Amplitude-only, passive, broadband, optical spatial cloaking of very large objects

John C. Howell,[1],* J. Benjamin Howell,[2] and Joseph S. Choi[3]

[1]Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627, USA

[2]TCMS, Rochester, New York 14618, USA

[3]The Institute of Optics, University of Rochester, Rochester, New York 14627, USA

*Corresponding author: howell@pas.rochester.edu

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We demonstrate three amplitude cloaks that can hide very large spatial objects over the entire visible spectrum using only passive, off-the-shelf optics. The cloaked region for all of the devices exceeds 10^6 mm^3, with the largest exceeding 10^8 mm^3. Although unidirectional, these cloaks can hide the cloaked object, even if the object is transversely illuminated or self-illuminated. Due to the small usable solid angle, but simple scaling, these cloaks may be of value in hiding small field-of-view objects such as mid- to high-earth orbit satellites from earth-based observation. Active phase front manipulation can also make these cloaks invisible to some forms of image homodyning.

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1. Introduction

The intriguing and exciting possibilities of optical spatial cloaking have attracted both the popular culture and the scientific community [1–14]. Great strides have been taken to achieve the "Holy Grail" of optical cloaking: broadband optical invisibility in both the phase and amplitude of the field, omnidirectionality, the ability to cloak macroscopic objects and be invisible. Many of the initial developments in experimental optical cloaking were based on transformation optics [1–3] and studied in metamaterials [1,4–10] and in patterned dielectrics [11,12] with the use of quasi-conformal mapping. While remarkable progress has been made, much work remains in terms of achieving the cloaking at optical wavelengths, increasing the bandwidth over which the cloak works, and scaling to large dimensions. Toward these goals, a recent classical optics method using birefringent calcite crystals [14] achieved a polarization-dependent, broadband, visible, unidirectional cloak of a small incline with a peak height of 2 mm. Another intriguing advance was the recent demonstration of temporal cloaking (hiding a temporal event) work [15] based on split temporal lensing and dispersive propagation in fibers.

One can consider cloaking to be an optical invisibility illusion. Cloaks based on transformation optics have the illusion of hiding objects such that both the phase and amplitude of a field are undisturbed [16]. The phase and amplitude requirement also makes them difficult to achieve. Without the requirement of phase preservation, one can make very simple cloaks based on passive linear refractive and reflective elements. However, wavefront sensing, such as image homodyning, can reveal the presence of "amplitude-only" cloaks by finding phase discontinuities.

Here, we report on "amplitude" cloaking devices based on off-the-shelf optics that can achieve broadband invisibility and arbitrary spatial scaling and be hidden themselves. We demonstrate cloaking over

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the visible spectrum with cloaking regions exceeding 10^6 mm^3, with the largest exceeding 10^8 mm^3. At its most basic level, the optical illusion is to simply guide light around an object as if the object isn't there. One might argue that an endoscope, an index-guiding fiber system used to image hollow organs in the human body, achieves this end. The etymology of "smoke and mirrors" implies the use of distraction and optical illusion through the careful guiding of light. Such illusions have been around for almost two centuries [17]. It should not come as a surprise that reflective and refractive optics can be used to cloak very large optics. To demonstrate this point, we built and report on three cloaking devices. Importantly, each device can be easily scaled to much larger systems. It should be noted from the outset that the purpose of this paper is to demonstrate the simplicity of amplitude cloaking.

The first device is based on the bending of light at a dielectric interface. We demonstrate a realization of the device using two L-shaped water-filled tanks. The second device uses quadratic phase elements, such as lenses, and doesn't suffer from the edge effect problems of the first device (this is the spatial equivalent of the temporal cloak [15]). The third device simply uses mirrors to guide light around the object. The latter cloak, while not new [17–19], is intended to demonstrate the ease of scaling of these systems.

