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Cloaks and antiobject-independent illusion optics based on illusion media

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ABSTRACT

Based on the transformation optics, we propose a new strategy of illusion media consisting of homogeneous and anisotropic materials. By utilizing the illusion media, invisible cloak is theoretically realized, in which objects covered with the illusion media could not be detected. The cloak here allows neither the propagation of light around the concealed region nor compensates the scattering field of object outside the media. What the cloak does is to shift the region into another place where outside the trace of light, so that objects in that region can disappear. Another application of the illusion media is to create the antiobject-independent illusion optics which means that two objects appear to be like some other objects of our choice. Finite element simulations for two-dimensional cases have been performed to prove these ideas.
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1. Introduction

Based on transformation optics [1], lots of novel and interesting devices have been investigated, such as invisible cloak [2–14], field rotator [15], beam concentrator [16], multi-beam emitter [17] and even applications in SPPs [18]. Among them, the most intriguing device is invisible cloak, which could hide the objects. Various kinds of invisible cloaks have been presented in the past few years. The first invisible cloak was called cylinder cloak, which made the light propagate around the object and had been realized by Schurig and co-workers experimentally in microwave regime [2]. Li and Pendry proposed another kind of invisible cloak called the carpet cloak [3], which made the way of reflection of light illuminate the same as the light illuminating on the flat ground plane, and it was also realized experimentally in microwave regime [4], terahertz region [5] and visible regime [6]. Due to those pioneering works, lots of further investigations on cloak have also been presented, including the open cloak [7], diamond cloak [8], elliptical cloak [9], and so on. In contrast to those internal cloaks, Lai et al. proposed another cloak called external cloak [10], which can hide objects at a distance outside the cloaking shell based on the anti-object.

The anti-object with negative refractive index can "cancel" a piece of region. Based on this concept, superscatterer, superabsorbers, superlenses and tunable electromagnetic gateways have been reported [19–27]. Moreover, the anti-object can be applied to design illusion optics, such as making one object appears like another one [28] and concealing entrance [29]. However, applications presented above have some common potential difficulties. If the object we want to conceal is PEC or PMC, then it seems not easy to find an anti-object to cancel the corresponding scattered field. In addition, when the shape of the hidden object is changed, we need to rebuild another kind of anti-object to cancel corresponding scattered field of new shape of object.

In this paper, a new strategy based on illusion media [30,31] is theoretically proposed for solving the problem. The mechanism of invisible cloak by using the illusion media is that it shifts the region to another place which is outside the trace of light. Hence, the object in the region is concomitantly folded outside the trace of incident light, which is equivalent to that the object is disappeared. Another application is the illusion optics which can also be created by using the illusion media. Unlike the illusion optics based on anti-object, which cancels the scattering of the hidden object, our illusion media serves to fold object we want to hide without any anti-objects and then displays other object in the trace of light.

2. Theory

Fig. 1 shows that regions ABFCDE and A′B′F′C′D′E′F′ are covered by hexagon transformation medium (gray shell). The transformation medium was called illusion media. In what follows, we would show

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how to accomplish such illusion media. As can be seen in Fig. 1, our purpose is that the regions $A_2B_2F_2C_2D_2E_2$ and $A'_2B'_2F'_2C'_2D'_2E'_2$ are both disappeared in the original spaces, and they will be detected in regions ABFCDE and A′B′F′C′D′E. Due to the symmetry of our structure shown in Fig. 1, we just consider the left side of the space in which the region $A_2B_2F_2C_2D_2E_2$ is shifted into region ABFCDE by using illusion media. To realize the illusion effect of the illusion media, we need to map the region ABB_1A_1, DCC_1D_1, EAA_1E_1, BFF_1B_1, EDD_1E_1, CFF_1C_1, onto the region $A_1B_1B_2A_2$, $D_1C_1C_2D_2$, $E_1A_1A_2E_2$, $B_1F_1F_2B_2$, $E_1D_1D_2E_2$, $C_1F_1F_2C_2$, respectively. We define the center of hexagon $A_1B_1F_1C_1D_1E_1$ as the origin of Cartesian coordinates, and the coordinate of each point have been established, i.e. A_1 $(-a_{21}, h_{21})$, B_1 $(-a_{21}, -h_{21})$, C_1 $(a_{21}, -h_{21})$, D_1 (a_{21}, h_{21}), E_1 $(0, h_{22})$, F_1 $(0, -h_{22})$, A_2 $(-a_{11}, h_{11})$, B_2 $(-a_{11}, -h_{11})$, C_2 $(a_{11}, -h_{11})$, D_2 (a_{11}, h_{11}), E_2 $(0, h_{12})$, F_2 $(0, -h_{12})$. Based on the definition above, the coordinate transformation of the illusion media can be expressed as

