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RESEARCH ARTICLE

Cloak an illusion

Ya-dong XU (徐亚东), **Lei GAO** (高雷), **Huan-yang CHEN** (陈焕阳)†

School of Physical Science and Technology, Soochow University, Suzhou 215006, China

E-mail: †kenyon@ust.hk

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An illusion counter-part displays the same scattering far-field pattern as that of a real object. In this paper, for the first time, we demonstrate that such an unreal illusion can be cloaked by an external cloak. This phenomenon shall be called “cloak an illusion”. Numerical simulations were performed to demonstrate such a phenomenon.

Keywords transformation optics, illusion optics, external cloak

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1 Introduction

Illusion Optics [1, 2], fueled by combining the concept of transformation optics [3, 4] and complementary media [5, 6], has recently attracted much research interest because of its novel illusion properties. For example, it has been used to propose devices with much larger extinction cross sections (super-scatterers [7] and super-absorbers [8]) than the original geometrical cross sections. The super-scatterer concept has been utilized to design the invisible gateway [9, 10]. Another kind of interesting application is the external cloak that can cloak an object at a distance [11, 12]. Other interesting designs include the shifted scattering device to form an image that is completely outside itself [13], the invisible tunnel to guide waves in vacuum [14], the focusing antenna with an enlarged effective diameter [15, 16], etc.. Although the optical illusion effect has been proposed, further numerical studies should be performed to verify that an “illusion object” (or illusion device) can indeed be treated as a real object optically and further used for other potential applications. In addition, the unnecessary illusion effects should be eliminated for some applications. For example, a mirage effect will disturb the drivers and cause accidents. If we can cloak the mirage effect, it will be helpful for drivers. Hence, in this paper, we will first use the illusion optics to design an illusion device that appears to anther object (i.e., to mimic a mirage effect). Then we implement an external cloak to make the illusion invisible (i.e., to cloak the mirage effect). We call this “cloak an illusion”.

2 Theory

We start from illusion optics to create an illusion object. Figure 1(a) is a schematic plot of an illusion device, where region 1 acts as the restoring medium, and regions 2 and 3 as a pair of complementary media. The detailed folded coordinate transformation is [10]

$$
\begin{aligned}
&x = \begin{cases} -x_2^y + \frac{x_2+x_1}{x_2-x_1} \times (x' + x_2^y), & -x_2^y < x' < -x_1^y \\ -x', & -x_1^y < x' < 0 \\ x', & \text{else} \end{cases} \\
&y' = y \\
&z' = z
\end{aligned} \tag{1}
$$

where we map the virtual space (x-space) into the physical space (x'-space) with

$$
(x_1^y,\ x_2^y) = \begin{cases} \left(x_1 \frac{y_2-y}{y_2-y_1},\ x_2 \frac{y_2-y}{y_2-y_1}\right), & y_1 < y < y_2 \\ (x_1,\ x_2), & -y_1 < y < y_1 \\ \left(x_1 \frac{y_2+y}{y_2-y_1},\ x_2 \frac{y_2+y}{y_2-y_1}\right), & -y_2 < y < -y_1 \end{cases} \tag{2}
$$

The anisotropic material properties in region 1 are described by its permittivity and permeability tensors,

$$
\overleftrightarrow{\varepsilon}_p = \overleftrightarrow{\mu}_p = \begin{vmatrix} \frac{r^2+p^2}{r} & \frac{p}{r} & 0 \\ \frac{p}{r} & \frac{1}{r} & 0 \\ 0 & 0 & \frac{1}{r} \end{vmatrix} \tag{3}
$$

where $r = \frac{\partial x'}{\partial x} = \frac{x_2-x_1}{x_2+x_1}$, $p = \frac{\partial x'}{\partial y}$ [See Ref. [10] and Fig. 1(a)]. Region 2 is a double negative material (DNM) with permittivity $\varepsilon = -1$ and permeability $\mu = -1$.