2. Cloaking with Snell's Law

The experimental setup of the first device is shown in Fig. 1. The cloak is based on the idea that light is transversely shifted but has the same direction after passing through a tilted medium (having a different index of refraction) with two straight parallel faces. The setup uses two water-filled tanks to bend light around a cloaking region. The first tank causes all the rays below the optical axis to be shifted downward and the rays above the optical axis to be shifted upward. After the rays exit the second wall of the first tank, they are parallel to the optical axis but have a displacement relative to their original trajectory. The displacement hides any object in the middle. The second tank undoes the effects of the first tank so that the rays are once again parallel with the displacement undone. The diameter of the cloaking region can be found from Snell's law and the width of the tank. From Fig. 2, we can compute the size of the cloaking region. We use Snell's law $n_a \sin(\theta_a) = n_w \sin(\theta_w)$, where $n_a = 1$ $(n_w = 1.33)$ is the index of refraction of air (water) and θ_a (θ_w) is the angle of the ray relative to the normal in air (water). Using straightforward trigonometry, we find that the distance d between the incident ray and the ray after propagating through the medium is given by

$$d = x\frac{\sin(\theta_a - \arcsin(n_w^{-1}\sin(\theta_a)))}{\cos(\arcsin(n_w^{-1}\sin(\theta_a)))}. \qquad (1)$$

The tanks have a width of $x \approx 200$ mm, and the incident light rays have an angle of $\pi/4$, yielding a cloaking region of $2d = 105$ mm, in good agreement with the observed size.

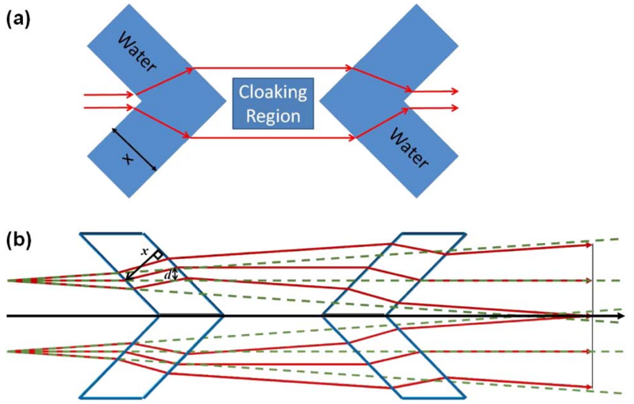

Fig. 1. Cloaking device based on Snell's law. Two L-shaped water-filled tanks bend light around a cloaking region. (a) Rays parallel to the optical axis: at the first interface, light bends away from the optical axis due to the interface with water. The light then bends back in the same direction at the second interface. The second tank brings the light back with both the same direction and no transverse displacement. (b) CODE V simulation of ray fans (solid/red arrows) displaced from the optical axis. Dashed lines indicate where the rays would go without the device. The final rays have the same angles. However, the rays not parallel to the axis are displaced, resulting in a shift in the perceived object position.

An alternative perspective to the functionality of this cloak is that the effect of the L-shaped tanks is to create a split linear phase ramp across the front of the electric field. The split linear phase ramp causes parallel rays to be deflected in opposite directions about the cloaking region. This is a unidirectional cloaking device, because some rays not parallel to the optical axis can penetrate the cloaking region [see Fig. 1(b)]. In addition, the nonparallel rays traverse different lengths of water and have different incident angles in the two tanks, causing distortion to the background. The transverse displacements of the rays not parallel to the optical axis

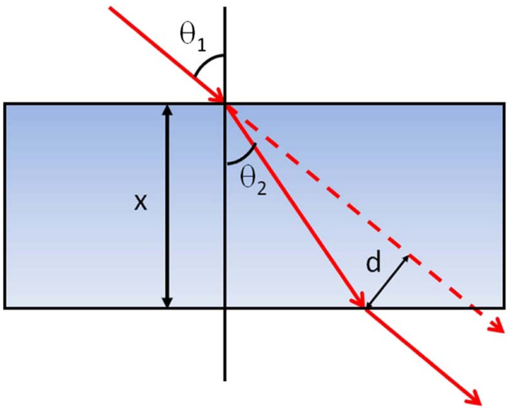

Fig. 2. Distance d between an unaltered ray and the path of the ray after exiting the water can be found from Snell's law and the width of the tank L.

can be seen in the CODE V simulation in Fig. 1(b). As expected, since no optical power is present in this device, the angles remain unchanged. However, the final rays that an observer sees (solid/red lines) have a narrower range of angles than what would happen without the cloaking device. This means that the objects will appear closer than where they are actually located.

