Optical illusions induced by rotating medium

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ABSTRACT

Different from the traditional single-function electromagnetic wave rotators (rotate the electromagnetic wavefronts), we propose that rotating medium can be extended to optical illusions such as breaking the diffraction limit and overlapping illusion. Furthermore, the homogeneous but anisotropic rotating medium is simplified by homogeneous and isotropic positive-index materials according to the effective medium theory, which is helpful for future device fabrication. Finite element simulations for the two-dimensional case are performed to demonstrate these properties.

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1. Introduction

Transformation optics (TO), proposed by U. Leonhardt and J. B. Pendry, respectively [1,2], is one of the most well-known theories to manipulate electromagnetic waves. One important application is the invisible cloak. In recent years, many kinds of cloaks, such as cylindrical cloak, square cloak, elliptic cloak, arbitrary shaped cloak, cloak of twisted domain, open cloak, the general open-closed cloak, complementary cloak, and so on have been theoretically studied [3–16]. Meanwhile, experimental verifications of invisible cloaks ranging from microwave to visible frequency have been also reported [17–23]. Besides the application of invisible cloak, TO can also be applied to design other kinds of devices, i.e., beam splitter, high-directional emission, electromagnetic black-hole, super-scatterers, tunable electromagnetic gateways, overlapped optics, etc. [24–36].

Recently, Chen and Chan have proposed electromagnetic waves (EM) rotator, where electromagnetic fields were rotated for a fixed angle, can give rise to a rotated world to the observers inside/outside the rotation coating [37]. Subsequently, the cylindrical micro-wave field rotators were experimentally realized. But the proposed of EM rotators suffered from the complex and inhomogeneous material parameters [38,39]. Then, Han et al. proposed a polygonal rotator with homogeneous, nonmagnetic, and isotropic materials, which is more feasible for future realization [40]. Up to now, all of the reported rotators mainly focused on one specific function—rotating the EM wavefronts. In other words, researchers usually think that EM rotator just provides only single function of rotating. Does it has any other kinds of functions or can we develop other new types of functions based on EM rotator?

Here, we have proved that EM rotator can be applied to realize optical illusions such as breaking the diffraction limit and overlapping illusion, simultaneously. This means that EM rotator can not only rotate the EM wavefronts but also be extended to break the diffraction limit and overlapping illusion, resulting in a multi-functional (tri-functional) device. Furthermore, based on the effective medium theory, we simplified the transformation medium, which is isotropic but homogeneous with positive permittivity and permeability. All of the functions of EM rotator are demonstrated by using the two-dimensional finite element simulation. We want to emphasize that in traditional case, the effects of (TO-based) breaking diffraction limit and overlapping illusion can’t be realized simultaneously in just one transformation device. That is to say, two different kinds of transformation medium i.e., complementary medium and shifting/compression medium [29,32,35] are needed to realize these two physical phenomena. In this paper, we mainly demonstrate that the positive-index rotating medium is designed to realize the effects of breaking the diffraction limit as well as overlapping illusion, simultaneously.

2. Theory

Fig. 1 schematically depicts the structure of a pentagon EM rotator in the cartesian coordinate system. Each side region consists of two triangles, embedded with different transformation medium. Here, the function of our pentagon EM rotator is to rotate the wavefronts and keep itself invisible. So, we must keep the outer boundary unchanged but rotate the inner boundary. The external triangle \( \Delta a'_1a_1' \) and internal
triangle \(\Delta a'1b'1\) in virtual space are mapping into \(\Delta a_{i+1}b_{i+1}\) and \(\Delta a_{i+1}b_{i}\) in real space, respectively [37]. Taking the region \(a_ia_ib_i\) as an example, the corresponding coordinate mapping between the virtual space and real space is by transforming \(\Delta a',b',\) and \(\Delta a',b',\) in virtual space into \(\Delta a,a,b\) and \(\Delta a,b,b\) in real space with the point-to-point mapping as follows:

\[
\begin{align*}
& a_i \leftrightarrow a'_i, \\
& a_2 \leftrightarrow a'_2, \\
& b_2 \leftrightarrow b'_2.
\end{align*}
\]