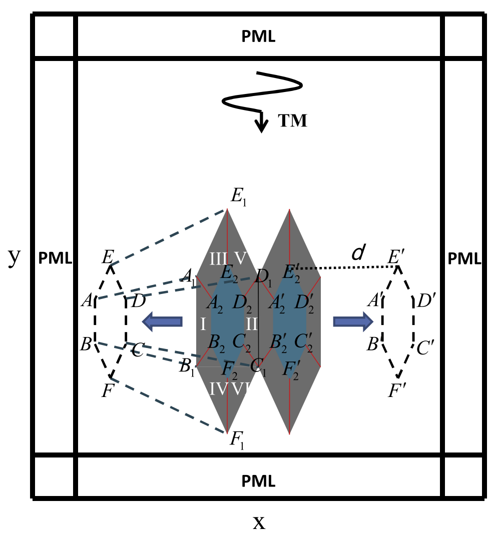

Fig. 1. The schematic of the shifting cloak. Regions $A_2B_2F_2C_2D_2E_2$ and $A'_2B'_2F'_2C'_2D'_2E'_2$ are shifted into the regions ABFCDE and $A'_2B'_2F'_2C'_2D'_2E'_2$, respectively.

Region I and II:

$$x' = \frac{(a_{21}-a_{11})x + d a_{21}}{a_{21}-a_{11}\mp d}, y' = y, z' = z \tag{1}$$

where "+" and "−" correspond to region II and I, respectively.

Region III and IV:

$$x' = x + \frac{d[h_{21} + (h_{22}-h_{21}/a_{21})(x'+a_{21})\mp y]}{h_{21}-h_{11} + (h_{22}-h_{21}/a_{21})(a_{21}-a_{11})}, y' = y, z' = z \tag{2}$$

where "+" and "−" correspond to region IV and III, respectively.

Region V and VI:

$$x' = x + \frac{d[h_{21} + (h_{22}-h_{21}/a_{21})(a_{21}-x')\mp y]}{h_{21}-h_{11} + (h_{22}-h_{21}/a_{21})(a_{21}-a_{11})}, y' = y, z' = z \tag{3}$$

where "+" and "−" correspond to region VI and V, respectively.

Here, d is the shifting distance. If $d>0$, the region $A_2B_2F_2C_2D_2E_2$ will be shifted into left side, and if $d<0$, it will be shifted into right side.

In the basis of Transformation Optics (TO) theory, we can obtain the permittivity and permeability of region I–VI by using $\gamma' = \Lambda\gamma\Lambda^T/\det(\Lambda)$.

Region I and II:

$$\varepsilon = \mu = \begin{pmatrix} m_i & 0 & 0 \\ 0 & 1/m_i & 0 \\ 0 & 0 & 1/m_i \end{pmatrix} \tag{5}$$

where $m_1 = (a_{21}-a_{11}/a_{21}-a_{11}-d)$, $m_2 = (a_{21}-a_{11}/a_{21}-a_{11}+d)$, corresponding to region I and II, respectively.

Region III and IV:

$$\varepsilon = \mu = \frac{1}{m_3}\begin{pmatrix} m_3^2 + m_4^2 & \mp m_4 & 0 \\ \mp m_4 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{6}$$

where

$$m_3 = \frac{a_{21}(h_{21}-h_{11}) + (h_{22}-h_{21})(a_{21}-a_{11})}{a_{21}(h_{21}-h_{11}) + (h_{22}-h_{21})(a_{21}-a_{11}-d)},$$

$$m_4 = \frac{d}{a_{21}(h_{21}-h_{11}) + (h_{22}-h_{21})(a_{21}-a_{11}-d)},$$

and "+" and "−" correspond to region IV and III, respectively.

