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Macroscopic Invisibility Cloak for Visible Light

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Invisibility cloaks, a subject that usually occurs in science fiction and myths, have attracted wide interest recently because of their possible realization. The biggest challenge to true invisibility is known to be the cloaking of a macroscopic object in the broad range of wavelengths visible to the human eye. Here we experimentally solve this problem by incorporating the principle of transformation optics into a conventional optical lens fabrication with low-cost materials and simple manufacturing techniques. A transparent cloak made of two pieces of calcite is created. This cloak is able to conceal a macroscopic object with a maximum height of 2 mm, larger than 3500 free-space-wavelength, inside a transparent liquid environment. Its working bandwidth encompassing red, green, and blue light is also demonstrated.

Among various devices conceptualized in the emerging field of transformation optics [1], the most attractive one might be the cloak of invisibility, which can render an object invisible by precisely guiding the flow of light around the object, as if the object does not exist [2–5]. The underlying mechanism stems from the formal invariance of Maxwell's equations: a coordinate transformation does not change the form of Maxwell's equations, but only changes the constitutive parameters and field values. The hidden object is rendered invisible simply because it is out of the transformed electromagnetic space. Great interest in realizing invisibility in practice has fueled massive research efforts from microwave to optical frequencies [6–14].

Significant progress has been made during the exploration of invisibility cloak. The first theoretical model of a transformation-based cloak [3] required extreme values of the constitutive parameters of materials used and can only work within a very narrow frequency band [3,15]. Schurig *et al.* overcame the first flaw by using simplified constitutive parameters at microwaves based on metamaterial technologies [6]. To bypass the bandwidth limitation and push the working frequencies into the optical spectrum, it has been proposed that an object sitting on a flat ground plane can be made invisible under a fully dielectric gradient-refractive-index "carpet" cloak generated by quasiconformal mapping [5]. This carpet cloak model has led to a lot of subsequent experiments in both microwave [8,13] and infrared frequencies [9–11,14]. However, a serious limitation of carpet cloaks was recently pointed out: the quasiconformal mapping strategy will generally lead to a lateral shift of the scattered wave, whose value is comparable to the height of the hidden object, making the object detectable [16]. Furthermore, all previous experiments of invisibility in the optical spectrum, from infrared [9–11,14] to visible [7,12] frequencies, were demonstrated under a microscope, hiding objects with sizes ranging from

the order of 1 wavelength [7,9–11,14] to approximately 100 wavelengths [12]. How to "see" the invisibility effect with the naked eye, i.e., to cloak a macroscopic object in visible light, is still a crucial challenge. In addition, most previous optical cloaks [7,9–11,14] required complicated nano- or microfabrication, where the cloak, the object to be hidden, and the surrounding medium serving as the background were all fabricated in one structure. Thus they could not be easily separated from their embedded structures and transferred elsewhere to cloak other objects. These limitations, such as detectability, inadequate capacity to hide a large object, and nonportability, must be addressed before an optical cloak becomes practical.

The above limitations boil down to two difficulties in the fabrication of cloak materials—anisotropy and inhomogeneity. The previously proposed quasiconformal mapping strategy attempted to solve anisotropy in order to facilitate metamaterial implementation [5]. However, in conventional optical lens fabrication, the inhomogeneity is more difficult to implement than anisotropy. While there is still a long way to go before achieving practical applications of nanobuilt metamaterials, the transformation principle can be directly incorporated into conventional optical lens fabrication, if the difficulty of inhomogeneity can be lifted. Here, we report the first realization of macroscopic invisibility cloaking at broadband visible wavelengths by applying transformation optics design into conventional optical lens fabrication. The cloak is implemented with calcite, a common anisotropic optical material. Since calcite itself is transparent in visible light, the concern of energy loss for metamaterials does not exist in this case, nor the bandwidth limitation associated with metal ingredients [1]. To our knowledge, in our experiment invisibility was demonstrated for the first time by "seeing" through the cloak directly, i.e., by placing a target object behind the cloak, illuminating the system with visible light, and showing that there is no evidence of the cloaked object in the image of

the target object. It is, therefore, closest to the idealized concept of a cloak—being invisible to the eye.

