A chirality switching device designed with transformation optics

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Abstract: Based on transformation optics theory, we designed a chirality switching device, such that an object hidden inside would exhibit a reversed chirality (i.e., from left-handedness to right-handedness) for an observer at the far field. Distinct from a perfect mirror which also creates a chirality-reversed image, our device makes the original object completely invisible to the far field observer. Numerical simulations are employed to demonstrate the functionalities of the designed devices in both two- and three-dimensional spaces.

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References and links

4. In this paper, we consider only those sources emitting light rays symmetrically, i.e., for any ray emitted from the source, we can always find another emitted ray going to the opposite direction.
19. All lengths are rescaled by the working wavelengths taken in the simulations.
20. Here the shape of device is shown only for identifying the position.
21. The directional source is formed by an array of $6 \times 6$ line sources (with lattice constant 0.5). The pumping fields of these sources are chosen as

$$\begin{pmatrix}
+1 & -1 & +1 & -1 & +1 & -1 \\
+1 & -2 & +2 & -2 & +2 & -1 \\
+1 & -2 & +4 & -4 & +2 & -1 \\
+1 & -2 & +4 & -4 & +2 & -1 \\
+1 & -2 & +2 & -2 & +2 & -1 \\
+1 & -1 & +1 & -1 & +1 & -1 \\
\end{pmatrix}$$

22. The point source consists of three mutually orthogonal antennae, with pumping fields carefully adjusted to ensure that the resultant radiation pattern in free space exhibits a spherical symmetry.

1. Introduction

Molecular chirality plays a crucial role in biochemistry and asymmetric synthesis [1]. For example, while L-form amino acids are considered as the building blocks of most natural proteins, their mirror images find no way inside life on earth [2]. It is thus highly desirable if the chirality of a certain object can be freely “tuned”. Unfortunately, this is not an easy task since one may have to change the object’s structure mechanically. Here, we demonstrate an optical approach to “change” the chirality of an object. We show that an optical device can be designed, such that any object (with certain chirality) placed inside the device would exhibit a reversed chirality for an observer at the far field.

![Fig. 1.](image)

Fig. 1. (a) A point source placed inside a semi-infinite $n = -1$ medium creates a real image in the air region. (b) A point source placed inside a finite-sized $n = -1$ medium creates multiple images, each observable within only a certain viewing angle range.

One may argue that a perfect mirror can achieve this end since it creates a virtual image with opposite chirality. However, in this approach, the original object itself is still visible to the observer, and the same is true for the mirror. Material with refractive index ($n$) equal to $-1$ behaves like a mirror plane on its interface with air [3]. As shown in Fig. 1(a), light rays emitted from a source [4] located inside an $n = -1$ semi-infinite medium are focused to a point in air region [5]. Therefore, for an observer at the far field (in the air region side), the realistic point source seems to be moved from its original position (inside the $n = -1$ medium) to its symmetry point [6]. Push the idea forward, a chiral object (assumed as containing many point sources) placed inside the $n = -1$ medium must exhibit a reversed chirality for a far-field observer at the air side. Unfortunately, the device shown in Fig. 1(a) can never be realized since it requires an infinite boundary. One may immediately think of a bounded area of $n = -1$ medium, as shown in Fig. 1(b). However, such a device would create multiple images, each observable only within a certain range of viewing angles, as schematically depicted in Fig. 1(b). Recently, illusion optics theory [7] was established, which could in principle create any optical illusion as desired. The idea is to first optically cancel an object with complementary medium [8] and then project an illusion of different object through some restoring medium [7]. While in principle one can
employ this theory to design a chirality-switching device, such an approach suffers a limitation that the objects hidden inside the device must be transparent.

In viewing these previous efforts, we find it still highly challenging to design a general chirality-switching device. In this paper, we employ the transformation optics theory to realize such a design, which can overcome the shortcomings mentioned above. We first introduce the transformation that leads to our design in the next section and then perform full wave simulations to illustrate the functionalities of our devices in Sec. III. Conclusions are summarized in the last section.

