

## A Simple Unidirectional Optical Invisibility Cloak Made of Water

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**Abstract**—Previous invisibility cloaks were based on metamaterials, which are difficult for practical realization in visible light spectrum. Here we demonstrate a unidirectional invisibility cloak in visible light spectrum. By using water as the effective material and separated into several regions by glass sheets, a simplest and cheapest invisible device is realized. This device can hide macroscopic objects with large scale and is polarization insensitive. Owing to simple fabrication and easily acquisitive materials, our work can be widely applied in our daily life.

### 1. INTRODUCTION

Invisibility cloaking [1, 2, 7–20] has attracted the attention of scientific community but remains a science fiction until the pioneering theoretical works based on transformation optics principles [1, 2]. The invisibility cloak does not make the object disappear, but guides the light around the hidden object and makes it appear on the other side without deflection, which makes the hidden object undetectable. Metamaterials [1, 3–8] with anisotropic and inhomogeneous parameters are needed in the initial proposal for such a transformation-based cloak. It involves spatially dependent constitutive parameters as well as extreme tensor values, which make it difficult for practical realization. Great efforts are taken to simplify the complexity of cloaking [7–20]. For example, with a discrete method of multiple layers using metallic split-ring resonators, the first cylindrical cloak was experimentally achieved at microwave frequencies [7]. Furthermore, in order to remove the singular constitutive parameters associated with the initial cylindrical cloak, a concept of “carpet cloak” [9–15] was proposed where the hiding object was placed on a conducting ground plane. To further simplify the complexity of the parameters and make it easy for realization, a broadband cylindrical invisibility cloak in free space without superluminal propagation was designed with an integration of the advantages of previous cloaking methodologies [18].

While remarkable progress has been made, cloaking at optical wavelength [8, 11–15] with broad frequency bandwidth and large hidden region is still a significant goal especially because of its visualization for human sensing. An optical carpet cloak made of dielectrics was experimentally demonstrated with a hidden region at the scale of micrometers [11], which was fabricated by using a hole array with variable density on a silicon-on-insulator wafer. Advancement follows when natural anisotropic crystal of calcite was used to realize a carpet cloaking at the scale of millimeters in visible spectrum [14, 15]. A polygonal optical cloak that can hide an isolated macroscopic object was also demonstrated using calcite [19]. By abandoning the phase preservation requirement in the transformation optics based cloak design, a natural light cloak that can hide living creatures from plain sight was experimentally realized using conventional optical glasses [20]. In this case, the cloak was simplified to ray optics cloak where the observers were phase and time insensitive. Geometric optical cloaks are also proposed based on the reflections from mirrors [21] and some polarization beam splitters [22]. These works show that, instead of using metamaterials, which requires a complex nanofabrication

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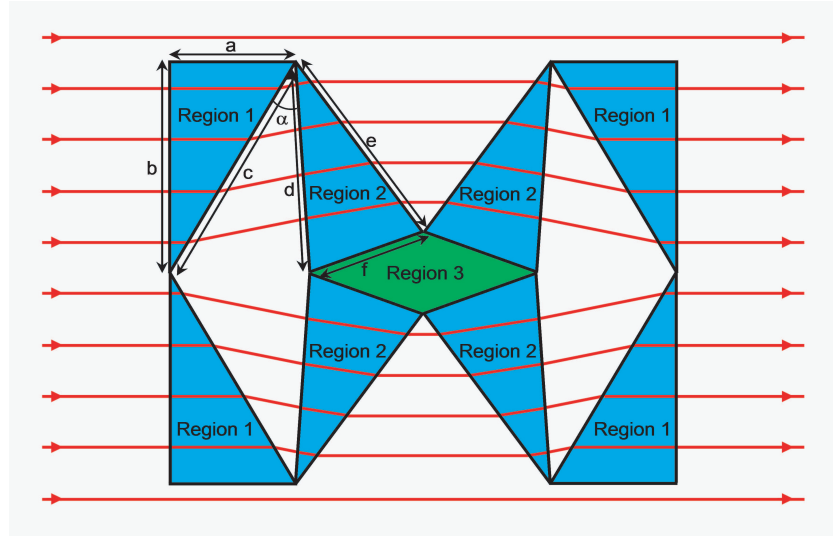
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techniques and is much expensive, invisibility cloak working for certain observation angles can also be reached with conventional natural materials.

In this paper, instead of using metamaterials and conventional optical materials, we propose the simplest and cheapest invisible cloak in visible light frequencies. The cloak is realized simply using bulks of water, a common fluid with stable optical properties in visible spectrum. Instead of using metamaterials or optical materials, water is easy to acquire and has relative low fabrication difficulty because of fluidic properties. Our work makes the optical cloak a practical device for mass production.