Unlike other cloaks and the second device discussed later, there isn't an effective compression of the field. This lack of field compression leads to edge effects. This first device will suffer from edge effects at the extreme wings of the device. Due to the deflection without compression of the rays at the first interface, the second interface of the tank has to protrude farther than the first interface. So, unless the tanks are infinite in extent, the edges will have some problems. It should also be noted that transverse illumination or self-illumination of the cloaked object cannot be observed in the cloaked direction, since the tanks will deflect the light away from the observer.

The actual experimental setup is shown in Fig. 3. An aerial view of the setup shows a helicopter in the cloaking region between the two water tanks. The cloaking ability of the first cloaking device is shown in Fig. 4. Below the waterline in the picture, the helicopter cannot be seen and the truck appears in its place. However, above the waterline, the helicopter is visible and in front of the truck. The bending of the light causes the light to pass around the bottom of the helicopter and bend back so that the truck can be viewed in its place. The transverse width of the helicopter is approximately 125 mm, being approximately 20 mm larger than the cloaking diameter. A small white brightly lit piece of the helicopter at its widest point can be seen. It should be noted that the helicopter is illuminated directly from above and remains invisible. Thus, the transverse illumination of the cloaked object does not reveal its presence, as one would expect from a cloaking device.

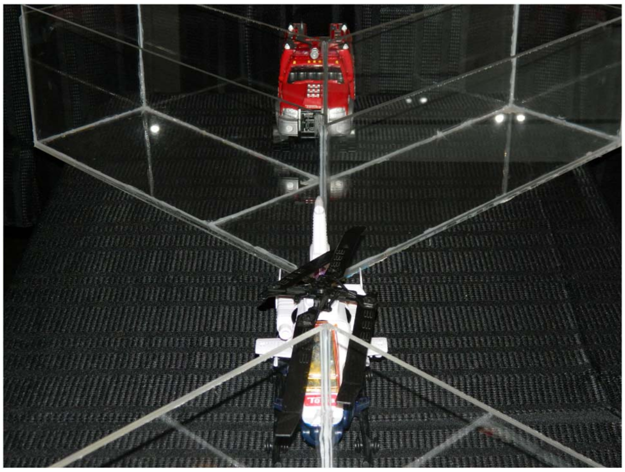

Fig. 3. Aerial view of the first cloaking device. A helicopter is shown inside the cloaking region of the first device. A truck is shown on the other side of the viewing region. The truck will appear in the helicopter's place when water is inside the tanks and viewed along the optical axis.

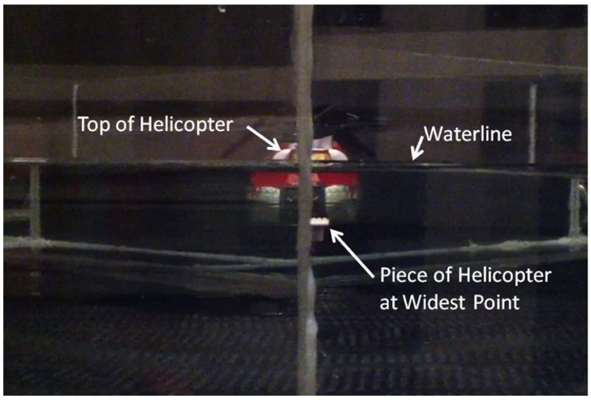

Fig. 4. Below the water line, the helicopter is cloaked and the truck appears in its place. The light coming from the truck passes around the helicopter via the water tanks and is then seen in place of the helicopter. Above the waterline, the helicopter is shown in front of the truck.

While the first cloaking device is straightforward to implement, the scaling to very large objects becomes rather impractical unless one wishes to carry around very large tanks of water. A generalization of this device is to have a device that causes a split linear phase ramp. This can be achieved with a hologram, a spatial light modulator, and a large piece of glass with long prism-like wedges (equivalent to a Fresnel lens but with linear rather than quadratic etching).

