

Invisibility cloaking based on geometrical optics for visible light

H. Ichikawa
ichikawa@ehime-u.ac.jp

Faculty of Engineering, Ehime University, 3 Bunkyo, Matsuyama 790-8577, Japan

M. Oura

Artner Co., Ltd., 3-2-18 Nakanoshima, Kita-ku, Osaka 530-0005, Japan

T. Taoda

Faculty of Engineering, Ehime University, 3 Bunkyo, Matsuyama 790-8577, Japan

Optical cloaking has been one of unattainable dreams and just a subject in fiction until recently. Several different approaches to cloaking have been proposed and demonstrated: stealth technology, active camouflage and transformation optics. The last one would be the most formal approach modifying electromagnetic field around an object to be cloaked with metamaterials. While cloaking based on transformation optics, though valid only at single frequency, is experimentally demonstrated in microwave region, its operation in visible spectrum is still distant from realisation mainly owing to difficulty in fabricating metamaterial structure whose elements are much smaller than wavelength of light. Here we show that achromatic optical cloaking in visible spectrum is possible with the mere principle based on geometrical optics. In combining a pair of polarising beam splitters and right-angled prisms, rays of light to be obstructed by an object can make a detour to an observer, while unobstructed rays go straight through two polarising beam splitters. What is observed eventually through the device is simply background image as if nothing exists in between.

[DOI: <http://dx.doi.org/10.2971/jeos.2013.13037>]

Keywords: Invisibility cloaking, geometric optical design, polarisation-selective devices, propagating methods

1 INTRODUCTION

History of invisibility cloaking in real world is not old. The first technological achievement of a sort of cloaking would perhaps be stealth technology which enables fighter jets to be undetected by enemy radars [1, 2]. Its principle is that the surface of an airplane either absorbs or scatters incident microwaves from radars by, e.g. modifying surface structures or using materials with special properties. The second technological achievement, which operates with visible light, have emerged in totally different environment from the former. Optical camouflage consists of two fundamental parts sandwiching an object to be cloaked: a camera taking background image and a screen on which the image is projected [3, 4]. Thus, observed image through the device is not physical phenomenon, but merely processed information. With the aid of rapidly advancing information technology, however, optical camouflage will have a lot of applications in variety of fields.

Perhaps, the most formal and rigorous approach to invisibility cloaking is transformation optics with metamaterials: manipulating material constants of a surrounding medium of an object, so that incident electromagnetic wave upon the object emerges as if nothing exists. Shortly after the first theoretical work by Pendry [5] and Leonhardt [6], the first cloaking was experimentally demonstrated in microwave region [7]. There are, however, serious problems associating with this type of cloaking, e.g. strong dispersion, narrow band and non-perfect conducting nature in optical frequencies [8]. In order to overcome those problems, so-called carpet cloak was proposed [9]

and experimentally demonstrated in near-infrared frequencies though it was a few micrometres in size [8]. Recently, further development has been reported: broadband cloaking potentially for an object of the scale of centimetres in visible light with calcite crystals [10, 11].

The fourth approach to cloaking based upon totally new concept has been recently proposed by some of us [12]. It does not require neither nanostructures nor sophisticated information technology, but some of the most basic optics, i.e. mirrors and 1:1 polarising beamsplitters which can be found in any optics laboratory around the world.

2 PRINCIPLE

The principle is shown in Figure 1(a) where paths of rays are indicated in one side of the symmetrical structure. Note that angles between mirrors are 90 degrees and polarising beamsplitters are placed in parallel to the neighbouring mirrors. In addition, incident angle of light on the mirrors and polarising beamsplitters is assumed to be 45 degrees. At the gate 1, incident s-polarised light (solid red line) is reflected by two mirrors and two polarising beamsplitters and emerges from the device at the gate 3, while p-polarised light (broken blue line) is reflected by the first mirror, transmits through the first polarising beamsplitter and goes out from the side of the device. On the other hand, at the gate 2, p-polarised light (solid blue