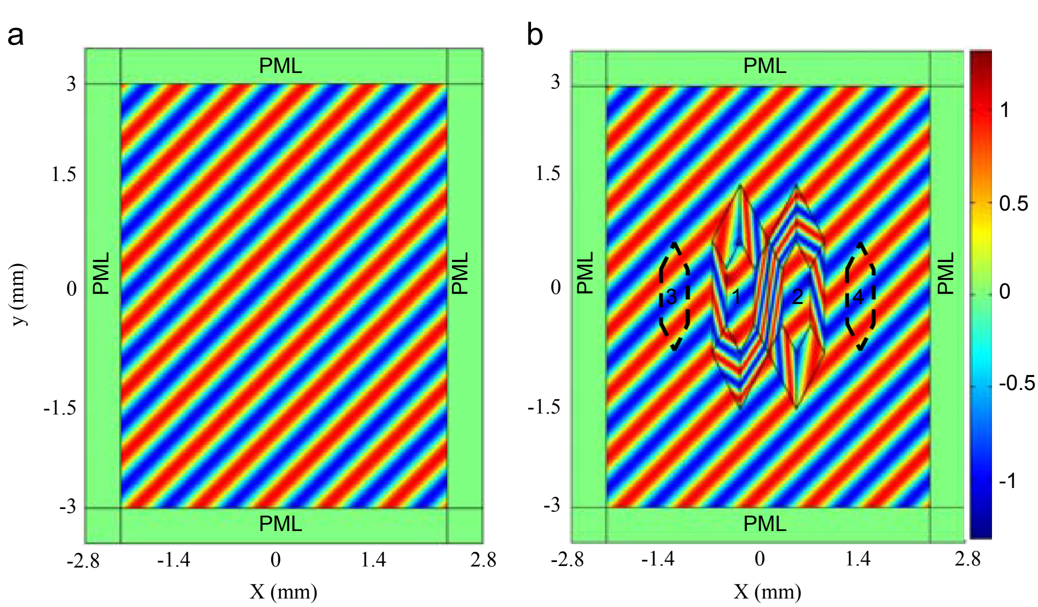

Fig. 2. Light propagates in air which interacts with nothing (a), with illusion media (b). Regions 1 and 2 are equivalent to region 3 and 4, respectively.