## 2. CLOAK DESIGN AND EXPERIMENTAL SETUP

The principle of the cloak is shown in Figure 1 where paths of rays are indicated. The regions 1 and regions 2 are filled with water with a refractive index of  $n_1 = 1.333$  while the rest of the space is air with a refractive index of  $n_0 = 1$ . Region 3 is the cloaked region. The regions 1 are composed of four equal right triangles with side lengths of  $a = 10$  cm,  $b = 17.3$  cm and  $c = 20$  cm. The regions 2 are composed of four equal triangles with side lengths of  $d = 17.4$  cm,  $e = 17.2$  cm and  $f = 9.6$  cm. The angle between region 1 and region 2 is  $\alpha = 33.3^\circ$ . The incident rays will obey the Snell's law when they arrive at the interface between two mediums. We can see from the figure that the parallel rays refract around the cloaked region and remain in the same lines as the incident rays, which make the cloaked region invisible without any side shadow. It should be announced that the permeability in all regions equal to one. The resultant impedance mismatch will cause reflection at the interfaces, which can be suppressed by practical anti-reflection techniques and thus is not considered here.



**Figure 1.** The principle of the cloaking device. Parallel rays are incident from left to right. The regions marked in blue are filled with water with a refractive index of  $n_1 = 1.333$  while the region marked in green is the cloaked region. The rest part of the space is air with a refractive index of  $n_0 = 1$ . The parallel rays obey the Snell's law and refract around the cloaked region while remaining in the same lines as the incident rays.

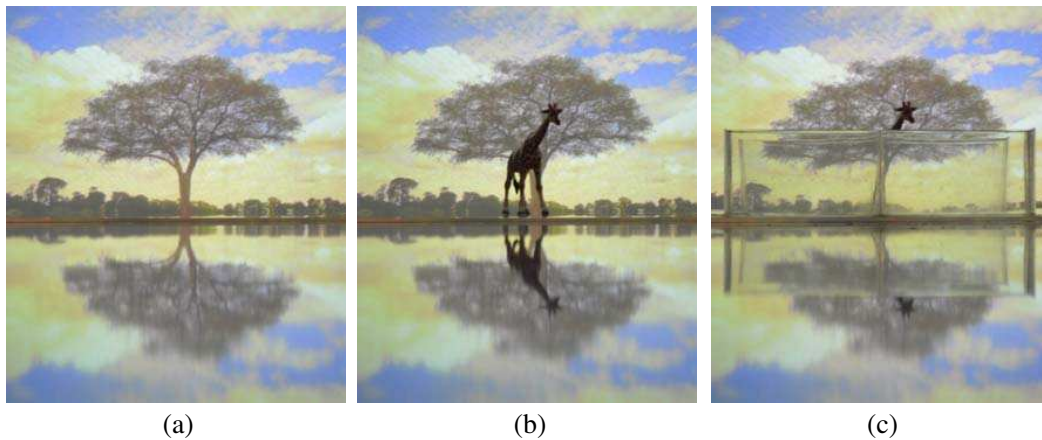
The example of experimental device is shown in Figure 2. The regions in blue are pure water while the background medium is air. The two mediums are separated by transparent and thin glass sheets (not shown in the figure) with little influence on the light rays. The size of the device is the same as Figure 1 and the height of the device  $h = 10$  cm. In our experiment, we use a projector to project a static image, and a screen is used to display the image. The light is randomly polarized, incoherent and has continuous visible spectrum, which is similar to natural light captured by human eyes. A giraffe toy with a height of 14 cm is used as the object to be cloaked and put into the cloaked region.



**Figure 2.** Experimental setup of the cloak. The regions in blue are water while the background medium is air. The height of the cloaking device is  $h = 10$  cm. A giraffe toy with a height of 14 cm is stand inside the cloaked region. The forest image on the screen is used as a background. A camera in front of the cloak records the scenery from the front observation angle.

### 3. RESULTS AND DISCUSSION

The performance of the cloak is shown in Figure 3. The background image is a field scene displayed in the screen behind the cloaking device, as shown in Figure 3(a). Figure 3(b) shows the result without the cloak. The giraffe toy is put directly between the camera and the screen. Parts of the picture are covered by the toy. Figure 3(c) shows the case when the giraffe toy was put inside of the cloak, and one can see that the body of the giraffe is well cloaked and only the head of the giraffe can be seen. On the other hand, the background behind the cloaking device is still in good continuity. This reflects that the rays are guided around the hidden object and transmitted back to their original path, as shown in Figure 1.

