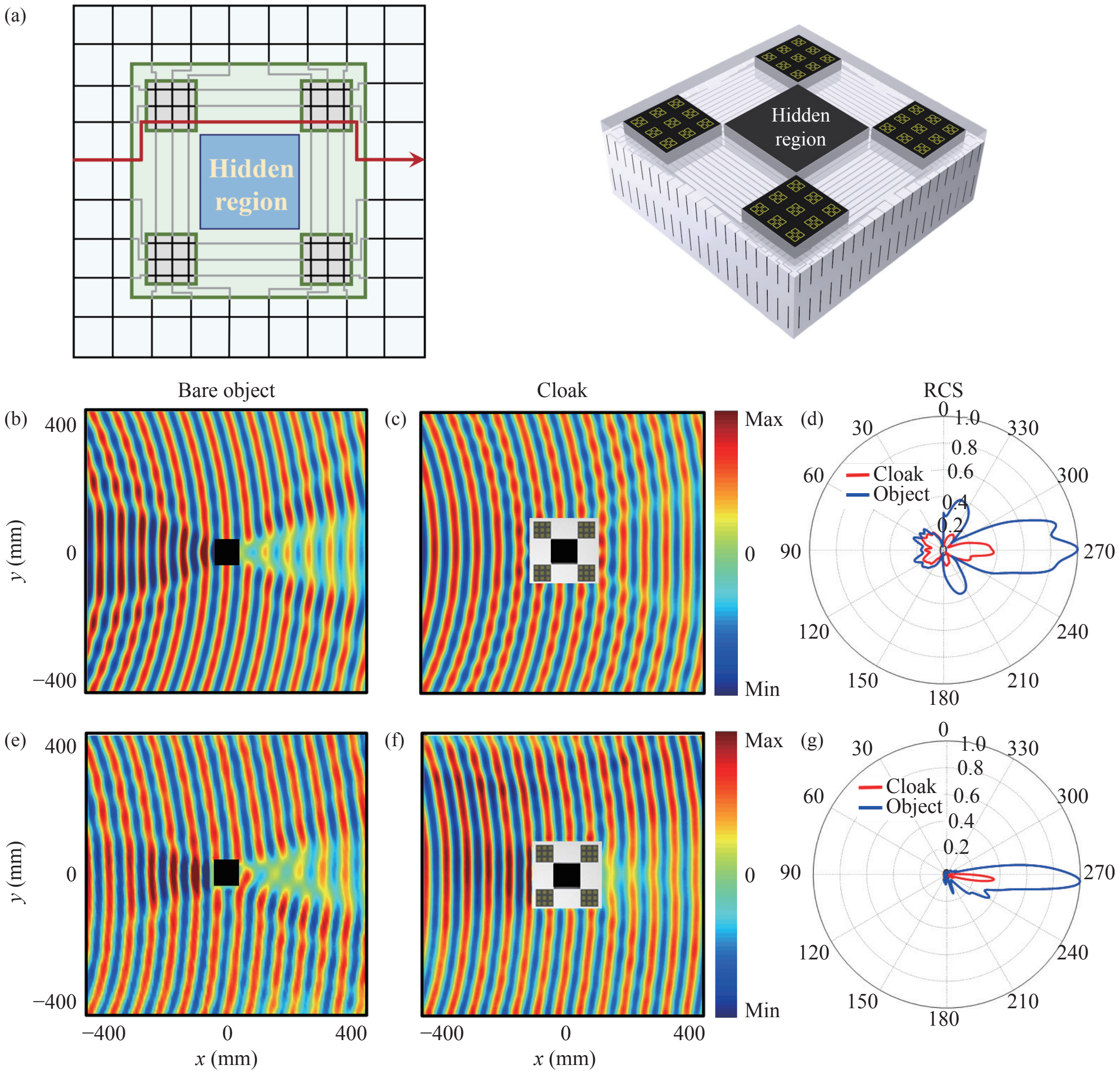

Figure 4 (a) Mesh grid and schematic of a cloak with another shape; (b)–(c): Simulated distributions at 5 GHz for the bare object (b) and the cloaked object (c) under normal incidence; (d) RCS result of the simulation; (e)–(f): Experimental magnetic field distributions for the bare object (e) and the cloaked object (f) under normal incidence. (g) RCS result of the experiment.

We highlight that although we only implement central and four-corner square hidden areas, the shapes of the cloak and hidden regions can be flexibly engineered. When the object is of other shapes, we only need to change the orientation of the metallic channels to guide the EM waves around the object, with the constitutive parameters unchanged. This remarkable property makes our approach a powerful route to design ideal TO cloaks with arbitrary shapes.

V. Conclusion

In conclusion, we introduce a new path towards the realization of full-parameter invisibility cloaks under the framework of TO. It helps conventional TO overcome the dilemma associated with extreme EM parameters. As a demonstration, we design, fabricate and experimentally characterize the full-parameter omnidirectional cloak in free space for arbitrary shapes. Both the simulation and experimental results clearly demonstrate the omnidirectional performance of the designed cloak, which validates the correctness of our design. This suggests a potential way to achieve arbitrary shape cloaking and may provide an avenue for developing other ideal TO devices. Although we validate the proof-of-concept at microwave frequencies, the concept can be readily extended to higher frequencies and other physical fields, such as acoustics, water waves and thermodynamics.

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Authors' Contributions

B. Z., H. C., and Y. L. conceived the idea and supervised the research; Y. L. and H. C. guided the theory, simulations, and experiments; H. L. and B. Z. designed the structure and performed the simulation; H. L. performed the experimental verifications; B. Z., H. L., C. Q., D. Y., Y. L., and H. C. analyzed the data; B. Z. and H. L. cowrote the paper. All authors discussed the results and commented on the manuscript.

Supporting Information

Supplementary Notes 1–5. The supporting information is available online at www.emscience.org. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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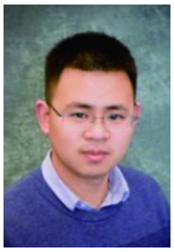

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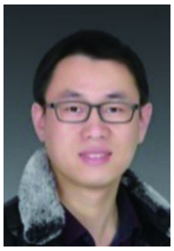

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