3. Cloaking with Lenses

The second scheme is shown in Fig. 5. This scheme can be considered as the spatial equivalent of the temporal cloak used in [15]. Lenses are used to guide light around the cloaking region. Fresnel lenses are used at the interfaces of the cloaking device, because of their low mass, scalability, and rectangular shape. Unfortunately, passing through a focus inverts the background behind the object. In this spatial cloak, diverging lenses between the Fresnel lenses prevent the light from passing through a focus, which means

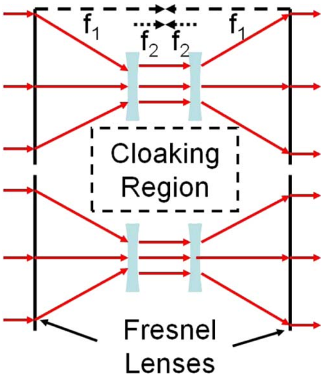

Fig. 5. Experimental cloaking schematic of the second device. Converging and diverging lenses are used to map light around the cloaking region.

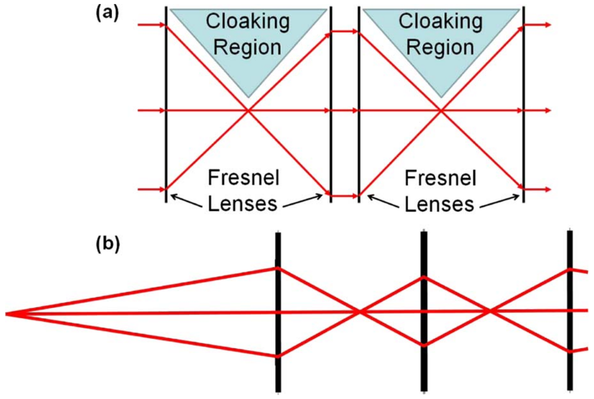

Fig. 6. Alternative schematic for the second device. Four Fresnel lenses in series are used. Two sets of Fresnel lenses with each set separated by twice the focal length make it so the image is not inverted. The distance between lens pairs can be arbitrarily small. In the actual experiment, they were mounted together as if they were a single lens. (a) On-axis marginal rays for an object at infinity. (b) CODE V simulation of the same rays as in the actual experiment. The object was placed 750 mm from the first Fresnel lens. The figure is not to scale for ease of viewing.

that the image will be upright rather than inverted. They also have the interesting property that the separation between lenses can be quite large after the rays are collimated, so that the cloaking region can be extended longitudinally.

An alternative but slightly larger design was actually used to demonstrate the cloaking. The alternative design, shown in Fig. 6, removes the two diverging lenses from the setup. However, with the two diverging lenses removed, the image of the background is inverted. To make the image upright, we use another set of Fresnel lenses also separated by $2f_1$ in series with the first two lenses. In the actual experiment, the two middle Fresnel lenses were mounted together as if they were a single lens. The design of the device is shown in Fig. 7, and the cloaked helicopter is shown in Fig. 8. It can be seen that the tail of the helicopter is cloaked and the truck behind the helicopter appears in its place. One can notice that in the uncloaked region, a small portion of the truck in the background can be seen above the helicopter. Four 175 mm × 250 mm Fresnel lenses were used, each having a focal length of 200 mm. The truck is placed a distance of 750 mm from the first lens, and it is observed with a 21× magnification camera (the highest magnification of the camera) at ≈6.4 m (the largest distance allowed by the physical space) from the rear lens. The image quality is limited by the quality of the Fresnel lenses.

4. Cloaking with Mirrors

The last cloak is the most obvious design one would use to make light pass around an object. The design of the device is shown in Fig. 9. Invisibility with mirrors has been previously done. The point we wish to emphasize is not the novelty but the ease of scaling to nearly arbitrary size. The first mirror reflects the light away from the cloaking region. The light then bounces off of a retroreflecting mirror pair (two mirrors at right angles), and then it reflects off of the mirror behind the object.