To explain our cloak design, let us first consider why an object is visible. Figure 1(a) shows a ray of light incident on the ground plane with an angle θ. As the observer can see, when there is nothing on top of the ground plane, the light will just be mirror reflected with the same angle θ from the ground plane. When an object is placed on top of the ground plane, like the triangle in Fig. 1(b), the reflected light will change its reflection angle. This change can be easily noticed by the observer. The most convenient way to restore the angle of the reflected light is to put another flat ground plane on top of the object directly, as shown in Fig. 1(c). However, although the angle has been restored, the reflected light experiences a noticeable lateral shift, which unveils the existence of the object. It is, therefore, necessary to restore both the angle and the position of the reflected light in order to render the object invisible under a cloak. A homogeneous cloak of a triangular shape made of uniaxial medium is possible if the electromagnetic space above the triangular object is squeezed upwards uniformly inside another larger triangle [17], since the optical path is preserved in this transformation. For material savings without affecting the essential cloaking function, we can truncate the cloak to a trapezoid with a small triangle etched away from the bottom. The final structure is shown in Fig. 1(d). It is necessary that the material in the left and right regions should have two principal refractive indexes, n_1 and n_2, as indicated in the figure [17]. The background should have a refractive index n matched to a value between n_1 and n_2 [18] though using air as background is also possible [19]. Ray tracing in Fig. 1(d) clearly shows that, within the range limited by the truncated size of the cloak, an arbitrary incident ray can be guided ideally and emitted

with the same angle and from the same position as in Fig. 1(a). This is because the anisotropic cloak is equivalent to a squeezed electromagnetic space, where the light is "deceived" as if it were propagating in the empty space of Fig. 1(a) with nothing on top of the ground plane.

To implement this anisotropic cloaking principle easily at optical frequencies, we chose a two-dimensional (2D) geometry with light polarized such that the magnetic field is parallel to the horizontal reference plane. Let us first consider the following transformation [17] from the original coordinates (x, y) into a new set of coordinates (x', y')

$$x' = x; \qquad y' = \kappa y + \tau(a - |x|), \qquad (1)$$

where $\kappa = [\tan(\alpha + \beta) - \tan\beta]/\tan(\alpha + \beta)$ and $\tau = \tan\beta$.

Through this transformation, we can obtain the constitutive parameters for the material in the first quadrant as

$$\bar{\bar{\epsilon}}' = \frac{\bar{\bar{J}} \cdot \bar{\bar{J}}^T}{|\bar{\bar{J}}|} = \begin{pmatrix} 1/\kappa & -\tau/\kappa \\ -\tau/\kappa & \kappa + \tau^2/\kappa \end{pmatrix}; \qquad (2)$$

$$\mu' = \frac{1}{\kappa}, \qquad (3)$$

where $\bar{\bar{J}}$ is the Jacobian of the transformation. The material in the second quadrant has the same parameters except for a mirror reflection with respect to the vertical plane.

To make this work with a nonmagnetic material, we scale the permittivity tensor such that

$$\bar{\bar{\epsilon}}'_{\text{nm}} = \begin{pmatrix} 1/\kappa^2 & -\tau/\kappa^2 \\ -\tau/\kappa^2 & 1 + \tau^2/\kappa^2 \end{pmatrix}. \qquad (4)$$

This guarantees $\mu'_{\text{nm}} = 1$. To determine the principal axes of the uniaxial crystal, we diagonalize $\bar{\bar{\epsilon}}'_{\text{nm}}$ and obtain the crystal axis orientation with respect to the vertical plane as

$$\gamma = \frac{1}{2} \arctan\left(\frac{2\tau}{\kappa^2 + \tau^2 - 1}\right). \qquad (5)$$

To fix the geometry, we let $\alpha = 66°$ and $\beta = 6°$ and obtain $n_1^2 = 1.48^2$, $n_2^2 = 1.66^2$, and $|\gamma| = 37.5°$ for background refractive index equal to 1.57. For green light at wavelength 561 nm (where human eyes are most sensitive in common environments [20]) and magnetic field oriented parallel to the mirror, this can be realized simply as calcite with its crystal axis oriented according to (5).