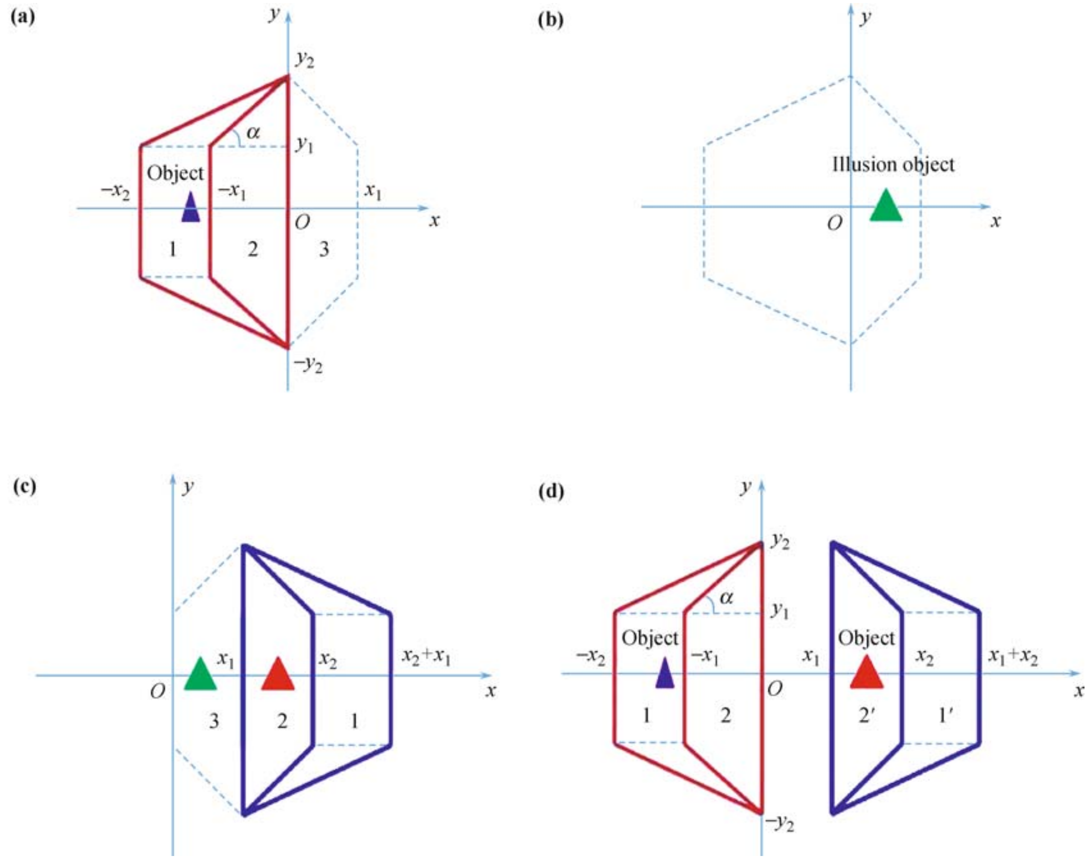

Fig. 1 **(a)** The schematic plot of an illusion device, adapted from Ref. [10]. **(b)** The equivalent illusion object of the device in (a). **(c)** The schematic plot of an external cloak. **(d)** The schematic plot for "cloak an illusion". Region 1′ is identical to Region 1 in (c) while Region 2′ is identical to Region 2 in (c).

Region 3 is air. If an object [the purple triangle in Fig. 1(a)] is embedded in the restoring medium with $\overleftrightarrow{\varepsilon}_{\rm c} = \varepsilon_{\rm c}\overleftrightarrow{\varepsilon}_p$ and $\overleftrightarrow{\mu}_{\rm c} = \mu_{\rm c}\overleftrightarrow{\mu}_p$, it will appear as if it is another object with $\varepsilon_{\rm c}$ and $\mu_{\rm c}$ in the air for a far-field observer [see the green triangle in Fig. 1(b)]. Such an image can be called as an "illusion object".

