

A New Invisible Cloak with Broad Stealth Angle Based on Isotropic Material

Zhao Jingbo*

Science College
Air Force Engineering University
Xi'an, China
e-mail: chjzjb@163.com
* Corresponding Author

Yao Hong

Science College
Air Force Engineering University
Xi'an, China

Du Jun

Institute of Aeronautics and Astronautics
Air Force Engineering University
Xi'an, China

Liu Yijing

Science college
Air Force Engineering University
Xi'an, China

Jiang Jiulong

Institute of Aeronautics and Astronautics
Air Force Engineering University
Xi'an, China

Dong Yake

Institute of Aeronautics and Astronautics
Air Force Engineering University
Xi'an, China

Abstract—Study on invisible cloak has attracted considerable attention from all over the world thanks to its potential application value. However, it is still difficult to achieve fully movable invisible cloak due to material and other constraints currently. Here, the design and experimental demonstration of a new invisible cloak for visible light is reported, which is composed of ordinary homogeneous and isotropic glass material, and the ingenious structural design creates an illusion by guiding the light around the hidden object and making it appear on the other side without any deflection. Moreover, the cloak possesses broad oblique viewing angle with perfect stealth effects. Experiments on the designed invisible cloak validate the effectiveness of the proposed cloak structure for visible light.

Keywords- Invisible cloak; Structure design; Deflection; Isotropic; Stealth angle

I. INTRODUCTION

Research on invisible cloak has made progress in transformation optics[1] and conformal mapping theory[2]. The cloaks include three types, cylindrical[3-5], spherical[1] and carpet cloak[6-19]. Since the first experimental demonstration of the cylindrical cloak in 2006[3], it is difficult to achieve an isolated invisibility cloak because of the extreme values of the materials and the spatially dependent anisotropic parameters. Linear homogeneous coordinate transformation is used to achieve movable invisible cloak for visible light. The idea on homogeneous

cloak is firstly studied[20], where a one-directional diamond cloak created with homogeneous material is proposed. In fact, all these difficulties in implementation stem from the need to bend light around the hidden object while preserving its phase. In 2012 and 2013, a polygonal optical cloak was reported that it can hide an isolated macroscopic object in visible light, and the design abolished the phase preservation requirement. A big hidden region is transformed into a much smaller one, which can be hardly seen by the naked eye. The linear homogeneous transformation leads to homogeneous and finite materials parameters in the cloak. It is a new step toward feasible human cloaking devices[21,22]. However, one of the key problems for the designed cloak is the cloaking performance can tolerate an viewing angle variation of $\sim 4^\circ$.

In this paper, a new optical cloak composed of ordinary homogeneous and isotropic glass material is reported. It can hide isolated macroscopic object in visible light in an ambient air environment. The cloak can guide ray trajectory around the hidden object and making it appear on the other side without any deflection. Our theoretical and experimental work shows that the designed cloak possesses broad stealth viewing angle. The designed optical cloak has ordinary homogeneous and isotropic glass material, broad invisible angle, and ambient air environment for arbitrary polarization over a broad range of optical frequencies three major advantages.

II. DESIGN OF BASIC INVISIBLE UNIT

Figure 1(a) shows the structure of the unit processed with ordinal glass, which is homogeneous and isotropic organic glass (light transmission rate of 92%, refractive index of 1.49). The device has two glass flanks included angle 60 degrees. Fig. 1(b) shows stealth effect of the structure. An ordinary pen is placed stealth region (near outside tip) and the background pattern is the letters and logo of Air Force Engineering University. It can be seen from the figure, although stealth object is invisible, the letter 'eer' and part logo of the background pattern has also been hidden at the same time. Thus it can not be called true stealth, but can be applied in some special situation, for example, the shape and color of the background are exactly the same. Fig. 1 (c) shows the mechanism analysis of basic invisible unit. The red circle means stealth object. The orange lines with arrowheads mean incident rays. The main reason of the object can be hidden lies to total reflection. As it is known, when light enters from a denser medium into the optically thinner medium, if the incident angle

is large to a certain extent, so that when the refraction angle will reach 60° . With increase of the incidence angle, the light is not refracted, and when the light will be reflected, without refraction, this phenomenon is called "total reflection". The total reflection angle of common glass is 38° for this kind of glass. In the structure of the invisible unit with 60 degree included angle, rays emitted from object are all reflected in inner surface of glass in the range of observation, and do not enter the inside glass, so the object can be invisible. While the same reason that the background pattern is hidden off a block. According to the principle of reversibility of light, after the rays emitted from the inside of the unit pass through the invisible unit, the stealth region formed near the unit tip outside because of refraction, that is to say, the rays emitted from stealth region object can not enter the interior side of unit. But it must be pointed out that, with increasing of the distance between the tip and the object, the incident angle of the rays from object at the inner surface of the glass becomes smaller. When the incident angle is less than total reflection angle, the rays will enter the inside glass, thus observers can see the object or background pattern. The specific mechanism of ray trace can be seen in Fig 1 (d).