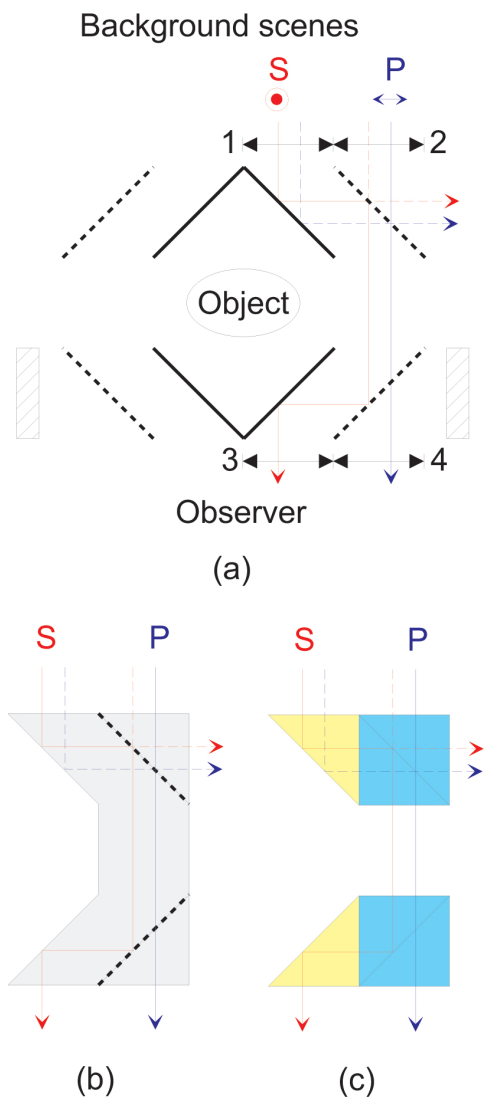


FIG. 1 The basic idea of the proposed cloaking device is illustrated in (a). Thick solid and dashed lines denote mirrors and polarising beamsplitters, respectively. Black lines with a number and arrows indicate gates where light passes. Thin solid red and blue lines denote paths of light rays for s- and p-polarisation, respectively. Two rectangles with hatching inside are for blocking incoming unwanted light from the sides. Examples of realising the principle are shown in (b) and (c), which are integral structure and the easiest set-up, respectively. S and P denote s- and p-polarisation, respectively.

line) goes straight, while s-polarised light (broken red line) is reflected by the first polarising beamsplitter and goes out of the device. The hatched rectangles in the figure are necessary to block incoming unwanted light from the sides of second polarising beamsplitters. As a result, incident light rays at the gates 1 and 2 exclusively go to the gates 3 and 4, respectively.

Examples of practical experimental set-up are given in Figures 1(b) and 1(c). Although an integral structure of Figure 1(b) would be more stable and efficient with less multiple reflection, we used the one in Figure 1(c), which is much simpler to construct and has an extra freedom of controlling a distance between two sets of elements. Here, yellow-coloured are right-angle prisms acting as mirrors with 100% efficiency owing to the effect of total internal reflection and blue-coloured are cube-type polarising beamsplitters. In our experiments, polarising beamsplitters were anti-reflection coated, while

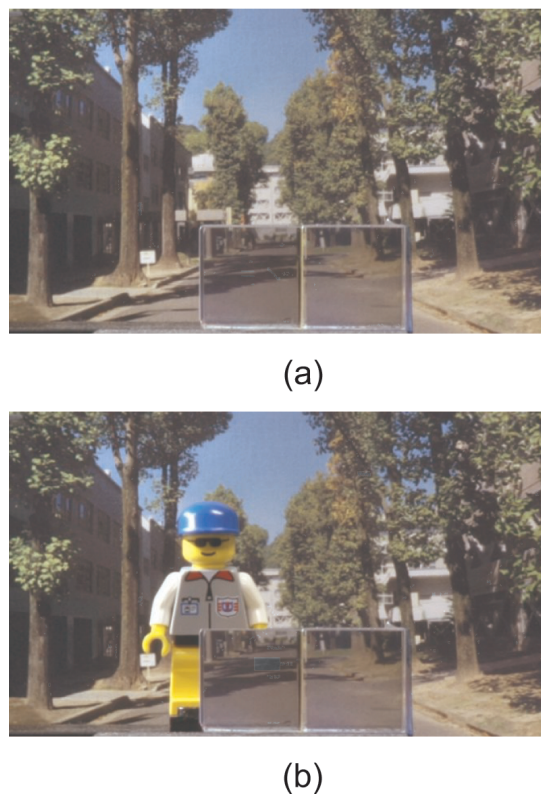


FIG. 2 Demonstration of the proposed cloaking device. (a) Placed in front of a printed photograph as background scene. (b) An object to be cloaked is simply put inside the device.

right-angle prisms were uncoated. The both elements are made of optical glass BK7 and attached together with glycerine. Each side of the polarising beamsplitters and prisms were 20 mm long and thus working area of the (half-sized) cloaking device were $20 \times 40 \text{ mm}^2$. Although unwanted multiple reflection between consisting elements exists, even this sort of simple device would be suffice to demonstrate fundamental performance of the proposed cloaking principle.