It has been well known that a real object can be cloaked by a similar device [11, 12]. For instance, Fig. 1(c) shows such an external cloak. Region 1 is the restoring medium whose material parameters can be calculated likewise. Region 2 is a DNM (with $\varepsilon = -1$ and $\mu = -1$), and Region 3 is air. To cloak a real object with $\varepsilon_{\rm c}$ and $\mu_{\rm c}$ [see the green triangle in Fig. 1(c)] in Region 3, we need to embed an "anti-object" with $-\varepsilon_{\rm c}$ and $-\mu_{\rm c}$ [see the red triangle in Fig. 1(c)] in Region 2 to form a new pair of complementary media so that the whole device becomes invisible.

Up to now, we are describing phenomena found in literature of illusion optics. Such an illusion effect can be treated as a kind of mirage effect that we want to further cloak and eliminate. In Fig. 1(d), we put the external cloak right to the illusion device that is described in Fig. 1(a). The related illusion object [green triangle in Fig. 1(b)] is in the same position to the real object [green triangle Region 3 in Fig. 1(c)] so that it can be cloaked. We will demonstrate such a cloaking effect numerically in the next section, which could be termed as "cloak an illusion". It also shows that an illusion object can be optically treated as a real object so that it can be further used for other potential applications.

3 Simulation results

To demonstrate the above cloaking effect, we perform full wave simulations by using the COMSOL Multiphysics finite-element-based electromagnetics solver. We consider the scattering of transverse electric (TE) polarization waves in two-dimensional (2-D) cases for simplicity. The TE wave is propagating from left to right at an angle of 45° from the x-axis with a wavelength of 0.25 m. All the size parameters of the illusion device in Fig. 1(a) are taken the same as that in Ref. [10], i.e., $x_1 = 0.1$ m, $x_2 = 0.2$ m, $y_1 = 0.1$ m, $y_2 = 0.2$ m, and $\alpha = 45°$. Therefore, the upper part of Region 1 is an anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 17/3$, $\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = 4$; the middle part of Region 1 is an anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 1/3$, $\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = 0$; the lower part of Region 1 is an anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 17/3$, $\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = -4$. The embedded object (the purple triangle in Fig. 1(a)) is set to be an anisotropic material with $\varepsilon_z = 7.5$, $\mu_{xx} = 1/3$,