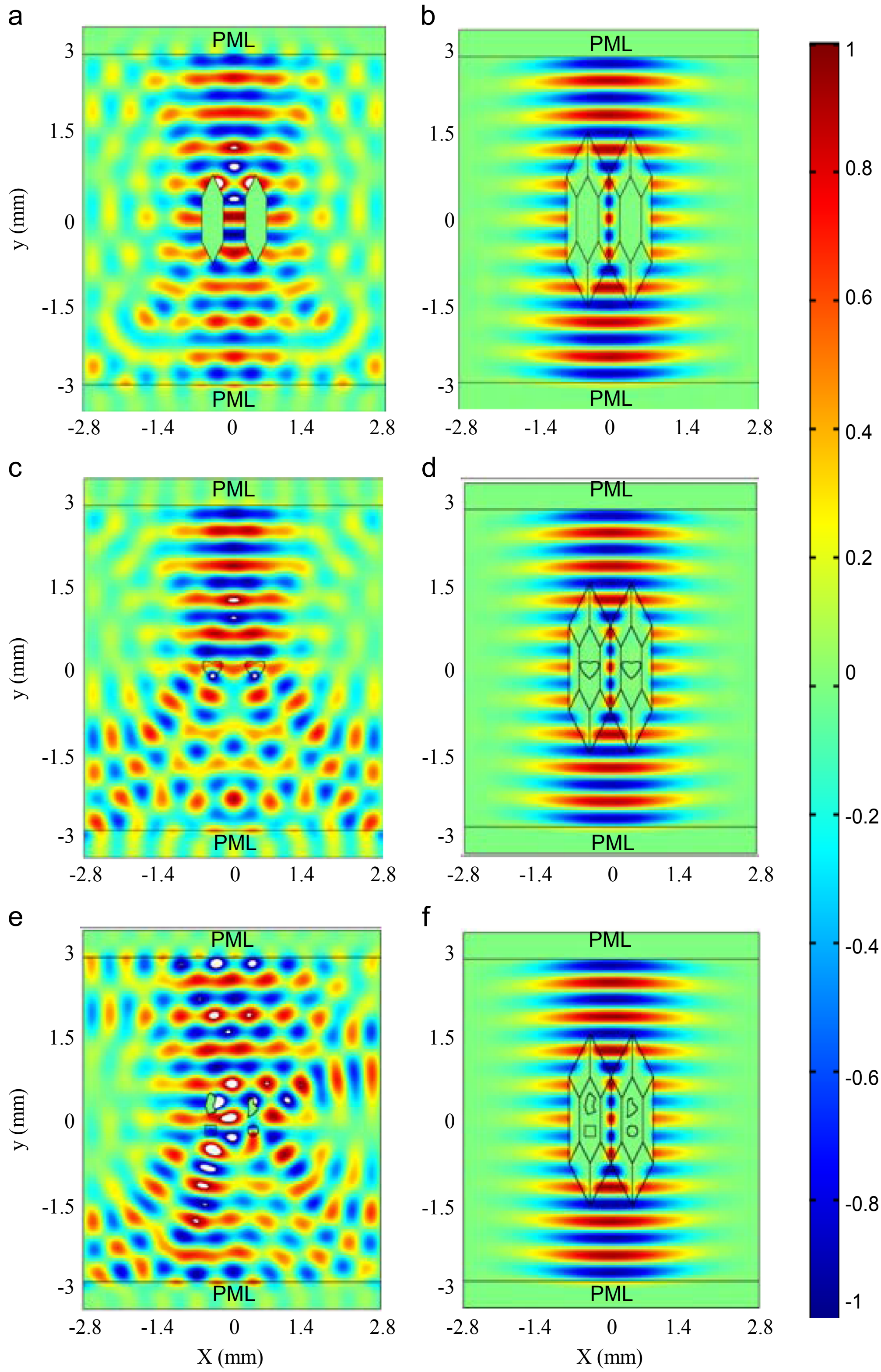

Fig. 3. PEC, Heart-shaped object, arbitrary covered without illusion media (a), (c), (e), with illusion media (b), (d), (f). The frequency and waist width of TM Gaussian beam we use here is 0.475 THz and λ.

Region V and VI:

$$\varepsilon=\mu=\frac{1}{m_5}\begin{pmatrix} m_5^2+m_6^2 & \mp m_6 & 0 \\ \mp m_6 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{7}$$

where,

$$m_5=\frac{a_{21}(h_{21}-h_{11})+(h_{22}-h_{21})(a_{21}-a_{11})}{a_{21}(h_{21}-h_{11})+(h_{22}-h_{21})(a_{21}-a_{11}+d)},$$

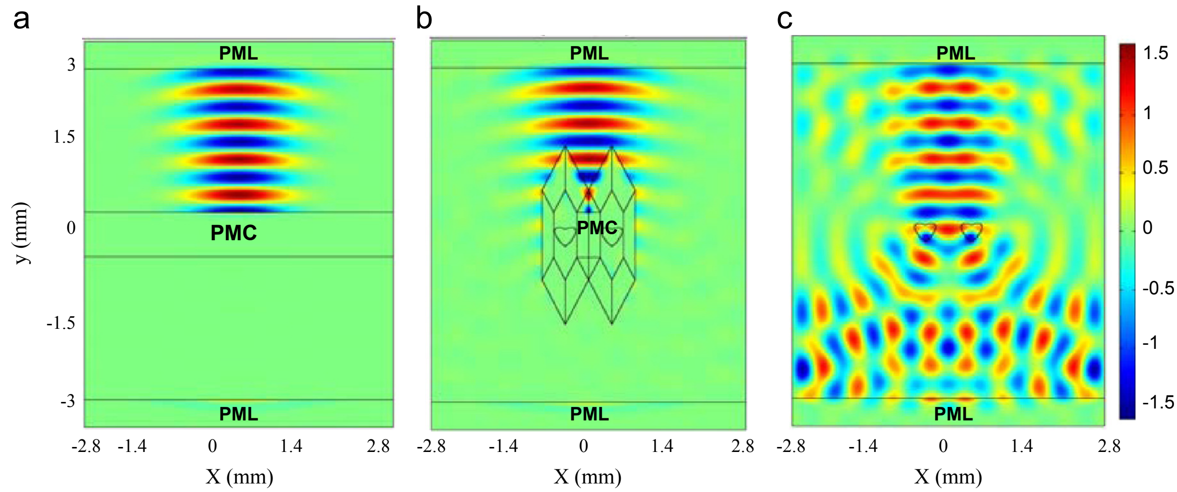

Fig. 4. Magnetic distribution when TM Gaussian beam illuminates on (a) the PMC wall, (b) a tiny PMC wall and two heart-shaped object cloaked with illusion media, (c) two heart-shaped object cloaked without illusion media. The frequency and waist width of TM Gaussian beam we use here is 0.475 THz and λ.

$$m_6 = \frac{d}{a_{21}(h_{21}-h_{11}) + (h_{22}-h_{21})(a_{21}-a_{11}+d)},$$

and "+" and "−" correspond to region VI and V, respectively.