We fabricated the experimental cloak as shown in Fig. 2. Because of fabrication errors in the calcite crystal, angles were accurate up to $15'$, while the length of each side may have error up to 1 mm. The two pieces of calcite were back-to-back cemented at the location of the dotted line indicated in Fig. 2 with Norland Optical Adhesive 61, a clear, colorless, liquid photopolymer that cures when exposed to ultraviolet light. The front, back, and top surfaces of the cloak were painted black to absorb scattered light. The bottom was fully polished and then coated with silver. The left and right surfaces were fully polished and served
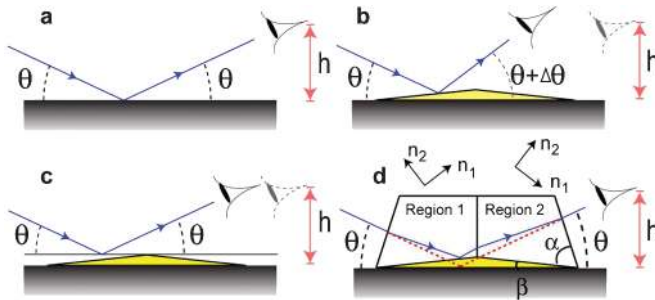

FIG. 1 (color).   (a) A light ray is incident on a flat ground plane and reflected back with the same angle. (b) When an object is sitting on the ground plane, the reflected ray changes its angle. (c) When another flat ground plane is put on top of the object, the reflected ray restores its angle but suffers a lateral shift. (d) When a transformation-based anisotropic cloak is covering the object, the reflected ray restores both its angle and position. The anisotropic medium has two principal refractive indexes n_1 and n_2 along two orthogonal directions. The observer in all cases is assumed to have a fixed height of h. In (b) and (c), the original position of the observer is indicated with a dotted eye.
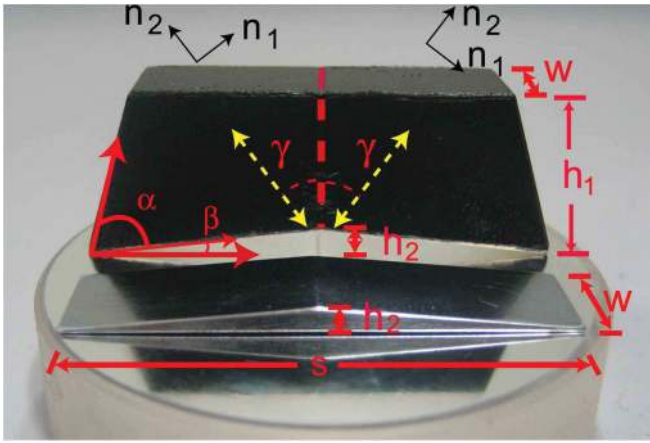
FIG. 2 (color).   A transformation-based anisotropic cloak compared to a steel wedge on top of a mirror. The cloak is made of two pieces of calcite crystal with specific orientations of the optical axis indicated by the yellow dotted arrows. For green light, with its magnetic field perpendicular to the optical axis, $n_1 = 1.48$ perpendicular to the optical axis and $n_2 = 1.66$ along the optical axis. $\alpha = 66°$, $\beta = 6°$, and $|\gamma| = 37.5°$. $w = 10$ mm, $h_1 = 14.5$ mm, $h_2 = 2$ mm, and $s = 38$ mm.

as the input and output for the light, respectively. The object to be hidden was a steel wedge that fit into the void under the cloak and is also shown in Fig. 2. Any object smaller than this steel wedge can be alternatively adopted. Since this design aims at invisibility in a transparent medium with refractive index close to $n = 1.57$, a value similar to the background refractive index in [9], it is not subject to the limitations of delay-bandwidth and delay-loss for cloaking in air [21].