2. Operation, transformation, and device parameters

Before we present our design, it is helpful to briefly review the essence of the transformation optics theory [9]. The theory actually established a correspondence between the material filling the space (the transformation medium) and a coordinate transformation [10], which is mediated by a particular operation performed in certain space region [11]. For instance, the operation adopted to design the field rotator [12] is a proper rotation of 3D coordinate system by a specific angle; a field concentrator [13] could be viewed as a plate employing an stretching operation; and one can easily identify the operations for the hyper-lens (stretching) [14] and the beam shifter (twisting) [15]. The perfect lens effect [5] can also be explained by the transformation optics theory, and the operation was identified by Leonhardt and Philbin as a space “folding” [16]. The folded area in electromagnetic (EM) space turns out to be a slab of material with negative $n$ in the physical space [10]. Therefore, to design any functional device based on transformation optics, the first and most important task is to identify the “operation” required to achieve the desired function. In addition, to make a good design, the operation should follow some general rules. First, the operation should be performed uniformly if one wants to obtain a homogeneous transformation medium [10]. Second, the operation cannot tear any boundary if one does not want reflections at the boundaries of the transformation medium [17].

We now identify the operation related to the chirality-switching functionality. Consider the simple two-dimensional (2D) case to elucidate the logics. To “change” the handedness of a 2D object, say, a glove for a human’s right hand, the easiest operation is to turn over the object. Since the final space must be physical to contain no folded area, the EM space on which the operation should be performed, must exhibit a folded geometry. Considering the constraints that the operation should be performed within a fixed area with boundaries not tore up (for realizing a finite-sized reflectionless device), it is not difficult to understand that the starting EM space should contain a folded area, as shown in Fig. 2(a). Different from the perfect lens case [16], here the folded space only occupies a fixed area (the inner rhombus with long axis length $2a$ and short axis length $a$), and the operation is performed strictly inside the square (blue) region. In other words, the boundaries of the outer square are fixed during the transformation and the region outside the square suffers no transformation. Inside the inner rhombus, there are three layers sticking together. Light rays travel in straight lines in all three layers since there is no distortion in spatial metrics. The operation performed on this EM space is to unfold the originally folded tri-layers while keeping the boundary of the operation area fixed, as schematically depicted in Fig. 2(b) and (c). The physical space obtained after this operation is shown in Fig. 2(d). According to the transformation optics theory, light rays are conformally attached to the space which is distorted or rotated during the operation. The evolutions of three typical light rays are shown in Fig. 2(a-d). It is clear that, inside the operation region, the inner (red) region is not distorted but only folded by 180 degrees, so that the rays still propagate in straight lines though along a different direction. On the other hand, the remaining regions are distorted during the operation so that lights are also distorted and traveling in twisted ways. The distortions in these regions are performed uniformly since we want to obtain homogeneous transformation media.
Fig. 2. (a) Geometry of the original EM space in which three layers are sticking together to form a folded space in the inner rhombus region. (b) The inner area is unfolded a little bit. (c) The inner area is unfolded significantly. (d) Geometry of the final physics space where the inner area is unfolded completely. The arrows show the evolutions of three typical rays during the operation, and insets show how this “unfolding” operation is performed, viewed along the center symmetry line.

Transformation optics theory [9] tells us that an empty space with a distorted geometry is equivalent to a non-distorted space but filled with some material called transformation medium. According to the operation defined in Fig. 2(a-d), we can easily get the coordinate transformation and material properties of the transformation medium based on the theory developed in [9]. Let \{x, y, z\} and \{u, v, w\} be the coordinate systems in physical and EM space, respectively, we summarized the coordinate transformations and the corresponding materials parameters in different regions [see definitions in Fig. 3(a)] in Table 1.

