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Overlapped illusion optics: a perfect lens brings a brighter feature

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Abstract. In this paper, we show that a perfect lens can be employed to make multiple objects appear like only one object in the far field, leading to a new concept in illusion optics. Numerical simulations have been performed to verify the functionalities for both passive and active objects. The conceptual device can be utilized to enhance the illumination brightness for both incoherent and coherent systems.

A perfect lens [1] made of a negative refractive index material can form ideal images beyond the diffraction limit. Recently, combined with transformation optics [2]–[4], it was realized that many ‘magic’ illusion effects can be obtained with extended perfect lens geometries [5]–[7]. In this work, we show that such a perfect lens can also act as an ‘anti-mirror’ that makes multiple objects appear like only one object in the far field. Our numerical simulation verifies that this ‘overlapped illusion optics’ effect works for both passive and active objects (or sources). When applied to incoherent and coherent illumination systems, such as solid-state lighting, this technique can lead to dramatic enhancement of the illumination brightness and spatial mode quality, as well as the heat-dissipation efficiencies.

It is well known that, when an object is placed in front of a plane mirror, a virtual image is formed on the other side. This image looks identical (except for the opposite handedness) to the object viewed by an observer in front of the mirror. In other words, the mirror transforms a single object into two separate objects, as illustrated in figure 1(a). One may ask the following interesting question: Is this mirror effect invertible? Or, is there a way to make two objects look like one object, which we shall call the ‘anti-mirror’ effect? Our answer is yes! To illustrate the

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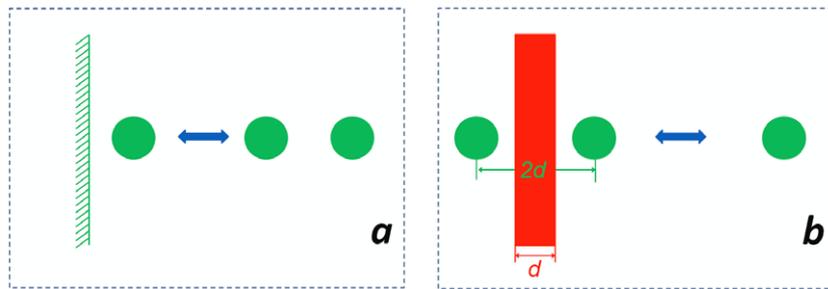


Figure 1. Mirror and ‘anti-mirror’ effects. (a) An object (green circle) in front of a plane mirror is equivalent to two identical objects (green circles). (b) Two identical PECs (green circles) on both sides of a perfect lens (red region) is equivalent to one PEC (green circle).

basic idea for simplicity, we consider here a two-dimensional (2D) case with transverse electric (TE) polarized waves. Two identical cylindrical perfect electric conductors (PECs) are placed on both sides of a perfect lens. The distance between them is $2d$, where d is the thickness of the perfect lens (see the schematic diagram in figure 1(b)). Such a system displays the ‘anti-mirror’ effect because the two PECs look like one PEC to observers on both sides of the lens. More interestingly, the effect is also valid for active sources, as we will show later.

Illusion optics [7] and transformation optics [2]–[4] tell us that a perfect lens can be viewed as a transformation medium from a simple 1D folded coordinate transformation [8]. The folded coordinate transformations can also bring a perfect lens with finite size. Here we use the folded coordinate transformations in [9] to illustrate the basic ideas. Figures 2(a) and (b) show how the illusion optics works. An illusion device with an elliptic cylindrical PEC (green circle in figure 2(a)) embedded in the restoring medium (blue regions in figure 2(a)) look like a bare circular cylindrical PEC (green dashed circle in figure 2(a), or green circle in figure 2(b)) [10]. Now in figure 2(c), if we put another cylindrical PEC in the same position and with the same shape as the illusion image in figure 2(a), following the image-forming principle of transformation optics [7], the new system will look like a bare circular cylindrical PEC (see in figure 2(b)) for the far-field observers. Figures 2(b) and (c) can be treated as an extension of figure 1(b). Such a phenomenon can become even more interesting. We can replace the real cylindrical PEC in figure 2(c) with another illusion device, which is from that in figure 2(a) rotated by 180° . Figure 2(d) presents a schematic diagram showing that two objects look like one PEC (green dashed circle in figure 2(d)) to the far-field observers. *This effect has not been found in nature before.* In fact, we can understand it easily. The two illusion devices are close to each other, and their virtual illusion spaces [7] share a common region. Inside the shared region, the same PEC image is formed simultaneously by both illusion devices. Our numerical simulations show that this ‘overlapped illusion optics’ (multiple objects look like one object) works for both PECs and active sources.