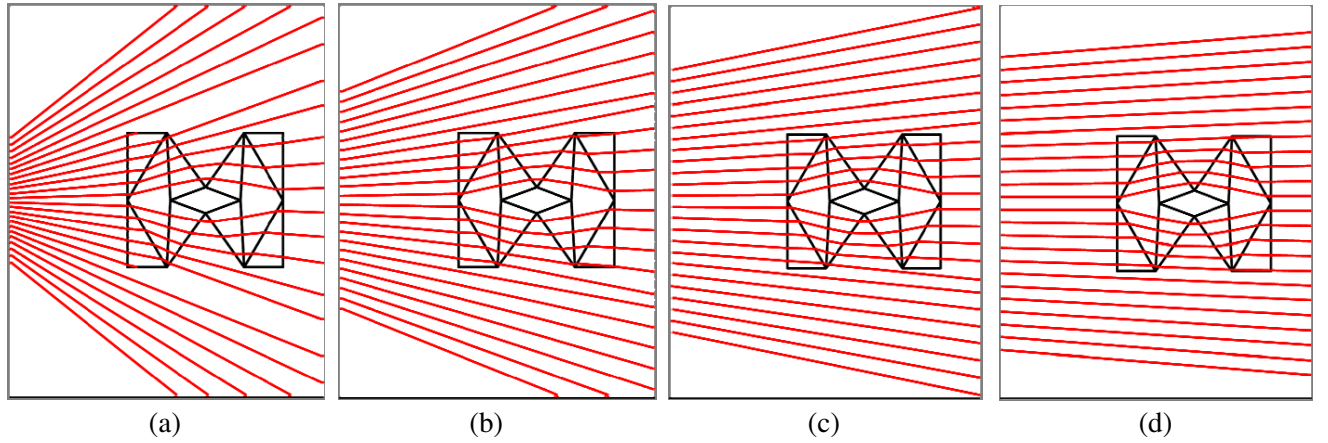


**Figure 3.** Experimental observation of a giraffe in the water cloak. (a) The image of the background. (b) The image captured by the camera when a giraffe toy without the cloak is put in front of the background. Part of the background image is blocked by the giraffe. (c) The image when the giraffe is cloaked with the device. The body of the giraffe is invisible with the background image still in good continuity.

Comparing Figure 3(c) and Figure 3(a), we can see that there are still some small differences between the results with cloak and pure background such as the small mismatch in the center of Figure 3(c). This is due to the fabrication limitation such as the gap between the glued boundaries of thin glass sheets as well as some fabrication errors. It can be overcome by advanced process with a more accurate method.

Though the refractive index is temperature and wavelength dependent, the liquid water has a relative stable refractive index in visible light spectrum. With the temperature changing from 10°C to 90°C, the refractive index of water changes from 1.334 to 1.321 at the wavelength of 589 nm [23]. This is less than 1% difference compared with theoretical value we use in the calculation thus will not affect the cloaking performance obviously.

Furthermore, the result of the device performance may be affected by the locations of the observer because the lights which the observer received are not always parallel rays. We use a point receiver to represent the observer and calculate the light traces with the point receiver placed at different locations. Figure 4 shows the calculated results. The distances between the point receiver and the device are (a) 50 cm, (b) 100 cm, (c) 200 cm and (d) 500 cm, respectively. When the observer is near the device, there is a disorder of light rays, which leads to a discontinuity of background. On the contrary, when the observer is far away from the device, the light rays can approximate parallel rays, and the device is still in good performance.



**Figure 4.** Calculated light traces of an observer at different positions. The distances between the observer and the device are (a) 50 cm, (b) 100 cm, (c) 200 cm, (d) 500 cm, respectively.

It should be noted that the performance of our device can be made theoretical perfect in one direction. On the other hand, the size of the cloaked region can be increased simply by changing the sizes of the bulks of water. Due to the fluidic properties of water, bulks of water can be easily changed by the arrangement of glass sheets. There is no technical difficulty in practical fabrication.

#### 4. CONCLUSION

In conclusion, we experimentally fabricate an invisible device using bulks of water, with glass sheets utilized to separate each region between water and air. Instead of using metamaterials with anisotropic and inhomogeneous parameters, which is difficult to realize in visible light spectrum, our device is convenient for material acquisition and simple for fabrication. Both water and glasses are easily acquired in daily life, which makes it a practical device for mass production. It is the simplest and cheapest invisible device up to now.

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