<table>
<thead>
<tr>
<th>Regions</th>
<th>(a \geq -x \pm \frac{1}{2}y \geq \frac{1}{2}a)</th>
<th>(u = 3x + 2a - 2[x])</th>
<th>(v = y)</th>
<th>(w = z)</th>
<th>(\varepsilon_r = \mu_r = \begin{pmatrix} 5 &amp; \pm 6 &amp; 0 \ \pm 6 &amp; 9 &amp; 0 \ 0 &amp; 0 &amp; 9 \end{pmatrix})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regions II</td>
<td>(a \geq -x \pm \frac{1}{2}y \geq \frac{1}{2}a)</td>
<td>(v = y)</td>
<td>(w = z)</td>
<td>(\varepsilon_r = \mu_r = \begin{pmatrix} \frac{5}{3} &amp; \pm 6 &amp; 0 \ \pm 6 &amp; 9 &amp; 0 \ 0 &amp; 0 &amp; 9 \end{pmatrix})</td>
<td></td>
</tr>
<tr>
<td>Regions III</td>
<td>(a \geq x \pm \frac{1}{2}y \geq \frac{1}{2}a)</td>
<td>(u = 3x - 2a + 2[x])</td>
<td>(v = y)</td>
<td>(w = z)</td>
<td>(\varepsilon_r = \mu_r = \begin{pmatrix} \frac{5}{3} &amp; \pm 6 &amp; 0 \ \pm 6 &amp; 9 &amp; 0 \ 0 &amp; 0 &amp; 9 \end{pmatrix})</td>
</tr>
<tr>
<td>Regions IV</td>
<td>(</td>
<td>x</td>
<td>+</td>
<td>y</td>
<td>\leq \frac{1}{2}a)</td>
</tr>
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At this point, it is intuitive to compare the proposed device with the scheme that we discussed in Fig. 1(b). In fact, the core area of the proposed device is nothing but an \(n = -1\) medium in a rhombus shape (see property of region V in Table 1). However, we have mentioned that such a system alone does not behave as a perfect mirror, as schematically shown in Fig. 1(b). The recipe here is to add four pieces of transformation media (regions I-IV) to surround such a rhombus \(n = -1\) area, which can help resolve the problems existing for a rhombus \(n = -1\) device alone. It is worth mentioning that, although \(\varepsilon_r, \mu_r\) look quite

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complicated at first sight, they can be easily diagonalized so that the transformation media are not that difficult to realize practically.

3. Numerical verifications

Full wave numerical simulations [18] are performed to demonstrate the functionality of the proposed device. We consider the simple 2D case first, and then extend to more complicated 3D case. However, an important difference between 2D and 3D cases should be mentioned first. Since a 2D structure does not exhibit real chirality, the 2D device works actually as a transforming mirror for 2D objects precisely speaking. On the other hand, for a realistic 3D chiral structure, the 3D device can indeed optically switch its chirality as a perfect mirror. In the following, we demonstrate two important characteristics for the proposed device:

1) for any true light source, the device effectively relocate its position to the mirror-reflection symmetry point with respect to the central plane of the device, for an observer at the far field;

2) for a ray (radiated from a true source) which originally propagates to left (right) direction, the device effectively redirect its propagation to right (left) direction, again for an observer at the far field.

![Radiation pattern images](image)

Fig. 3. (a) Radiation pattern of a line source placed inside the 2D device. (b) Radiation pattern of a line source placed in free space, at the mirror-reflection position of the source. (c) Radiation pattern of a directional source inside the device, which emits rays only along two directions \( \vec{k} = \pm \left( -\frac{1}{2}\sqrt{2}, \frac{1}{2}\sqrt{2}, 0 \right) k_0 \). (d) Radiation pattern of another direction source placed in free space, which emits rays only along two directions \( \vec{k} = \pm \left( \frac{1}{2}\sqrt{2}, \frac{1}{2}\sqrt{2}, 0 \right) k_0 \).

We now demonstrate the first characteristics. In our simulations, we set \( a = 6.25 \) [19] and assumed that the device medium properties were given by Table 1, and then placed a line source at a point \((x = 1.25, y = 1.25, z = 0)\) inside the device. The calculated radiation pattern (only \(E_z\) component is shown) of this source is depicted in Fig. 3(a). While the field distribution inside the device is rather complex, we find surprisingly that the radiation pattern outside the device is quite regular. As a comparison, we show in Fig. 3(b) the radiation pattern of a line source placed at a point \((x = -1.25, y = 1.25, z = 0)\) with the device removed [20]. Comparison
between Fig. 3(a) and Fig. 3(b) show that they are essentially the same, demonstrating that the proposed device can indeed effectively relocate the position of a source to its mirror-reflection symmetry point.

We next demonstrate the second characteristics of the device. We purposely constructed a directional source [21] which emits light rays only along two opposite directions, i.e., \( \vec{k} = \pm \left( -\frac{1}{2} \sqrt{2}, \frac{1}{2} \sqrt{2}, 0 \right) k_0 \). Placing this special source inside the device, we numerically calculated the radiation pattern and showed the result in Fig. 3(c). As expected, the rays radiated from this source undergo appropriate refractions inside the transformation media (regions I-IV), eventually resulting in two rays traveling along the other pair of directions, i.e., \( \vec{k} = \pm \left( \frac{1}{2} \sqrt{2}, \frac{1}{2} \sqrt{2}, 0 \right) k_0 \). Again, we showed in Fig. 3(d) the radiation pattern of another directional source which emits light rays only along \( \vec{k} = \pm \left( \frac{1}{2} \sqrt{2}, \frac{1}{2} \sqrt{2}, 0 \right) k_0 \), placed in free space without the device [20]. Comparison between Fig. 3(c) and (d) indicate that they are basically the same, demonstrating that our device indeed possesses the second characteristic as mentioned above.