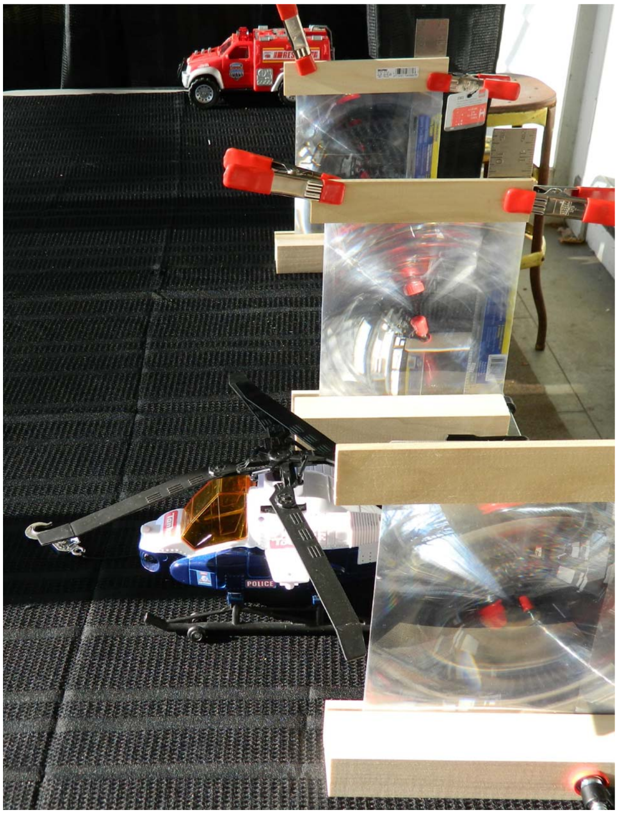

Fig. 7. Setup for the second cloaking device. The tail of a helicopter is at the focus of a Fresnel lens (light passes around it). Four Fresnel lenses (the two in the middle are in contact) allow for a one-to-one noninverted imaging of the background. The lenses have the dimensions of 175 mm × 250 mm and have a focal length of 200 mm. The truck is placed a distance of 750 mm from the last lens.

The retroreflecting mirrors make it so that rays leaving the cloak, even off-axis rays, leave at the same angle (magnification is 1), albeit with transverse shifts [see CODE V simulation shown in Fig. 9(b)]. The transverse shifts mean that this device works optimally at infinity (large distance from the observer). In contrast to the first cloaking device with

Fig. 8. Viewing along the optical axis, we see the truck appearing in the place of the tail of the helicopter. The observation was done with a 21× magnification camera at 6.4 m from the first lens.

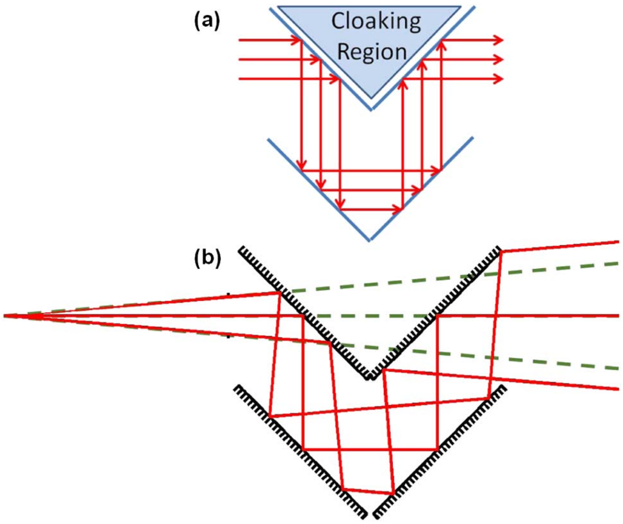

Fig. 9. Schematic for the third device. Mirrors reflect light around the cloaking region. (a) On-axis marginal rays for an object at infinity. (b) CODE V simulation of the same marginal rays for an object about 1.5 m from the mirrors. The angles of the rays do not change, but the object will appear to be farther away than its actual location.

water, here the output rays have a wider range of angles. The result is that the objects in the mirror are actually closer than they appear (as can be seen in Fig. 11). This can be understood by realizing that the cloaking device bends light around the hidden object. So the output light has actually traveled farther and expanded more than on a direct path. Hence, an observer will perceive the light to have started from farther away. In the first cloaking device, the index of refraction differences caused an opposite effect, but here light travels only in air, so its rate of expansion remains the same. The ideal scenario is then to have the distance between the mirrors be small, compared to the distance of the background objects from the mirrors. This can also occur when the observer is infinitely far away, as mentioned.