3 RESULTS

The cloaking performance demonstrated by the device is shown in Figure 2. Here, spacing between the two polarising beamsplitters was fixed at 20 mm. The background image was a photographed outdoor scene laser-printed with just an ordinary sheet of paper for daily office use and illuminated by several fluorescent lamps equipped at the ceiling of the laboratory. When a 45 mm tall doll was placed inside the cloaking device, what we could observe was in Figure 2(b). In order to demonstrate the effect of the device, the doll was positioned so that a part of its body was outside the device. It would be justified to declare that an object could nearly perfectly cloaked with this pretty simple device. The effect will be more noticeable with a moving object and background as in Figure 3. Here, the background was pre-recorded outdoor scene displayed on a PC display. The ghost images occasionally observed in the video might be due to the fact that both pre-recording background and recording experiments were carried out by the same digital camera.



FIG. 3 Video demonstration of the cloaking device (MOV format, 1.73 MB).

4 DISCUSSIONS

Although the visual effect is somewhat remarkable, there are obviously several drawbacks in this device. First of all, s- and p-components of the incident light on the device must have nearly equal radiance, i.e. the device may be illuminated by unpolarised light ideally. This also indicates that only a half of incident light energy transmits the device, even though the device is perfectly transparent and antireflection-coated. In fact, the background scene through the device is slightly darker than directly seen one, as seen in Figure 2. Here, signal transmittance for both polarizations was more than 95% in wavelength range of 450 - 700 nm.

Second, there is optical path difference between two paths. The s-polarised light from the gate 1 to the gate 3 makes a detour around the object, so that it needs to travel extra distance of $2a$, a being a length of the side, compared with p-polarised light from the gate 2 to the gate 4. In our demonstration here, the arrival time differs roughly 200 ps. Effects of such an order of time difference would be negligible as far as the device is viewed by naked eyes, though there will be some problems if the device is applied to ultra fast phenomena.

The third and the most serious drawback is its limited acceptance angle. For the perfect operation, all rays incident upon the gates 1 and 2 must exit from the gates 3 and 4, respectively. Any ray which fails to do this is a cause of poor performance. A typical example is shown in Figure 4(a), where an observer at O can see only limited view. More detail analysis is given in Figure 4(b), in which the maximum and minimum acceptance angles are evaluated in the observer plane parallel to and the distance y away from the exit plane of the device. When an observer goes farther away from the device, the angular gap between s- and p-polarised rays, such as found in Figure 4(a), becomes smaller and an acceptable angular range becomes narrower. Rigorously speaking, the field of view always has defects, i.e. what we observe at the point O for s- and p-polarised light is not continuous. In other words, we cannot see some part of the background scene. It means that perfect observation can be achieved only when the light enters the device normally, which corresponds to $\alpha = 0$ in Figure 4(b). We would like to mention that the field of view is also affected by the separation distance between the two beamsplitters. As the distance d becomes larger, the range of acceptance angle be-

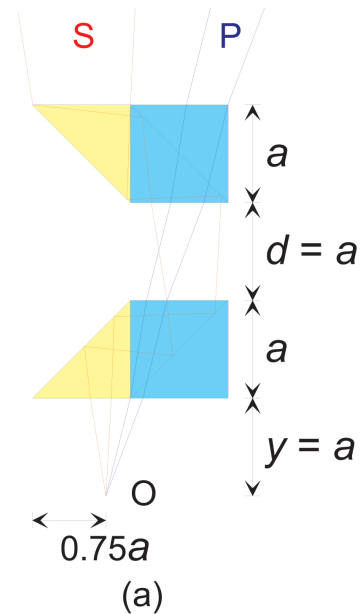


FIG. 4a (a) Ray tracing diagram in which an observer point is placed at the distance a from the position $x = 0.75a$ in the exit plane, as an example. The distance x is measured from the apex of the prism. Red and blue lines indicate boundaries of acceptable areas for s- and p-polarised light, respectively.

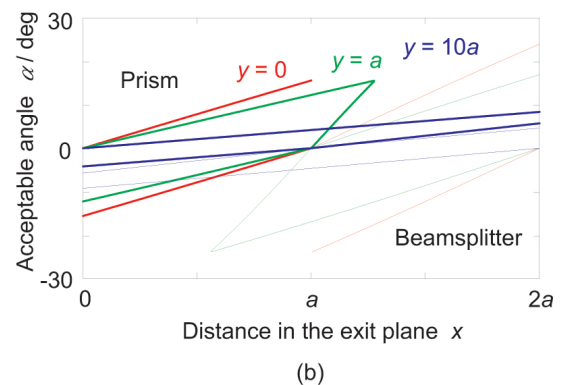


FIG. 4b (b) Vertical ranges between the two curves of the same colour and thickness denote ranges of acceptable angle in the plane parallel to the exit plane of the device when $d = a$. Each colour denotes different value of the distance y as indicated. Thick and thin curves denote rays for s- and p-polarisation, respectively.