As shown in Fig. 3(a), all objects: the cloak, the wedge to be hidden, and the mirror used as the ground plane, were immersed in a glass tank filled with a transparent colorless laser liquid (OZ-Laser IQ, CODE 5610, from Cargille
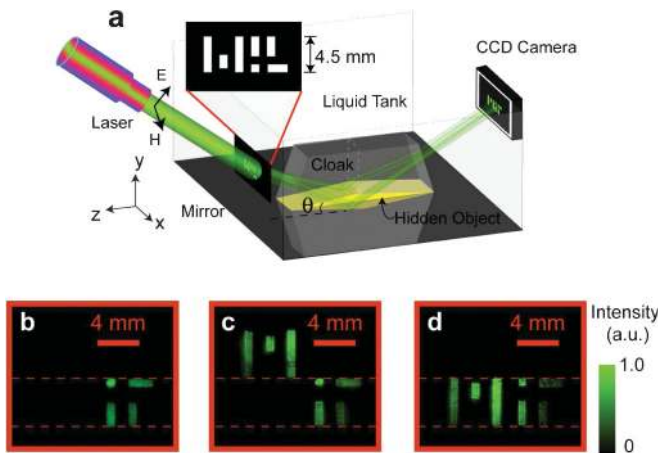

FIG. 3 (color).   (a) Schematic diagram of the experimental setup and images captured on the CCD camera (b) with the wedge only but without the cloak, (c) with a flat ground plane on top of the wedge, (d) with the cloak on top of the wedge.

Labs, $n = 1.53$ measured at wavelength 598.3 nm). A hollow transmission pattern reading "MIT" was printed on an opaque plastic plate with thickness of 500 μm using a stereolithography machine (Viper^{TM} SLA System). The resin was Accura 60 Plastic. This plate was inverted and then attached to the left-hand side of the transparent tank with adhesive tape. Because of the finite thickness of the plate, the final image of "MIT" looked slightly slimmer in the experiments.

The hollow pattern was then illuminated by a continuous wave (cw) laser diode at wavelength of 561 nm polarized with the magnetic field parallel to the mirror. The position where the pattern was placed was carefully chosen such that the light transmitted through the inverted "M" went through the cloak with the hidden wedge underneath and was reflected at the bottom of the cloak, while the light through the inverted "IT" was reflected on the mirror's surface directly without touching the cloak and the wedge. A charge-coupled-device (CCD) camera (Kodak ISS KAI-11002 with pixel size of 9 μm) was placed at a distance of approximately 10 cm from the cloak on the right-hand side outside the tank. Since this homemade cloak had side error up to 1 mm, in the experiment we adjusted the height of the cloak by inserting 100 μm-thick glass plates under the cloak to minimize distortion in the image.

Cloaking in the experiment of Figs. 2 and 3(a) is proven as follows: if the cloak can hide the wedge successfully, the CCD camera should capture an erect and undeformed "MIT" as if there were nothing on top of the mirror. We chose an incident angle $\theta = 18°$ inside the tank with respect to the horizontal reference plane (the external angle was adjusted in the experiment to match the nominal value of θ according to Snell's law). Figure 3(b) shows the image when the wedge only without the cloak was placed on top of the mirror. The letter "M", after being reflected on the wedge, is located very far away from "IT" and misses the CCD. Figure 3(c) shows the image when there is a flat ground plane on top of the wedge directly. We can see that "M" itself is undistorted, but it is shifted upwards compared to "IT", for the same reason as in Fig. 1(c). Figure 3(d) shows the image when the cloak is placed above the wedge. All letters in the captured image are located at the same altitude, as if the cloaked wedge were not there. To make sure the position where the light is reflected from the bottom of the cloak did not influence the cloaking effect, we moved the position of the cloak along the z axis. No obvious extra distortion was observed except when the reflection occurred across the conjunction line between the two pieces of calcite crystal.