We list some of the downsides for this cloak. First, there are edge effects if one moves to the side (unidirectional). Second, the retroreflecting mirror pair makes the cloak visible unless the mirrors are placed behind a wall or some large objects. Third, while the rays leave in the same directions, they leave with a transverse displacement that is proportional to the incoming angle relative to the optical axis. However, even with these drawbacks, it is clearly scalable to very large dimensions.

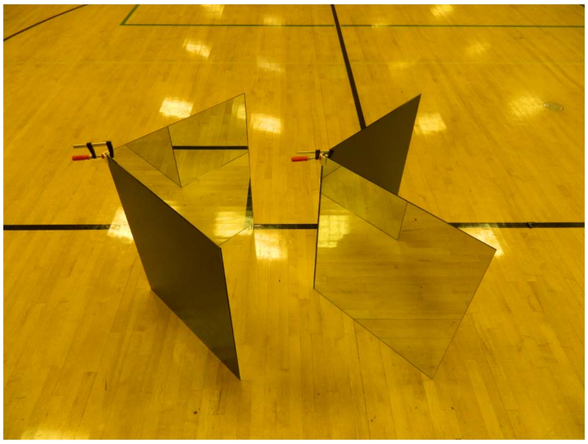

Fig. 10. Setup for the third device. Two sets of right angle mirrors guide light around the cloaked region.

Fig. 11. Chair is cloaked, and a rubbish can appears in its place.

The actual experiment is shown in Fig. 10. Two sets of mirrors are joined at right angles. It is important to align the mirrors so that the front and rear mirrors are perpendicular. To minimize background distortion, careful attention was given to securing the joined mirrors at right angles and to making them as vertical as possible. In Fig. 11 one can see that part of the chair is cloaked and the rubbish can in the background appears in its place. The image was taken approximately 25 m from the mirrors, thus ensuring that the cloak occupied a small field of view (unidirectionality). The mirrors have dimensions of 600 mm × 900 mm, with a total cloaking volume of $1.6 \times 10^8\ \mathrm{mm}^3$. This volume is sufficient to cloak a human, albeit with not as much convenience as Harry Potter's cloak. The simplicity of the device means that much larger cloaking devices can easily be built.

We have considered passive amplitude-only cloaks. However, making these cloaks active, in the sense that the phase may be adjusted based on feedback, may allow for phase and amplitude invisibility. The phase discontinuities caused by the cloak can be ameliorated unidirectionally for some types of image homodyning by adding a frequency-dependent phase shift to the field. If the cloak is being interrogated by a narrowband coherent field of a particular frequency, a modulation of the cloak to make the phase front smooth can be made. Thus, active phase front manipulation could achieve both amplitude and phase cloaking in this context.

5. Conclusions

In summary, we have demonstrated three "amplitude-only" optical cloaking devices. The cloaks work over the visible spectrum and have cloaking regions exceeding 10^6 mm^3, and with good coatings, the second device can be made nearly invisible. The second device does not suffer from edge effects for straight-on viewing. The downside is that all of these devices are unidirectional. The devices may have value, for example, in cloaking satellites in mid- to high-earth orbits or for any small field-of-view cloaking. It should be pointed out that transverse illumination or self-illumination of the cloaked object still renders the object invisible to the observer. While it has been shown that perfect invisibility cannot be attained [20], an open question is whether standard optics can achieve geometric (ray optic) omnidirectional or multidirectional cloaking [2]. Current efforts are exploring cloaks with spherical symmetry (much like retroreflecting spheres achieving multidirectional reflection), which may achieve multidirectional cloaking.

After submission of this paper to the arXiv [21–23], another amplitude-only cloaking scheme appeared [24]. Their scheme used passive refractive elements to mimic metamaterial cloaks.

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