It should be noted that the illusion media is homogenous and anisotropic.

3. Numerical simulation and discussion

In order to prove the illusion effect of the illusion media presented above, we perform numerical simulation by using the finite element method (FEM). Here, we define $a_{11}=0.2$ mm, $a_{21}=0.4$ mm, $h_{11}=0.4$ mm, $h_{21}=0.8$ mm, $h_{12}=0.8$ mm, $h_{22}=1.6$ mm, and $d=\pm 1$ mm. Fig. 2(a) shows the field distribution of the same TM wave propagating in free space (air). Fig. 2(b) depicts the magnetic field distribution when TM wave (frequency is 0.475 THz) with incident angle of $\pi/4$ illuminates on the illusion media. Comparing Fig. 2(a) and (b), we can find that they have identical magnetic field distribution outside the transformation region. Therefore, the light pass through region 1 is shifted to region 3 due to the illusion media, which implies that region 1 is shifted to region 3 (region 2 is equivalent to region 4).

Now we study invisible cloaks using illusion media. We choose the value of shifting distance $d=\pm 2.8$ mm, which makes the edge D_2C_2 or $A'_2B'_2$ overlapped with the right PMC and the left PMC, respectively. As we can see in Fig. 3(a), the first object we choose to prove the invisible cloak is a PMC which is filled in the regions $A_2B_2F_2C_2D_2E_2$ and $A'_2B'_2F'_2C'_2D'_2E'_2$, respectively.

Fig. 3(a) shows that when symmetrical PMCs are illuminated by TM wave, the huge scattered field can be observed. But when PMCs are covered with illusion media, the scattered field disappears (Fig. 3(b)), which means that the objects are shifted outside the light field. So, the PMC is hidden due to the illusion media. We can also hide arbitrary-shaped objects based on the illusion media. Here two heart-shaped objects with $\mu=3$ are both placed in the region $A_2B_2F_2C_2D_2E_2$ and region $A'_2B'_2F'_2C'_2D'_2E'_2$, respectively (Fig. 3(d)). Fig. 3(c) shows the magnetic field distribution when two heart-shaped objects are placed in the free space without illusion media, from which we can see huge scattered field after TM wave passing through them. But when two heart-shaped objects are covered with illusion media, there is no scattered field, as shown in Fig. 3(d). Here, it is also demonstrated that these objects covered with illusion media are also invisible. As can be seen in Fig. 3(f), an arbitrary-shaped PMC and a square object with $\varepsilon=1$, $\mu=3$ are placed in the left region $A_2B_2F_2C_2D_2E_2$, another arbitrary PMC object and a circle-shaped object with $\varepsilon=3$ and $\mu=2.5$ are both placed in the right region $A'_2B'_2F'_2C'_2D'_2E'_2$. Compared with the magnetic distribution in Fig. 3(e), all objects in Fig. 3(f) are hidden perfectly.

Not only invisible cloak can be achieved by using the illusion media, but also antiobject-independent illusion optics can be accomplished, which is independent of the anti-object. And, we can avoid potential problems presented above. The preparation for the antiobject-independent illusion optics can be separated into two steps. Firstly, two heart-shaped objects were placed in region $A_2B_2F_2C_2D_2E_2$ and region $A'_2B'_2F'_2C'_2D'_2E'_2$, respectively. Each object can be shifted outside of the PMC boundary. Secondly, we embedded another object in the center of region $D_2C_2C_1B'_2A'_2D_1$.

Fig. 4 display the antiobject-independent illusion optics presented above. The rectangular PMC in Fig. 4(a) looks like a wall which prevents the light from passing through it. Comparing with Fig.4(b) and (a), it can be found that both of them have the same field distribution outside the transformation region. It demonstrates that the illusion media successfully make two heart-shaped objects appear to be a PMC wall without using the anti-object. In addition, the corresponding scattered field distribution of these two heart-shaped objects without illusion media is shown in Fig. 4(c).

4. Conclusion

In summary, a new strategy of illusion media, which is homogeneous and anisotropic, was proposed based on transformation optics theory. Two kinds of applications have been achieved by using the illusion media. One is invisible cloak, which helps us to make objects with any arbitrary shape disappeardue to the shifting effect of the illusion media. Another application is antiobject-independent illusion optics, which is independent of the anti-object. Compared with previous works, the illusion optics based on the illusion media can avoid the change of anti-object when the shape of hidden object is varied.

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