The flat ground plane for Fig. 3(c) was implemented as follows: first we put a 2 mm-tall flat steel plate close to the wedge. We then placed a 1.5 mm-thick piece of glass with one side coated with chrome on top with the coated side touching both the wedge's peak and the flat plate. Since the refractive index of glass was almost perfectly matched to
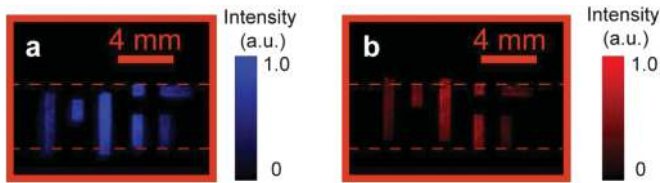
FIG. 4 (color).   Images captured on the CCD camera when the cloak is covering the wedge and the color of light is changed to (a) blue at a wavelength of 488 nm, and (b) red at a wavelength of 650 nm. The incident angle $\theta = 18°$ inside the tank.

the laser liquid environment, this thickness had negligible influence on the experimental results.

After the effectiveness of the cloak was tested under green light (561 nm), the color was switched to blue (488 nm) and red (650 nm), respectively. The resulting images in Fig. 4 show that the cloaking performance is still reasonably good. Because of the color aberration, there was a shift of 450 μm at blue and 400 μm at red, respectively, in the image of "M". The shift was less than 10% of the height of "M" (4.5 mm). Further reduction of the color aberration can be attained using methods inspired by complementary dispersion [22], which is out of the scope of this Letter.

To verify quantitatively that our cloak functions independently of incident angle, we used a simpler two-spot pattern [Fig. 5(a)] instead of the "MIT" pattern. The illumination wavelength was again 561 nm in this case. Performance was verified for $\theta = 0°$ and $\theta = 18°$ [Figs. 5(b) and 5(c)] but degraded somewhat for $\theta = 40°$ [Fig. 5(d)] because at so large a reflected angle, the error in the cloak dimensions was magnified. It is worth mentioning that at 0° incidence, the light did not actually touch the bottom of the cloak or the mirror's surface. This corresponds to a test of complete "seeing through."

The main limitation of our cloak currently is that it can only work in a 2D geometry (the light must propagate in the plane defined in Fig. 1) and for only one polarization. However, it is possible to extend this cloak to a three-dimensional (3D) geometry, just as the 2D carpet cloak [5,9–11] can be extended to the 3D carpet cloak [13,14]. Since it is well known that the light transmitted under water is mainly polarized with the magnetic field parallel
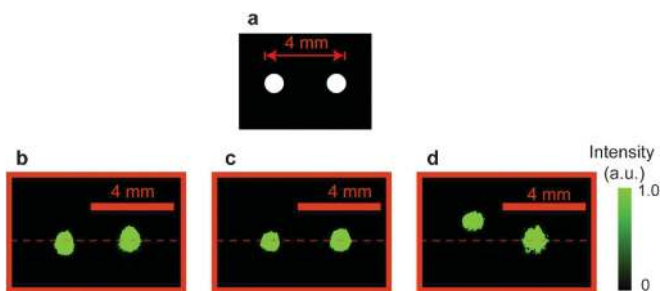

FIG. 5 (color).   Images of (a) two spots with incident angles inside the tank (b) $\theta = 0°$, (c) $\theta = 18°$, and (d) $\theta = 40°$.

to the ground, our design can be used in similar aqueous environments. The application of transformation optics design in conventional optical fabrication offers a cost effective yet accurate solution for making invisibility cloaks. We believe that this technique will open up the possibility of taking more transformation optics devices from concepts into practical applications.

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