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Homogeneous illusion device exhibiting transformed and shifted scattering effect

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ABSTRACT

Based on the theory of transformation optics, a type of homogeneous illusion device exhibiting transformed and shifted scattering effect is proposed in this paper. The constitutive parameters of the proposed device are derived, and full-wave simulations are performed to validate the electromagnetic properties of transformed and shifted scattering effect. The simulation results show that the proposed device not only can visually shift the image of target in two dimensions, but also can visually transform the shape of target. It is expected that such homogeneous illusion device could possess potential applications in military camouflage and other field of electromagnetic engineering.

1. Introduction

Transformation optics has attracted great attention since it was proposed by Pendry et al. in 2006 [1–37]. Various invisible cloaks considered as the most important and typical applications for transformation optics were proposed and analyzed in theory, and some have been experimentally realized [1–15]. Moreover, other devices based on transformation optics are also proposed and investigated, such as electromagnetic field rotators [16,17], concentrators [18,19], waveguide bends [20–22], complementary cloak [23,24], superscatterer [25], transparent device [26,27] and so on.

Recently, concept of illusion optics has been proposed, which has attracted more attentions since it may lead to many applications. Illusion device was firstly proposed by Y. Lai et albased on complementary medium [28]. Later, Y. Luo et al. proposed a type of inhomogeneous illusion device exhibiting magnified and shifted scattering effect [29]. However, the loss of complementary medium will dramatically deteriorate the illusion performance. To overcome such difficulties, improved illusion device consisting of only positive materials has been studied [30], and some spatial wave–dynamic experiments have been demonstrated to manifest the illusion effects [31,32]. To strengthen the illusion effect, ghost illusion device, which can make the scattering signature of the cloaked object equivalent to that of multiple other objects, was proposed and experimental demonstrated [33]. In the meantime, simple homogeneous illusion devices with shifting effect, which can visually move the object in one dimension, are proposed [32–35].

In this paper, a kind of homogenous illusion device exhibiting shifted and transformed scattering effect is proposed. The proposed device not only can visually shift the image of target in two dimensions, but also can visually transform the shape of target. Moreover, the constitutive parameters of the proposed device are homogeneous, so the difficulties in practical realization can be reduced in certain extent. Therefore, the proposed device could possess potential applications in military camouflage and other field of electromagnetic engineering.

2. Derivation of the constitutive tensor based on the theory of transformation optics

The space transformations for the proposed device with shifted and transformed scattering effect proceeds in two steps, i.e. step 1 and step 2, as shown in Fig. 1. Step 1 is shifting the region $A_2B_2D_2C_2$ to the identical region $A_1B_1D_1C_1$ while keeping the boundary ABDC unchanged, as shown in Fig. 1(a). Step 2 is that the transformed region $ABDCA_1B_1D_1C_1$ after step 1 is sketched (or compressed) to a big (or small) physical region $ABDCA_3B_3D_3C_3$, meanwhile the inner free space $A_1B_1D_1C_1$ is compressed (or sketched) to a small (or big) physical region $A_3B_3D_3C_3$ to restore the light path, as shown in Fig. 1(b). In Fig. 1, the center of

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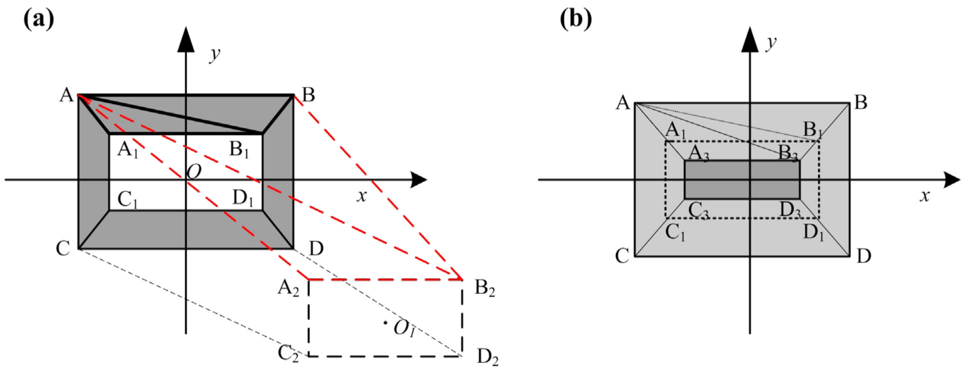

Fig. 1. Schematic diagram of the illusion device with shifted and transformed scattering effect (a) space transformation of step 1 (b) space transformation of step 2.

rectangle $A_2B_2D_2C_2$ is set as O_1 $(d_1, -d_2)$, and the center of the rectangle ABDC, $A_1B_1D_1C_1$ and $A_3B_3D_3C_3$ are set as origin O (0, 0). The length and height of the rectangle ABDC, $A_1B_1D_1C_1$ and $A_3B_3D_3C_3$ are set as (w_1, h_1), (w_0, h_0) and (w_2, h_2), respectively. After above two steps of space transformation, the device is invisible for outside observer. Moreover, the image of target located in the device center (0, 0) can be visually transformed and shifted to the location $(d_1, -d_2)$.