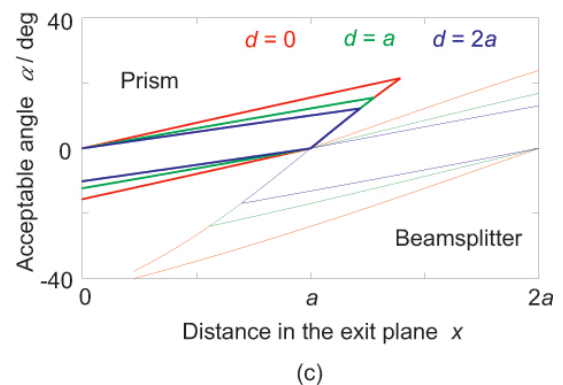


FIG. 4c (c) Similar to (b), but d is variable and $y = a$. Note that colour convention here is different from (b).

comes narrower as found in Figure 4(c). Remember that total internal reflection is violated inside the prisms when $|\alpha| > 5.6$ deg both in Figures 4(b) and 4(c).

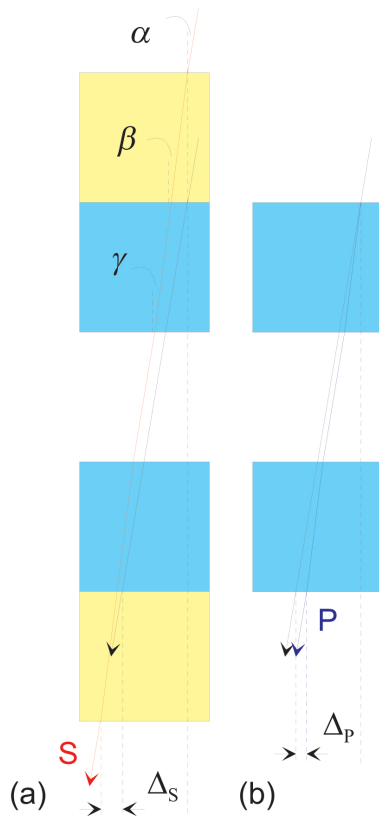


FIG. 5 Schematic illustration of image shift. Colour conventions follow those in Figure 1(c). Black lines denote ray paths without the cloaking device. α , β and γ are angles of rays in air, prisms and polarising beamsplitters, respectively. (a) For s-polarised light from the gate 1 to 3. (b) For p-polarised light from the gate 2 to 4.

Let us investigate this issue in a little more detail. The cloaking device effectively acts as multilayered rectangular parallelepipeds as shown in Figure 5. Obliquely incident rays upon the device appear at different positions in the gates 3 and 4 from the ones without the device. The amounts of the shifts for s- and p-polarised light are evaluated

$$\Delta_S = 2a(\tan \beta + \tan \gamma - \tan \alpha), \quad (1)$$

$$\Delta_P = 2a(\tan \gamma - \tan \alpha), \quad (2)$$

respectively. For example, in the case of our demonstration setup in Figures 2-4 at $\lambda = 632.8 \text{ nm}$, $\Delta_S = 0.108a$ and $\Delta_P = -0.122a$ for $\alpha = 10^\circ$. If ordinary mirrors are used instead of right-angled prisms, Δ_S increases to $0.231a$. This image shift becomes more and more unacceptable in increasing viewing angle as well as the limited field of view.

For the device to work ideally, therefore, the device must be viewed right in front of the device. In addition, the farther an observer is from the device, the less noticeable the device boundaries are. This problem is observed at the bottom centre in Figure 2, where two square-shaped frames are boundaries of prisms and polarizing beamsplitters. So, the edges of the cloaking device are visible, even though an object can be invisible.

5 CONCLUSIONS

Achromatic optical cloaking over nearly entire visible spectrum is shown to be possible with the mere principle based on geometrical optics combined with polarisation property and without such as metamaterials and complex systems. Although its effect is approximate, what is observed with naked eyes is striking and realistic, i.e. impossible to achieve by any other means at least in visible spectrum at the moment. This device can, therefore, be one of good candidates for practical cloaking, because there would be no single cloaking principle for universal applications and thus any technique is workable only under certain conditions. In addition, the proposed technique would have applications not only in cloaking but also such as metrology related to polarisation. We believe this work demonstrates an interesting example that a sort of simple classic optics sometimes can well compete with or even overtake modern high technology.

M. Oura was in Ehime University, when he conducted the research.

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