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Illusion optics by single and twin cylindrical cavity cloaks

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ABSTRACT

Creating optical illusion by using interior cavity cloak in 2D is discussed in this paper. An antiobject is embedded in the cloak shell and the corresponding imaginary object (under transformation optics) is observed in virtual space instead of any other object which was really exist inside the cavity cloak in physical space. Cylindrical single (twin) cavity cloak is used in this paper, that making one (two) object with arbitrary shape and material properties appears exactly like another object(s) with different shape and material make up for an observer who lies outside the cloaking shell. The simulation results prove that this illusion device with the proposed parameters is operationally possible. The advantage of using internal cloak instead of folded geometry which is usually used is that there is no negative refraction in the structure of the device.

1. Introduction

Recently the concept of transformation optics [1,2] has enabled the design of new materials that can guide light along arbitrary curves and the simulation based on finite element method confirmed the functionality of the designed devices [3–8]. Experimental application is also made possible by employing metamaterials [5,6,9]. Concentrators, rotators, wave-shape transformers and invisibility cloak are some example of these new devices. Some analytical solutions for Maxwell's wave equation using the data extracted from transformation optics are also approved the results of finite element approach [10–12]. Among various novel applications, the most facinating is a cloaking device.

Several kinds of invisibility cloak has been reported, carpet cloak, plasmonic cloak, internal cavity cloak and cloak at a distance can be named. Li and Pendry [8] proposed a kind of cloak that an object sitting on a flat ground plane can be made invisible under a carpet cloak [8]. In plasmonic cloaking with using plasmonic and metamaterial cover, the total scattering cross section for a particle [13] or collection of particles [14] is drastically reduced.

In the cavity cloak the transformation optics is used to create a hole in transformed coordinate system and an object in the hole can be concealed from detection [1,3,7]. Another approach was reported to produce similar effect in the geometric limit [2].

Lai et al. [15] first proposed a new kinds of invisibility cloak called cloak at a distance or external cloak. In this method it is possible to hide an object that lies outside the cloaking shell. The idea is based on combining the concept of complementary media [16] and transformation optics. In this approach for hiding an object which is outside of the cloak an antiobject is placed in the negative index shell of the cloak.

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Cloaking can be regarded as creating an illusion of free space. In 2009 Lai et al. [17] also introduced a more generalized concept of illusion which was: making an object of arbitrary shape and material property exactly like another object of some other shape and material property. The principle of illusion device which is designed by them is based on folded geometry [4,17] and external cloak. This device could transform the scattered light of an object as if the light is scattered from another object, outside a virtual boundary. A twin version of this device can also be found in [18]. Experimental verification for this illusion device was reported in [19]. Creating illusion effect using active source is another method which is reported by Zheng et al. [20]. Illusion media is the name which is chosen by Jiang et al. [21] for their illusion device. Some other illusion devices are also reported [22–24].

In this article we introduce an approach for 2D illusion device that the principle behind it is the concept of cavity cloak. In our method, we use cylindrical single and twin cavity cloak structures instead of Cartesian single cloak which is introduced and designed by Ref. [21], and object(s) will be able to hide instead of shrinking as can be seen in Ref. [22], moreover we also use cylindrical twin cavity cloak where two objects are disappeared and instead of them two (more or less) other imaginary objects are seen. In our explanation the first object (the object that is going to be invisible) is placed inside the cylindrical cavity of the cloak; an antiobject is also used, but here when an antiobject embedded in the cloak region in physical space the corresponding imaginary object (which is different from the first object) is observed in virtual space.

This paper is arranged as follow: after a brief review on transformation optics in Section 2, we discussed in detail all the properties for a single cylindrical cavity as well as a twin cylindrical cavity illusion devices in Section 3. The concluding remarks deduced from our approach are presented in Section 4.

2. Transformation optics

In all coordinate-transformation problems it is ordinary to imagine two spaces which are called physical space and virtual space. Physical space is a real space that all the structures are lied in it and the virtual space is an imaginary space whenever an observer looks at the physical space, sees a picture that is different from the real physical space. Invisibility cloaks mostly create a picture of empty space for observer, it means that the virtual space for these cloaks would be the empty space.

Suppose we assign a coordinate system to each of the space so that all the unprimed-parameter would be for physical space and virtual space would have primed-parameter. For an arbitrary coordinate transformation from the original Cartesian coordinate $\mathbf{x}'$ (virtual space) to a new coordinate $\mathbf{x}$ (physical space) of the form $x_i = x_i(x'_j)$, mathematical form-invariance of Maxwell's equation implies that material properties of transformed space ϵ and μ are related to the original one ϵ' and μ' by the equations [1,3]

$$\epsilon = \frac{\Lambda \epsilon\prime \Lambda^T}{\det \Lambda}, \quad \mu = \frac{\Lambda \mu\prime \Lambda^T}{\det \Lambda} \tag{1}$$

where $\Lambda_{ij} = \partial x_i / \partial x_j$ is the transformation matrix. The transformations for charge and current densities as well as fields can be found in [3,6].

3. Illusion optics

In the subsequent sections we will show how it is possible to have an illusion device with using interior cavity cloak. Cylindrical single and twin cavity cloaks are used for this purpose.

3.1. Cylindrical cloak

Consider a transformation relation in cylindrical coordinate as [6]

$$r = (1 - a/b)r\prime + a, \quad \theta = \theta\prime, \quad z = z\prime. \tag{2}$$

This transformation compress the cylindrical region $r' \le b$ in the old coordinate system (r', θ', z') into a concentric cylindrical shell of $a \le r \le b$ in the new coordinate system (r, θ, z). This also transforms the axis of the cylinder r'=0 into a hollow region of $r \le a$ in the new coordinates.

By constructing the transformation matrix according to relation (2) and inserting the resulting matrix in Eq. (1), one can obtain the dielectric properties of a cylindrical cloak as [6]

$$\begin{aligned}
\epsilon_r &= \mu_r = \frac{r-a}{r}, \\
\epsilon_\theta &= \mu_\theta = \frac{r}{r-a}, \\
\epsilon_z &= \mu_z = \left(\frac{b}{b-a}\right)^2 \cdot \frac{r-a}{r}.
\end{aligned} \tag{3}$$

where in the imaginary space is suppose to be vacuum i.e. $\epsilon' = \mu'$=1. Each object which is placed in the cavity of the cloak is disappeared from an external observer. Now if we place an antiobject inside the cloak region of the device $a \le r \le b$, the