Natural Light Cloaking for Aquatic and Terrestrial Creatures

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A cloak that can hide living creatures from sight is a common feature of mythology but still remains unrealized as a practical device. To preserve the phase of wave, the previous cloaking solution proposed by Pendry et al. required transforming electromagnetic space around the hidden object in such a way that the rays bending around it have to travel much faster than those passing it by. The difficult phase preservation requirement is the main obstacle for building a broadband polarization insensitive cloak for large objects. Here, we suggest a simplifying version of Pendry’s cloak by abolishing the requirement for phase preservation as irrelevant for observation in incoherent natural light with human eyes that are phase and polarization insensitive. This allows the cloak design to be made in large scale using commonly available materials and we successfully report cloaking living creatures, a cat and a fish, in front of human eyes.
Invisibility cloaking\cite{1-18} was almost inconceivable until the ingenious theory of macroscopic invisibility cloaking was proposed based on transformation optics principles\cite{2, 3}. Because of the tremendous difficulty in practical realization, various approximations\cite{4, 5-10} were generally taken to simplify the complexity of a perfect cloak. For example, nonmagnetic optical cloaking was proposed by embedding metal nanowires in a dielectric material\cite{5}. With these approximations, cloaks that could hide objects roughly one wavelength large (an optical wavelength amounts to the scale of single-celled organism) have been experimentally demonstrated in both microwave\cite{4, 7, 10} and optical spectrum\cite{8, 9, 11}. Shortly, successful attempts have been made to push the cloaking technology into much larger scales. The natural anisotropic crystal of calcite has been used to realize invisibility at the scale of millimeters\cite{12, 13} for specific polarized visible light in an environment of optical immersion oil. Developing a method of natural light cloaking in a livable environment for living creatures is a very challenging task. Recently, a significant step toward this direction was reported: a microwave unidirectional cloak for a polarized wave in air successfully hid a free-standing object along a single direction with almost ideal performance, whose size was about ten wavelengths large\cite{18}. However, making a large-scale living creature invisible to human eyes has not yet been possible.

In fact, all these difficulties in implementation stem from the need of bending light around the hidden object preserving its phase. Indeed, the rays that go around the hidden object have longer physical paths. In order to preserve the phase, they need to travel much faster than other rays going straightly in the external environment, which subsequently leads to superluminal phase propagation and extreme material parameters\cite{3, 4, 20}. The requirement of phase preservation is necessary at microwave frequencies because the phase of microwaves can be easily detected with an antenna. However, the premise of preserving the phase of light
in the natural light optical cloaking device lacks rationale. Indeed, natural light is essentially randomly polarized and incoherent and its phase is not well defined. Living creatures cannot sense the phase of light and most of them, like humans, are largely insensitive to polarization. Therefore, abandoning the requirement of phase preservation for natural light cloaking opens the door to hide large-scale living creatures.

Here we demonstrate in experiment that by abandoning the phase preservation requirement it is possible to create invisibility cloaking for natural light in multiple observation angles (see supplementary videos documenting real life cloaking performance). Such a cloak will act as a cloaking device operational on the ray optics approximation. It will disregard the fine effects of interference seen in wave optics but will offer good performance for hiding macroscopic objects much larger than the wavelength of light. Recent theoretical development in cloaking from non-Euclidean transformation\cite{21, 22} has provided an alternative way of abolishing phase preservation by incorporating anisotropic materials. Our experimental demonstration with only isotropic materials in incoherent light can serve as the first simplified test of phase non-preservation cloak. Compared with the previous design of unidirectional cloak\cite{18, 19}, our method can be easily extended into multiple directions for arbitrary polarization at broad range of optical frequencies, and therefore, can significantly simplify the construction of a cloak in many real applications where only a certain number of detectors or observers are involved. Using the widely available optical glass we constructed polarization insensitive cloaks hiding a fish in the fish tank and a cat in the environment of human habitat.

Results

We start with analysis on how to simplify a perfect cloaking device designed by the transformation optics approach proposed by Pendry et al.\cite{3}. For comparison, we first analyze the
case when phase preservation is maintained, and later we will abolish the phase preservation requirement. Consider a perfect square cloaking device (Fig. 1a) with a square “hole” at the center opened from coordinate transformation. In the regions marked in green in Fig. 1a, the wave needs to propagate with infinite phase velocity. (See more details in Supplementary Information.) Here the vertical coordinates (dotted red lines) represent wavefronts for the rays going around the cloaked area. In this special case of square cloak, we can make wavefronts perpendicular to rays everywhere in the cloaking device even if the phase of outgoing waves is preserved. As a result the cloak can be constructed without the need for metamaterials, using only isotropic and nonsingular medium (Fig. 1b). The requirement for infinite phase velocity is therefore removed. Because of its four-fold rotational symmetry, this simplified cloak can work for four different incident directions with arbitrary polarization.

The above example demonstrates the possibility to simplify a perfect cloaking device using isotropic materials. However, because the phase preservation is still maintained, superluminal phase propagation is still required in the design unless the ambient medium possesses a refractive index higher than unit (such as water). Therefore, firstly, to achieve a broadband cloaking device in the air environment, we have to abolish the phase preservation requirement. Secondly, extending the cloaking performance into more directions (e.g. six directions) using isotropic materials is almost impossible if phase preservation is required. In what follows we will explore a more complex hexagonal cloak to demonstrate cloaking without phase preservation in ambient water and air.

Fig. 1c shows a perfect, phase preserving omnidirectional hexagonal cloak with extreme and anisotropic material parameters designed with the transformation optics approach, which can be constructed using metamaterials only. In the simplified cloak, when abolishing the phase preservation requirement, we still expect the incident rays to return to
their original trajectories. Fig. 1d shows that the phase rearrangement causes wavefront dislocations in the simplified cloak. However, as will be demonstrated below, distortions caused by them can be disregarded in experimental observations.

