Hidden in Plain Sight

Baile Zhang[1], **Yuan Luo**[1,2] **and George Barbastathis**[1,2]

[1]Singapore-MIT Alliance for Research and Technology Centre, Singapore 117541, Singapore
Email: bzhang@smart.mit.edu
[2]Department of Mechanical Engineering, Massachusetts Institute of Technology
Cambridge, Massachusetts 02139, USA

Abstract

Invisibility cloaking has attracted a lot of interest from both the general public and the scientific community because of its possible realization. Here we discuss the first realization of invisibility cloaking of a macroscopic object in visible light. The underlining mechanism is based on the incorporation of transformation optics in a conventional optical lens fabrication. A common anisotropic optical material—calcite—is used. This technique may open up the possibility of taking more transformation optics devices from concepts into practical applications.

1. Introduction

The most attractive prospect of transformation optics might be the possibility to render an object invisible by precisely controlling the flow of light around the hidden object, as if the space is empty [1, 2, 3, 4]. The behind mechanism stems from the formal invariance of Maxwell's equations: a coordination transformation does not change the form of Maxwell's equations, but only changes the constitutive parameters and field values. The object can be hidden because it is out of the transformed electromagnetic space. The possibility of realizing invisibility cloaking in the near future will greatly impact the technology of the next generation.

A lot of effort has been made in the experimental implementation of invisibility cloaking. However, there are still several significant limitations that need to be overcome before invisibility cloaks become practical. The first limitation is the cloaking frequency band. The first cloak working at microwave frequencies [5] can achieve invisibility only in a very narrow frequency band [2, 6]. By utilizing a ground plane, it has been proposed that an object sitting on a flat ground plane can be made invisible at optical frequencies because of the effect of a "carpet" cloak [4]. This "carpet" cloak model has been implemented in both microwave [7, 12] and infrared frequencies [8, 9, 10, 13], and in both two dimensional [7, 8, 9, 10] and three dimensional geometry [12, 13]. However, this strategy in the aim of overcoming the frequency band limitation has caused another serious limitation: it has been shown that the quasiconformal mapping, based on which the carpet cloak is built, will generally lead to a lateral shift of the reflected beam, whose value is comparable to the height of the hidden object, and thus makes the object detectable [14]. The second limitation is the size of the object to be cloaked. Most previous experiments of optical cloaks were demonstrated under a microscope, cloaking only a small object at the scale from about one wavelength [8, 9, 10, 13] to about 100 wavelengths [11]. Therefore, it is still a crucial challenge to "see" the invisibility effect, i. e., to cloak a macroscopic object in visible light.

Most recently, two independent groups reported similar ideas and realization of invisibility cloaking of a macroscopic object in visible light [15, 16]. In this talk, we will introduce our recent work [15].

ISBN 978-952-67611-0-7

2. Design and Experimental Results

Instead of attacking the difficulty of anisotropy in transformation-based invisibility cloaks, we turned to solve the other difficulty, inhomogeneity. We built an invisibility cloak that can work at visible frequencies for cloaking large objects. The material that we use is calcite, a commonly used optical material in lens manufacturing. Utilizing the anisotropy of calcite, we can guide the light in the desired way. Since calcite is transparent in visible light, the energy loss during the guiding process is minimized.

The experimental setup is shown as in Fig. 1. The cloak is made of two pieces of calcite that were cemented together along the dotted white line. The dotted yellow arrows indicate their optical axes, respectively. The angle of each optical axis is specifically tuned according to the transformation optics design [15]. A steel wedge is hidden underneath the calcite cloak. The whole system is immersed in a liquid tank filled with a laser oil with refractive index 1.53. A laser beam with the magnetic field parallel to the horizontal plane is shone on a transmission pattern of an inverted "MIT" that is attached on one side of the liquid tank. The light transmitted through "M" will go through the calcite cloak with the wedge hidden underneath. The light transmitted through "IT" will go through the tank and be reflected on the surface of the mirror without touching the calcite cloak and the hidden wedge. All the letters will be finally projected onto a CCD camera on the other side of the tank. The experimental result on the right hand side shows that the camera can image a well-patterned "MIT", which means that the outside observer cannot tell whether there is some object sitting on top of the mirror.

We also discussed the influence of incident angles and the color abberation. More details can be found in [15].