To demonstrate the above effect, we perform full-wave simulations using the COMSOL Multiphysics finite-element-based electromagnetics solver. We set the unit to be a wavelength. All the circular cylindrical PECs (both real and virtual) are located at the origin, whose radii are 0.4. The material parameters are related to the geometric shapes of the illusion devices. We use similar shapes to that in [9] ($p = -4/3$ for regions I, $p = 0$ for regions II, $p = 4/3$ for regions III and $r = 1/3$). Regions I are anisotropic materials with $\varepsilon_z = 3$, $\mu_{xx} = 17/3$, $\mu_{yy} = 3$

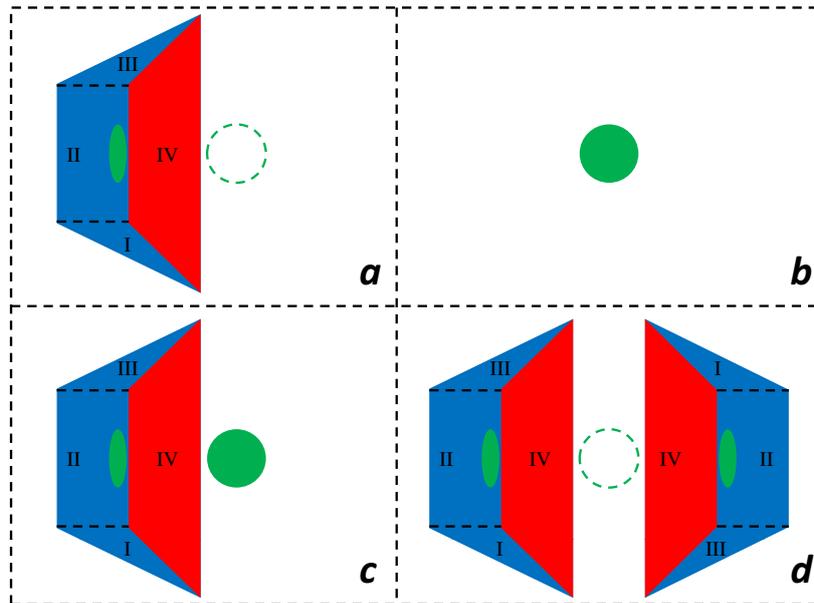


Figure 2. Overlapped illusion optics. (a) An illusion device to form a virtual PEC image outside it. (b) A bare cylindrical PEC. (c) The ‘anti-mirror’ effect with finite size. (d) Two illusion devices to form the same virtual PEC image, which shall be termed as the ‘overlapped illusion optics’. The PECs are shown in green. The virtual PEC images are denoted by green dashed circles. The perfect lenses are shown in red. The restoring media are shown in blue.

and $\mu_{xy} = \mu_{yx} = -4$. Regions II are anisotropic materials with $\varepsilon_z = 3$, $\mu_{xx} = 1/3$, $\mu_{yy} = 3$ and $\mu_{xy} = \mu_{yx} = 0$. Regions III are anisotropic materials with $\varepsilon_z = 3$, $\mu_{xx} = 17/3$, $\mu_{yy} = 3$ and $\mu_{xy} = \mu_{yx} = 4$. Regions IV are perfect lenses with permittivity $\varepsilon = -1$ and permeability $\mu = -1$. The distances between the centers of the circular cylindrical PECs and the perfect lens interfaces are set to be 0.5, from which we can obtain the detailed shapes and positions of the elliptic cylindrical PECs. The TE waves are incident upward along the y -axis. Figure 3(a) shows the scattering patterns of the illusion device in figure 2(a). The same rule applies to the remaining parts of figures 3 and 2. The identical far-field patterns in each part of figure 3 confirm the above finding.

The above overlapped illusion optics may provide solutions to modern solid-state illumination systems. Light-emitting diodes (LEDs) have been considered as the next generation lighting source because of their low operating voltage, small size, high energy-conversion efficiency and long lifetime. However, it is still a big challenge and costly to produce commercial single-LED bulbs to meet residential illumination requirements owing to heat dissipation and other manufacturing difficulties. To increase the illuminance level, a common solution is to package many LEDs inside a lamp. As a result, it is extremely difficult to generate spatial illumination uniformity for residential use. With the overlapped illusion optics proposed in this paper, this problem can be solved by overlapping the illusion images from all LEDs located physically at different positions—for an observer, it looks just like a single-LED source! Such a solid-state lighting device not only provides high illuminance level with spatial uniformity, but also dissipates heat efficiently.