To derive the parameters of the above device, the original region $A_2B_2D_2C_2$ is shifted to the identical region $A_1B_1D_1C_1$ while keeping the boundary ABDC unchanged firstly. For simplicity, we take transformation of region ABB_2A_2 to region ABB_1A_1 as an example. In order to obtain the homogeneous parameters, the above transformation can be realized by two linear transformations, that is, transforming region ABB_2 and AB_2A_2 to region ABB_1 and AB_1A_1 respectively. The linear transformation equation can be expressed as:

$$x' = a_{11}x + b_{11}y + c_{11}$$
$$y' = a_{12}x + b_{12}y + c_{12}$$
$$z' = z \tag{1}$$

where (x, y, z) and (x', y', z') are coordinates for original and transformed space, a_{11}, b_{11}, c_{11}, a_{12}, b_{12} and c_{12} are constants coefficients. These coefficients can be solved by the boundary conditions. For transformed triangular region AB_1A_1, $a_{11} = 1$, $a_{12} = 0$, $b_{11} = 2d_1/(2d_2 - h_0 + h_1)$, $b_{12} = -(h_0 - h_1)/(2d_2 - h_0 + h_1)$, $c_{11} = -(d_1h_1)/(2d_2 - h_0 + h_1)$ and $c_{12} = (d_2h_1)/(2d_2 - h_0 + h_1)$. Similar, coefficients for other transformed region of $ABDCA_1B_1D_1C_1$ can be solved.

Next, the transformed region $ABDCA_1B_1D_1C_1$ is sketched (or compressed) to physical region $ABDCA_3B_3D_3C_3$ while keeping boundary ABDC unchanged. For simplicity, we take transformation of region ABB_1A_1 to region ABB_3A_3 as an example. This transformation can also be realized by two linear transformations, that is, transforming region ABB_1 to region ABB_3, and transforming region AB_1A_1 to region AB_3A_3 respectively. The linear transformation equation can be expressed as:

$$x'' = a_{21}x' + b_{21}y' + c_{21}$$
$$y'' = a_{22}x' + b_{22}y' + c_{22}$$
$$z'' = z' \tag{2}$$

where (x'', y'', z'') and (x', y', z') are coordinates for physical and transformed space, a_{21}, b_{21}, c_{21}, a_{22}, b_{22} and c_{22} are constants coefficients. For transformed triangular region AB_3A_3, $a_{21} = w_2/w_0$, $a_{22} = 0$, $b_{21} = -(-w_0w_1 + w_1w_2)/(h_0w_0 - h_1w_0)$, $b_{22} = -(h_1 - h_2)/(h_0 - h_1)$, $c_{21} = w_1(h_0w_0 - h_0w_2)/(h_0w_0 - h_1w_0)$ and $c_{22} = -(-h_0h_1 + h_1h_2)/(h_0 - h_1)$. Similar, coefficients for other transformed region $ABDCA_3B_3D_3C_3$ can be solved. Substituting (1) into (2), the final linear transformation equations for the physical region A B_3 $A_3$are expressed as:

$$x'' = a_1x + b_1y + c_1$$
$$y'' = a_2x + b_2y + c_2$$
$$z'' = z \tag{3}$$

where $a_1 = a_{21}a_{11} + b_{21}a_{12}$, $b_1 = a_{21}b_{11} + b_{21}b_{12}$, $c_1 = a_{21}c_{11} + b_{21}c_{12} + c_{21}$, $a_2 = a_{22}a_{11} + b_{22}a_{12}$, $b_2 = a_{22}b_{11} + b_{22}b_{12}$ and $c_2 = a_{22}c_{11} + b_{22}c_{12} + c_{22}$.

According to the theory of transformation optics, the permittivity and permeability of physical region A B_3A_3 can be expressed as following.

$$\varepsilon'' = \mu'' = \begin{pmatrix} (a_1^2 + b_1^2)/(a_1b_2 - a_2b_1) & (a_1a_2 + b_1b_2)/(a_1b_2 - a_2b_1) & 0 \\ (a_1a_2 + b_1b_2)/(a_1b_2 - a_2b_1) & (a_2^2 + b_2^2)/(a_1b_2 - a_2b_1) & 0 \\ 0 & 0 & 1/(a_1b_2 - a_2b_1) \end{pmatrix} \tag{4}$$

Similar, the permittivity and permeability for other physical region of $ABDCA_3B_3D_3C_3$ can be solved.

Finally, inner free space $A_1B_1D_1C_1$ is compressed (or sketched) to a small (or big) physical region $A_3B_3D_3C_3$ to restore the light path. The transformation equations for physical region $A_3B_3D_3C_3$ can be expressed as:

$$x'' = (w_2/w_0)x$$
$$y'' = (h_2/h_0)y$$
$$z'' = z \tag{5}$$

The permittivity and permeability of physical region $A_3B_3D_3C_3$ can be expressed as following.

$$\varepsilon''_b = \mu''_b = \begin{pmatrix} (w_2h_0)/(w_0h_2) & & \\ & (w_0h_2)/(w_2h_0) & \\ & & (w_0h_0)/(w_2h_2) \end{pmatrix} \tag{6}$$

It is noted that the illusion shape of the target is decided by the Eq. (5). For the Eq. (5), there are four cases. Case (I): $w_2/w_0 = h_2/h_0 = 1$, that is, illusion shape of the target is unchanged. Case (II): $w_2/w_0 = h_2/h_0 < 1$, that is, illusion shape of the target is linearly magnified in w_0/w_2 times. Case (III): $w_2/w_0 = h_2/h_0 > 1$, that is, illusion shape of the target is linearly minified in w_0/w_2 times. Case (IV): $w_2/w_0 \neq h_2/h_0$, that is, illusion shape of the target is transformed to another shape. To demonstrate our above idea, the full wave simulations are performed to validate the electromagnetic properties of the proposed device in four cases in the next section.

3. Results and discussions

In this section, the electromagnetic properties of the proposed device are simulated by finite element software COMSOL under TE wave illumination. In the simulation, the frequency is 0.5 GHz. The whole computational domain is surrounded by the perfectly matched layer to simulate infinite free space.