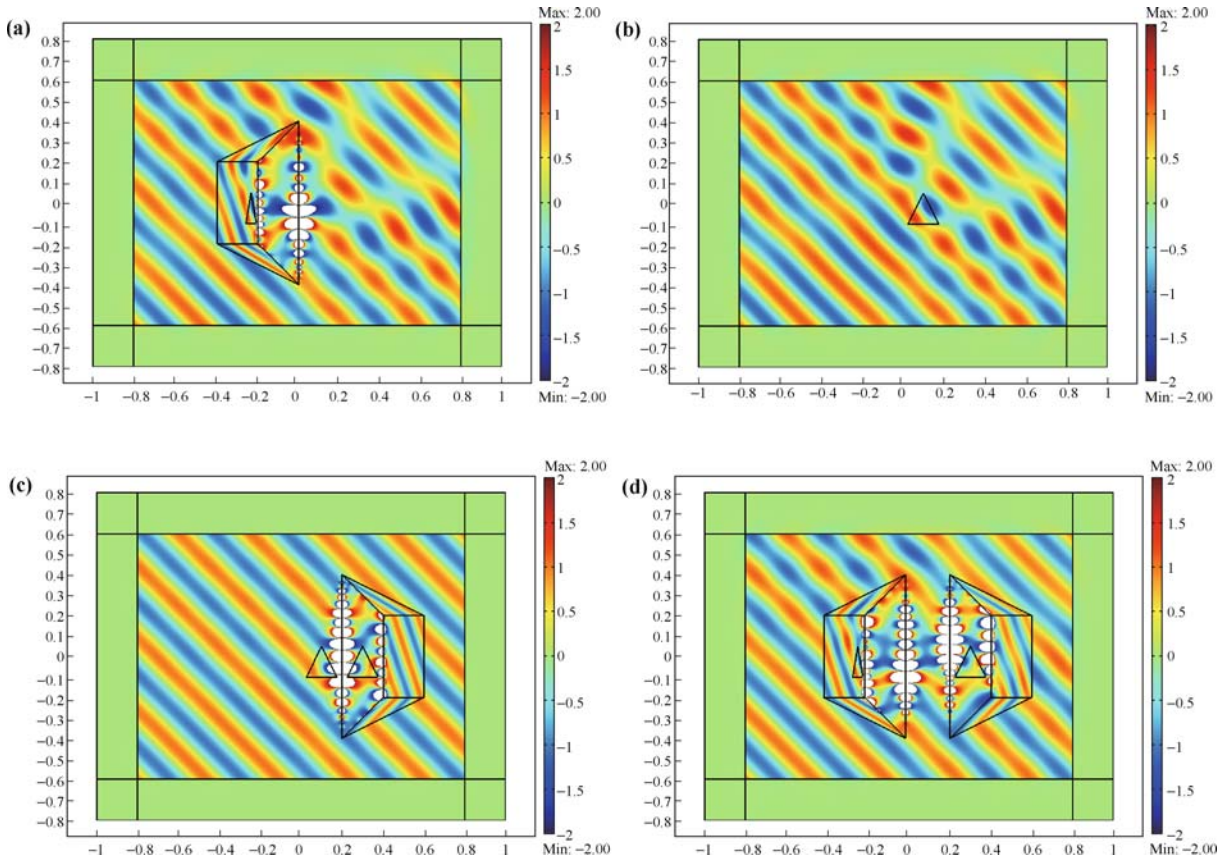

Fig. 2 The scattering pattern of an illusion device **(a)**, a real object **(b)**, an external cloak **(c)**, and the current device that can cloak an illusion **(d)**.

$\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = 0$ (i.e., $\varepsilon_c = 2.5$ and $\mu_c = 1$). Figure 2(a) shows the scattering pattern of such an illusion device, whose far-field pattern is identical to that of the scattering pattern of a bare object with $\varepsilon_c = 2.5$ and $\mu_c = 1$ in the air [shown in Fig. 2(b)]. The detailed shape and position of such an illusion object are related to those of the embedded object in Region 1 from the illusion optics.

If we want to cloak a real object with $\varepsilon_c = 2.5$ and $\mu_c = 1$, we need to put an external cloak beside it [see in Fig. 1(c)]. The upper part of Region 1 is an anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 17/3$, $\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = -4$; the middle part of Region 1 is an anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 1/3$, $\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = 0$; the lower part of Region 1 is an anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 17/3$, $\mu_{yy} = 3$, and $\mu_{xy} = \mu_{yx} = 4$. (The above material parameters are calculated likewise to Eq. (3) due to the similarities of the devices.) The embedded "anti-object" is an isotropic material with $\varepsilon = -2.5$ and $\mu = -1$. Figure 2(c) shows the scattering pattern of such an external cloak, which claims that the real object is cloaked as the whole device becomes invisible.

In Fig. 2(d), we plot the scattering pattern when the above external cloak is put right to the illusion device in the way like in Fig. 1(d). The whole device is invisible, which means that an illusion object can be cloaked like a real object. In other words, we "cloak an illusion".

4 Conclusions

In summary, we have extended the concept of illusion optics and demonstrated that an illusion object can be cloaked with an external cloak. We show that an illusion object can be treated as a "real" object for future potential applications. In a sense, it shows that the unnecessary mirage effect can be reduced or even annihilated. Full wave simulation was performed to demonstrate such a cloaking effect.

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