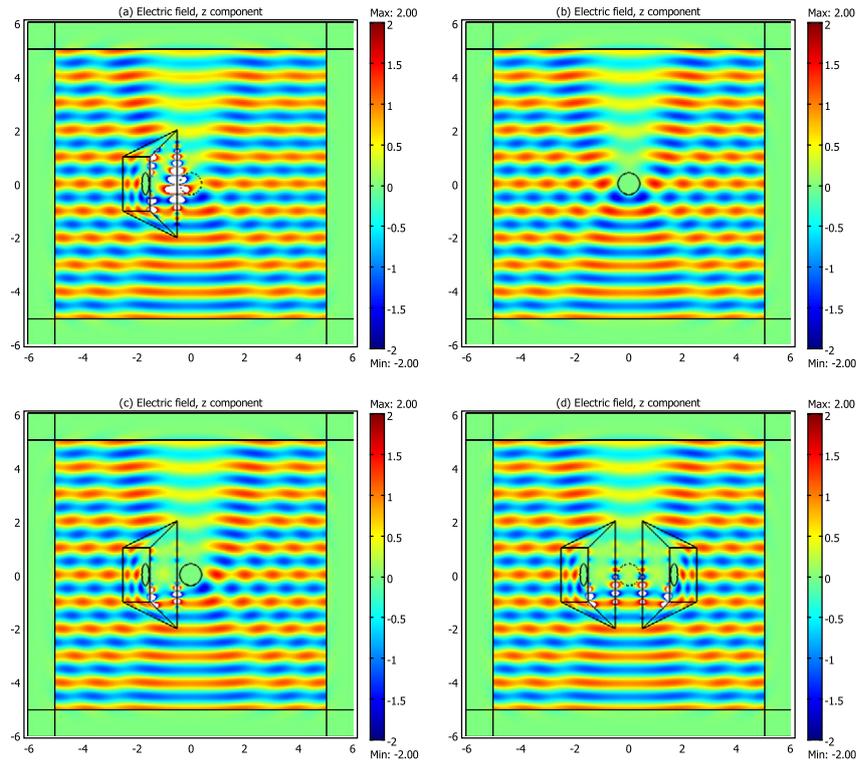


Figure 3. Simulation results. Panels (a), (b), (c) and (d) are the scattering patterns of the devices in figures 2(a), (b), (c) and (d), respectively.

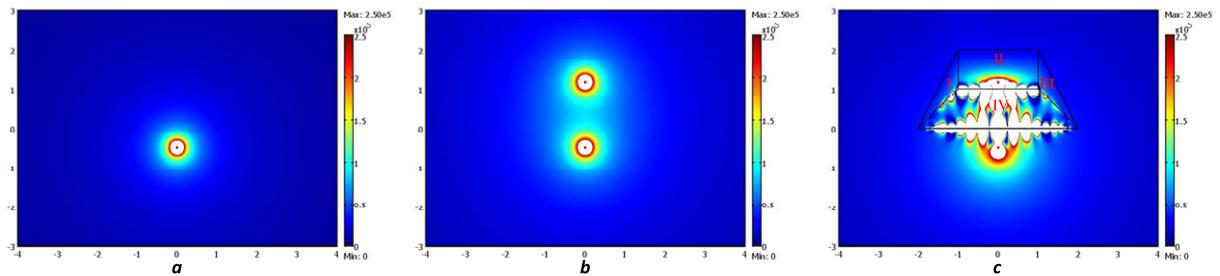


Figure 4. An improved incoherent illumination system with overlapped illusion optics. (a) A single-LED bulb: a single line current source in vacuum. (b) A double-LED bulb: two line current sources in vacuum. (c) An improved double-LED bulb: two line current sources in the ‘anti-mirror’ system. The intensity of the electric field is plotted.

Here we construct a model to simulate the proposed LED bulb. For comparison, in figure 4(a) we show a plot of the intensity of the electric field ($|E_{z1}|^2$) of a single-LED source simulated by a line source with $I_1 = 1\text{A}$ current and located at $\vec{r}_1 = (0, -0.5)$. The electric field E_{z1} is [11] $E_{z1} = -\frac{1}{4} \frac{2\pi}{\lambda} \sqrt{\frac{\mu_0}{\epsilon_0}} I_1 H_0^{(1)}\left(\frac{2\pi}{\lambda} |\vec{r} - \vec{r}_1|\right)$. When two LED sources (simulated by two incoherent sources) sit in parallel, as shown in figure 4(b), the far-field light intensity is the sum of those of the two incoherent sources, with unavoidable spatial fluctuations. Here we set one