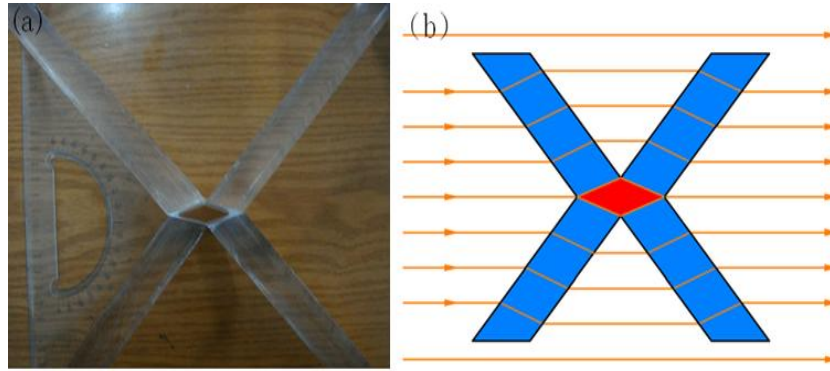


Figure 1. Design and stealth mechanism of the basic invisible unit

In order to solve the narrow stealth angle, a new invisible cloak is designed. Fig. 2 shows the structure and mechanism of the second invisible cloak. Two glass flanks included angle 60 degrees and the hole located in cloak center is stealth region in Fig. 2(a). Fig. 2(b) shows the stealth mechanism. Artful structure design makes the light path round stealth objects, to the other side, trajectory without any offset, realizing the object stealth.

Fig. 3(a) shows the map of the exhibition of experimental setup. A column is put inside the cloak as a hidden object, and the upper part of the column is unwrapped by the cloak for comparison. The cloak with stealth object is placed in air. The letters and the logo of Air Force Engineering University, printed on a paper placed behind the cloak in the xz plane. To facilitate

comparison, a camera is placed in front of the cloak, rotate the cloaks to change viewing angles from 0° to 30° , then from 0° to -30° . The stealth effects for the cloak are shown in Fig. 4. One can see that the background can be seen completely at the viewing angle 0° (Fig. 3(b)), -30° (Fig. 3(c)), $+30^\circ$ (Fig. 3(d)) respectively. The column object is invisible and the background is visible in viewing angle variation of $\sim 60^\circ$ (from -30° to $+30^\circ$). It should be pointed that in Fig. 4(c) and Fig. 4(d), the line is slight thick because of the mismachining tolerance for the cloak. The results indicate that the cloaking performance is valid when viewed at the broad oblique angle range $\sim 60^\circ$.

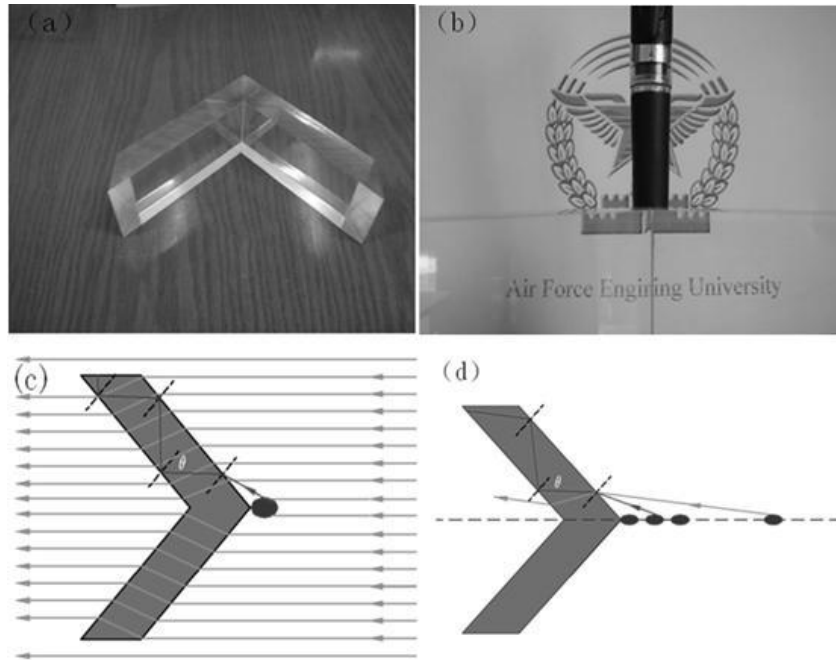


Figure 2. The second invisible cloak (a) The structure of the second invisible cloak (b) The invisible mechanism of the second invisible cloak