Now extend the discussions to an arbitrary 2D source placed inside the device. Suppose we could regard the complex-shaped source as a collection of line sources, then applying the above two characteristics, we understand that our device effectively replaces the original source by a virtual source, which is the mirror image of the original one, for a far field observer.

Fig. 4. Propagations of plane EM waves polarized with \( \vec{E} \parallel \hat{z} \) passing through the device along (a) \( \hat{x} \) direction and (b) \( (\hat{x} - \hat{y}) \) direction.

One important merit of our device is that it makes itself and the original object invisible to a far field observer, completely different from an ordinary mirror. This has already been partially demonstrated in Fig. 3(a) and (c), where only the virtual mirror-image source can be detected for an observer at the far field. More interestingly, our device is also invisible to external radiations. To demonstrate this effect, we depicted in Fig. 4 the simulated field distributions when the device is under radiations of external plane waves polarized with \( \vec{E} \parallel \hat{z} \). While EM waves are distorted within the device, they are restored to their original propagation direction after leaving the device, making the device completely undetectable for a far field observer. This is easy to understand from the operation as specified in Fig. 2(a-d), since the operation is performed with a restricted area and thus does not affect the light ray trajectories outside the device. In particular, we note that the propagation directions inside the inner rhombus (with \( n = -1 \)) are different from the original direction, in consistency with Fig. 2(d). Another merit of our device is that it does not require the objects hidden inside to be transparent as in illusion optics theory [7], and therefore, our device may have a wide application range.
The extension to the 3D case is straightforward. When taking the $z$ coordinate into consideration, the design for 2D space extends to infinity along the $z$ axis. However, a real 3D device must be finite along all directions. Unfortunately, just truncating the device at some points at the $z$ axis does not work well since the upper and lower boundaries may cause undesirable reflections. This problem can be solved by taking advantage of the fact that the functionality of the 2D device is independent of the value of $a$ (see Table 1). Therefore, shrinking the cross section of the device gradually to zero as $|z|$ increases to a certain value, we obtain a design for the 3D device which is finite along all directions. By doing so, all potential reflections could be eliminated since the device no longer tears up any boundary. Inset to Fig. 5(a) shows the designed 3D chirality-switching device, which is an octahedron with its material parameters obtained by substituting $a$ in Table 1 by

$$a(z) = a_0 - |z|$$  \hspace{1cm} (1)

for the $xy$ plane at a particular $z$ point. Obviously, the total height of the 3D device is $2a_0$.

Numerical simulations [18] are again performed to demonstrate the chirality switching effect for this 3D device. Restricted by our computational resources, we cannot study a real chiral object placed inside the device. Instead, we consider only a point source and demonstrate that the device behaves as a perfect mirror for this point source. The size of the device is set as $a_0 = 2.35$ [19]. As shown in Fig. 5(a), we placed a point source [22] at point $(x = -0.235, y = 0.235, z = -0.235)$, which is at a distance of 0.235 away from the middle symmetry plane, and then performed numerical simulations to compute the radiation patterns. While the near field distribution is very complicated, Fig. 5(a) shows that the far-field wave pattern is rather regular, and it seems that the waves are coming from a virtual point source. To identify the position of this virtual source, we drew in Fig. 5(b) the 2D near field pattern on the $xy$ plane with $z = -0.235$ (the plane where the source is located). We found that this virtual source is located at point $(x = 0.235, y = 0.235, z = -0.235)$, which is at the exact mirror-reflection symmetry point of the true source position. This fact has clearly demonstrated that the device can indeed work as a mirror for any source placed inside, while keeping the device and the original object invisible to an observer located at the far field. Extending the discussions to a more complicated 3D source, we expect that a realistic chiral object hidden inside such a device would exhibit an opposite chirality for an observer at the far field.

4. Conclusions

In conclusion, we have identified a new type of operation performed on a fixed area in EM space, based on which a device can be designed which can optically change the chirality of an
object hidden inside. The functionalities of the proposed device are demonstrated in both 2D and 3D spaces by full wave numerical simulations.

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