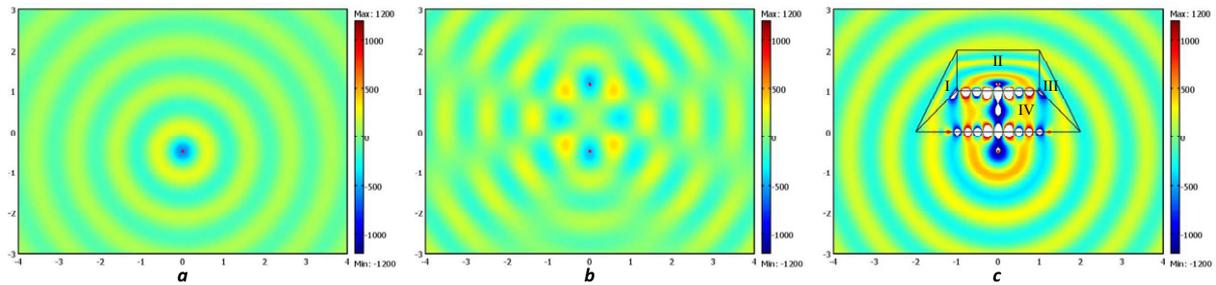


Figure 5. Coherent sources with overlapped illusion optics (to motivate a new laser beam combining technique). (a) A single line current source in vacuum. (b) Two coherent line current sources in vacuum. (c) A combination of two coherent sources: two coherent line current sources in the ‘anti-mirror’ system.

source to be at $\vec{r}_1 = (0, -0.5)$ with a current $I_1 = 1\text{A}$ and the other at $\vec{r}_2 = (0, \frac{7}{6})$ with another current $I_2 = e^{i\varphi}\text{A}$, where φ is a randomly different phase. To eliminate the intensity fluctuations at far field, we follow the proposed overlapped illusion optics and replace the two PECs in figure 2(c) (or figure 3(c)) with two line current sources. For esthetic reasons, we rotate the device by 90° around the origin. The two line current sources are at the same positions as those in figure 4(b). Region I is anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 3$, $\mu_{yy} = 17/3$ and $\mu_{xy} = \mu_{yx} = 4$. Region II is anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 3$, $\mu_{yy} = 1/3$ and $\mu_{xy} = \mu_{yx} = 0$. Region III is anisotropic material with $\varepsilon_z = 3$, $\mu_{xx} = 3$, $\mu_{yy} = 17/3$ and $\mu_{xy} = \mu_{yx} = -4$. Regions IV are perfect lenses with permittivity $\varepsilon = -1$ and permeability $\mu = -1$. Figure 4(c) shows the intensity distribution of the improved double-LED bulb. Compared to figure 4(b), it has the same level of light brightness but the device behaves like a single-LED bulb with perfect spatial quality. The result can be simply extended to many (>2)-LED bulbs.

When applied to coherent sources, our proposed method may be useful for developing high-power and high-radiance coherent illumination sources with preserved spatial quality. In figure 5(a), we simulate a single coherent source with a line current $I_1 = 1\text{A}$ at $\vec{r}_1 = (0, -0.5)$. In figure 5(b), the spatial quality degrades when two coherent sources are aligned in parallel because of their interference. Figure 5(c) shows the simulation result of our anti-mirror effect (the same configuration as the LED bulb in figure 4(c) where the two LEDs are replaced with two coherent sources here). When the two sources are operated at the same optical frequency and phase, the light amplitude increases by a factor of 2 and thus the total power by a factor of 4! Such a coherent system can be achieved using feedback control with heterodyning detection. The increase of the output of the energy is not surprising because of the constructive interference of the fields (here we assume that each source has the same field amplitude). This technique may have potential applications in the beam-combining technique [12, 13] for developing high-power laser sources with preserved beam quality. Such effects cannot be obtained from the traditional beam-combining techniques.

In summary, we have demonstrated the anti-mirror effect of the perfect lens. Transformation optics extends such an effect to make multiple objects look like one object in the far field. Based on this concept, we proposed and numerically verified the overlapped illusion optics. When applied to incoherent illumination systems, we designed a many-LED bulb with a brighter feature and much better spatial uniformity than a conventional one. Such

a method may also be potentially applied in the beam-combining technique to generate high-power coherent laser beams from multiple laser diodes (LDs) with preserved beam and spatial mode qualities. Therefore, the proposed anti-mirror effect and overlapped illusion optics may have wide applications.

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