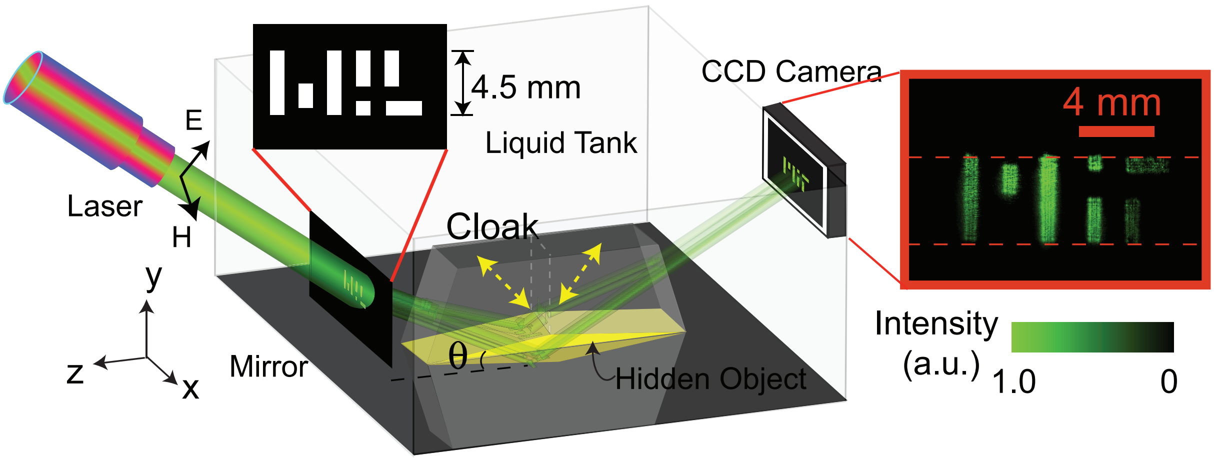

Fig. 1: Experimental setup of invisibility cloaking of a macroscopic wedge under a calcite cloak in a liquid tank.

3. Conclusion

In this contribution, we have introduced the design and experimental result of macroscopic invisibility cloaking in visible light in a liquid environment. This is the first and only experiment so far providing the shift-free evidence of a target image in presence of the hidden object through a direct imaging method. Therefore, it is closest to the idealized concept of a cloak—being invisible to the eye.

References

[1] U. Leonhardt, Optical Conformal Mapping, *Science,* vol. 312, p. 1777, 2006.

[2] J. B. Pendry and D. Schurig and D. R. Smith, Controlling Electromagnetic Fields, *Science,* vol. 312, p. 1780, 2006.
[3] U. Leonhardt and T. Tyc, Broadband Invisibility by Non-Euclidean Cloaking, *Science,* vol. 323, p. 110, 2009.
[4] J. Li and J. B. Pendry, Hiding Under the Carpet: a New Strategy for Cloaking, *Physical Review Letters,* vol. 101, p. 203901, 2008.
[5] D. Schurig and J. J. Mock and B. J. Justice and S. A. Cummer and J. B. Pendry and A. F. Starr and D. R. Smith, Metamaterial Electromagnetic Cloak at Microwave Frequencies, *Science,* vol. 314, p. 977, 2006.
[6] B. Zhang and B.-I. Wu and H. Chen and J. A. Kong, Rainbow and Blueshift Effect of a Dispersive Spherical Invisibility Cloak Impinged On by a Nonmonochromatic Plane Wave, *Physical Review Letters,* vol. 101, p. 063902, 2008.
[7] R. Liu and C. Ji and J. J. Mock and J. Y. Chin and T. J. Cui and D. R. Smith, Broadband Ground-Plane Cloak, *Science,* vol. 323, p. 366, 2009.
[8] J. Valentine and J. Li and T. Zentgraf and G. Bartal and X. Zhang, An Optical Cloak Made of Dielectrics, *Nature Materials,* vol. 8, p. 568, 2009.
[9] L. H. Gabrielli and J. Cardenas and C. B. Poitras and M. Lipson, Silicon Nanostructure Cloak Operating at Optical Frequencies, *Nature Photonics,* vol. 3, p. 461, 2009.
[10] J. H. Lee and J. Blair and V. A. Tamma and Q. Wu and S. J. Rhee and C. J. Summer and W. Park, Direct Visualization of Optical Frequency Invisibility Cloak Based on Silicon Nanorod Array, *Optics Express,* vol. 17, p. 12922, 2009.
[11] I. I. Smolyaninov and V. N. Smolyaninova and A. V. Kildishev and V. M. Shalaev, Anisotropic Metamaterials Emulated by Tapered Waveguides: Application to Optical Cloaking, *Physical Review Letters,* vol. 102, p. 213901, 2009.
[12] H. F. Ma and T. J. Cui, Three-dimensional broadband ground-plane cloak made of metamaterials, *Nature Communications,* 1:21 doi: 10.1038/ncomms1023, 2010.
[13] T. Ergin and N. Stenger and P. Brenner and J. B. Pendry and M. Wegener, Three-Dimensional Invisibility Cloak at Optical Wavelengths, *Science,* vol. 328, p. 337, 2010.
[14] B. Zhang and T. Chan and B.-I. Wu, Lateral Shift Makes a Ground-Plane Cloak Detectable, *Physical Review Letters,* vol. 104, p. 233903, 2010.
[15] B. Zhang and Y. Luo and X. Liu and G. Barbastathis, Macroscopic Invisibility Cloak for Visible Light, *Physical Review Letters,* vol. 106, p. 033901, 2011.
[16] X. Chen and Y. Luo and J. Zhang and K. Jiang and J. B. Pendry and S. Zhang, Macroscopic Invisibility Cloaking of Visible Light, *Nature Communications,* 2:176 doi: 10.1038/ncomms1176, 2011.