The general expression of the \(i\)th vertex in Fig. 1 can be defined as:

\[
\begin{align*}
x_{a_i} &= a \cos \left( (i-1) \frac{2\pi}{5} \right), \\
y_{a_i} &= a \sin \left( (i-1) \frac{2\pi}{5} \right), \\
x_{b_i} &= b \cos \left( (i-1) \frac{2\pi}{5} \right), \\
y_{b_i} &= b \sin \left( (i-1) \frac{2\pi}{5} \right),
\end{align*}
\]

where \(1 \leq i \leq 5\), and \(a(b)\) is the corresponding distance between the center of the device and \(a(b)\).

For the external triangles, the corresponding coordinate transformation is expressed as:

\[
\begin{align*}
& x = m_1x^i + m_2y^i + m_3, \\
y = n_1x^i + n_2y^i + n_3, \\
z = z',
\end{align*}
\]

where \(\begin{bmatrix} m_1 & m_2 & m_3 \\ n_1 & n_2 & n_3 \end{bmatrix} = A^{-1} \begin{bmatrix} x_i & y_i & 1 \\ x_{a_{i}} & y_{a_{i}} & 1 \\ x_{b_{i}} & y_{b_{i}} & 1 \end{bmatrix}\), and \(A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\).

For the internal triangles, the corresponding coordinate transformation can be written as:

\[
\begin{align*}
& x = p_1x^i + p_2y^i + p_3, \\
y = q_1x^i + q_2y^i + q_3, \\
z = z',
\end{align*}
\]

where \(\begin{bmatrix} p_1 & p_2 & p_3 \\ q_1 & q_2 & q_3 \end{bmatrix} = B^{-1} \begin{bmatrix} x_i & y_i & 1 \\ x_{a_i} & y_{a_i} & 1 \\ x_{b_i} & y_{b_i} & 1 \end{bmatrix}\), and \(B = \begin{bmatrix} x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \\ x_3 & y_3 & 1 \end{bmatrix}\).

Actually, there are many kinds of coordinate transformations to realize the mapping shown in Fig. 1. The forms in Eqs. (2) and (3) are similar to quasi-conformal transformations like in [40–44]. Therefore, the corresponding material parameters are not space variant, in which, it can be realized by conventional materials such as uniaxial crystal [45,46].

Based on the above equations, we deduce the expression of the permeability tensor and permittivity.

For the external triangle (Fig. 1(a)):

\[
\begin{align*}
\varepsilon_{\text{outer}} &= \varepsilon_0 \begin{bmatrix} m_1 + m_2 & m_1n_1 + m_2n_2 \\ m_1n_1 + m_2n_2 & n_1 + n_2 \end{bmatrix}, \\
\mu_{\text{outer}} &= \mu_0.
\end{align*}
\]

For the internal triangle (Fig. 1(a)):

\[
\begin{align*}
\varepsilon_{\text{inner}} &= \varepsilon_0 \begin{bmatrix} p_1 + p_2 & p_1q_1 + p_2q_2 \\ p_1q_1 + p_2q_2 & q_1 + q_2 \end{bmatrix}, \\
\mu_{\text{inner}} &= \mu_0.
\end{align*}
\]

3. Numerical simulation and discussion

First, the functionality of the field rotating is demonstrated in Fig. 2. The corresponding parameters are as follows: \(a = 0.75\) mm, \(b = 0.5\) mm and the frequency of the point source is 0.3 THz (the corresponding wavelength \(\lambda\) is 1 mm). Fig. 2(a) depicts the magnetic field distribution of a point source located at point \(b_1\) and covered with transformation medium. Fig. 2(b) shows the corresponding magnetic field distribution (in free space) of the identical point source located at point \(b'_1\). Comparing with Figs. 2(a) and 2(b), both of them have the same field distribution outside the rotator, although the field distributions inside the rotators are totally different from each other. It means that the point source located in point \(b_1\) (in the physical space of Fig. 2(a)) and coated with the transformations medium is virtually rotated into point \(b'_1\) in the virtual space (with intersection angle of \(\Delta b'_1/\omega b'_1\) is 72°), demonstrating the rotating feature of our designed field rotator. When
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