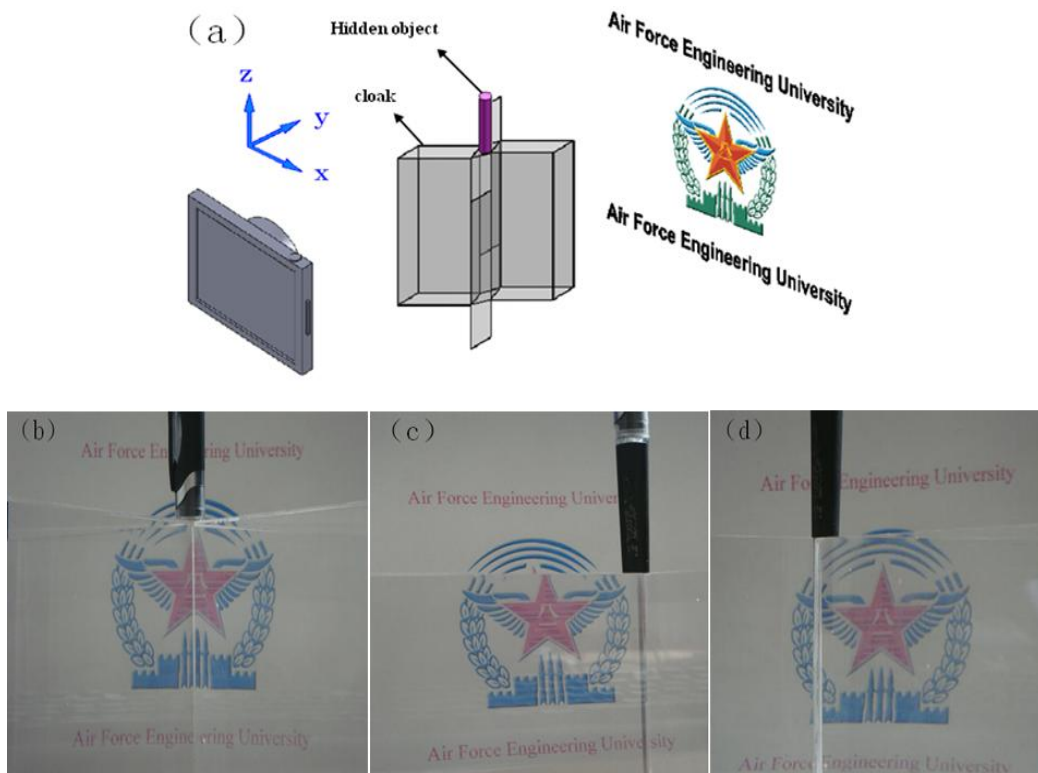


Figure 3. The experiment effect of the second invisible cloak (a) schematic of experiment setup (b) The invisible effect at the viewing angle 0° (c) The invisible effect at the viewing angle $+30^\circ$ (d) The invisible effect at the viewing angle -30°

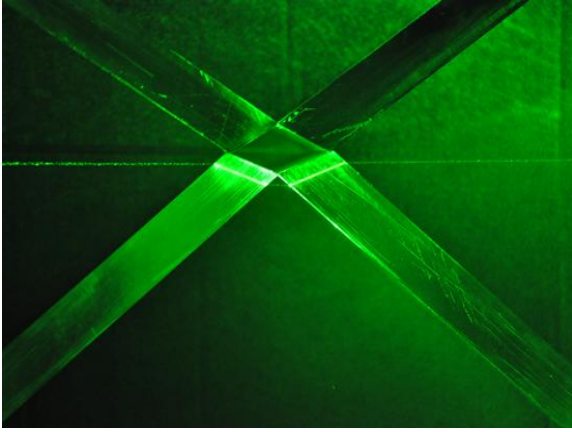


Figure 4. The propagation of the laser beam through the cloak

At the wavelength of $\lambda = 532\text{nm}$ laser irradiation, the light propagation path of the second invisible cloak can be clearly seen, as shown in Figure 3. As it can be seen from the picture, the ray paths are bypassing the stealth region, and are still in the same straight line. The refraction characteristics of laser path further validate the stealth principle and feasibility of the designed invisible cloaks.

The second invisible cloak has three advantages: first, the invisible cloak has broad stealth angle range $\sim 60^\circ$. At the angle range, the invisible cloak has perfect stealth effect. Secondly, the invisible cloak can be fabricated using common homogeneous and isotropic glass materials, without using the anisotropic materials and sophisticated processing technology. Thirdly, the invisible cloak can realize the full range of perfect optical camouflage in air environment.

III. CONCLUSIONS

In the paper, a new invisible cloak is designed. The stealth mechanism analysis and the experiment have proved the effects of the invisible cloak. The second invisible cloak with broad oblique viewing angle is made of ordinary isotropic glass material, without using sophisticated materials. Therefore, the invisible cloak possesses important value in large-scale engineering application. Meantime, it also has the important enlightenment significance to the non-visible light wave electromagnetic wave stealth.

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