Using the simplified six-fold cloaking design, we first construct a cloak hiding a fish in the aquatic environment using the widely available optical glass. Fig. 2a shows the experimental setup where a cloak is immersed in a fish tank filled with water as a living environment for a goldfish. The cloak is constructed with six pieces of glass with $n = 1.78$ placed in a hexagonal hollow transparent container with negligible thickness. A camera placed in front of the tank records the dynamic scene from the front observation angle. Figs. 2b-e show the dynamic process of the goldfish swimming from inside the cloak to the external aquatic environment. When swimming inside the cloak, the goldfish becomes invisible and does not block the scene of green plants behind the cloak. The edges of the transparent container are still visible because of some glue residue left at the edges of this homemade container. This cloak works for six different incident directions.

Now we proceed to extend the simplified cloak from the aquatic environment to a terrestrial one with air as ambient medium. Here we could construct a four-directional cloak by using design in Fig. 1b. However, for simplicity of demonstration, we construct a uni-directional cloak instead that can hide terrestrial creatures from forward and backward observation angles. We use a cat as the terrestrial creature in the experiment. The cloak is constructed with a few pieces of the same glass material with $n = 1.78$, as indicated in dark blue in Fig. 3a. To demonstrate decisively the capability of this cloaking strategy in hiding creatures especially in a dynamic background in natural light illumination, we use an office projector equipped with an incandescent bulb to project a dynamic field scenery through the cloak. The light emitted from the incandescent bulb has very similar characteristics to
natural light in terms of random polarization, incoherence, and continuous visible spectrum. A screen behind the cloak is used to display the projected image. Video recording illustrated the cloak performance can be found in Supplementary Information.

Figs. 3b-d show pictures on the screen captured by a digital camera behind the screen. Fig. 3b is the picture when there is just the cloak in front of the background scenery where a yellow butterfly is flitting around flowers. The cloak casts some moderate edge shadows due to the fact that the light coming from the projector is divergent rather than being ideally parallel. In Fig. 3c, a living cat is stepping into the cloak. One can see clearly that the head and forelegs of the cat inside the cloak become invisible. In Fig. 3d, the main body of the cat has settled inside the cloak and becomes invisible, while the head and forelegs of the cat outside the cloak are still visible and block the white flower in the middle. Particularly, at this moment, the butterfly is flitting quickly from the upper left to the lower right behind the cloak, but still can be seen clearly on the screen through the body of the cat.

Discussion

Although the demonstrated cloaking solution is only effective for several observation directions, our work has successfully made a step toward practical application of invisibility cloaking in hiding large-scale creatures in plain sight. By reconfiguring the prisms the cloak operators could make them disappear from the sight along any given direction which lands to important security, entertainment, and surveillance applications.
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Author Contributions

H.C. conceived the original idea. B. Zhang provided the explanation on incoherence. H.C., H.W., B. Zheng, and B. Zhang designed the cloaks. H.C., B. Zhang, and X.Z designed and supervised the experiments. B. Zheng and L.S. carried out experiments. B. Zhang, H.C., and N.Z originated the manuscript and supplementary materials and interpreted the results. All authors joined discussion and reviewed the manuscript.

Competing Financial Interests statement

The authors declare no competing financial interests.

Links to the supplementary videos:

https://www.dropbox.com/s/6kslerc5rpyek38/ChenS1.mov

https://www.dropbox.com/s/4tw4jg1hr9mh0zk/ChenS2.mov
FIG. 1: Principle of natural light cloak. Horizontal rays are incident from left to right. Red dotted vertical lines represent wavefronts when illumination is coherent. The central hidden region is marked with yellow. a, A perfect square cloak designed by applying a coordinate transformation to open a square “hole” at the center. The wave has to propagate with infinite phase velocity in the singular anisotropic region (marked in green). b, A four-directional square cloak with incident rays propagating horizontally. Wavefronts are perpendicular to rays. c, A perfect hexagonal cloak designed from coordinate transformation. d, A six-directional hexagonal cloak with incident rays propagating horizontally. Wavefronts are perpendicular to rays. In a and c, the cloaks require extreme and anisotropic material parameters. In b and d, the cloaks can be greatly simplified with
FIG. 2: **Experimental observation of fish in aquatic ray cloak.**  

**a**, Experimental setup in a fish tank. The cloak is constructed with six pieces of glass with $n = 1.78$ (indicated in dark blue) enclosed in a hollow hexagonal container. **b-e**, Dynamic monitoring of a fish swimming through the aquatic ray cloak. The outline of the invisible fish body is indicated by dotted lines. **b**, The main fish body inside the cloak is invisible but only the tail outside of the cloak is visible. **c**, Only the fish head outside of the cloak is visible. **d**, The main body of the fish comes out of the cloak and thus becomes visible. **e**, The whole fish has come out from the cloak.
FIG. 3: Experimental observation of cat in terrestrial ray cloak. a, Experimental setup to test the cloaking performance. The cloak in dark blue is constructed with glass ($n = 1.78$) and has dimensions of 0.3 m long (along the $y$ direction), 0.26 m wide (along the $x$ direction), and 0.07 m high (along the $z$ direction). An office projector projects a movie through the cloak onto the screen behind the cloak. A camera (not shown here) placed behind the screen records the movie on the screen. A live cat is sitting inside the cloak. b-d, The images displayed on the screen when (b) only the cloak is present, (c) a live cat is stepping into the cloak, and (d) the cat’s main body has settled inside the cloak, respectively. The outline of the invisible body of the cat is indicated by dotted lines. During the whole process, the butterfly in the background scenery is flitting about.