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Focusing optical waves with a rotationally symmetric sharp-edge aperture

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ABSTRACT

While there has been various kinds of patterned structures proposed for wave focusing, these patterned structures usually involve complicated lithographic techniques since the element size of the patterned structures should be precisely controlled in microscale or even nanoscale. Here we propose a new and straightforward method for focusing an optical plane wave in free space with a rotationally symmetric sharp-edge aperture. The focusing phenomenon of wave is realized by superposition of a portion of the higher-order symmetric plane waves generated from the sharp edges of the apertures, in contrast to previously focusing techniques which usually depend on a curved phase. We demonstrate both experimentally and theoretically the focusing effect with a series of apertures having different rotational symmetry, and find that the intensity of the hotspots could be controlled by the symmetric strength of the sharp-edge apertures. The presented results would advance the conventional wisdom that light would diffract in all directions and become expanding when it propagates through an aperture. The proposed method is easy to be processed, and might open potential applications in interferometry, image, and superresolution.

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1. Introduction

Recently, there has been continuing interest in focusing optical waves within or beyond the diffraction limit by means of micro- or even nano-patterned structures, which provide potential opportunities in miniaturized and integrated photonic components. Until now, various kinds of structures, e.g., metallic nanoslit arrays [1–4], metal-based waveguide arrays [5–7], structures that are based on metamaterials or metasurfaces [8–13] etc., have been proposed and studied both theoretically and experimentally. These patterned structures could be used for significant light field concentrations due to the created curved phase induced by each individual element of the structures. For example, by carefully controlling each slit width in a nanoscale slit array in metallic film, a parabolic curved phase could be achieved [3], leading to plasmonic light field focusing. Most recently, the concept of superoscillations, which refers to the phenomenon of a band-limited function that oscillates faster than its highest Fourier component [14,15], has been used for creating a super-oscillating structure [16–19], e.g., a binary amplitude mask. When a wave is diffracted by this nanostructured mask, a superoscillatory wave function is formed, producing a hotspot within subwavelength scale [16,20]. However, we should point out that the experimental realizations of these patterned structures mentioned above usually involve complicated lithographic techniques since the size of each element in such structures should be precisely controlled in microscale or even nanoscale [3], which is still a great challenge.

Here a question of interest is whether optical wave focusing could be achieved with much more straightforward optical element, e.g., a single aperture, as compared with such patterned structures.

In this article, we reveal an intriguing phenomenon that optical plane waves could be focused into a series of hotspots in free space with a simple sharp-edge aperture (SEA). Our introduced SEA is based on the equilateral polygon, having rotational symmetry C_n (here n is an integer and $n \geq 2$). The SEA is amplitude-modulated, generating a light field at the aperture plane with sharp-edge amplitude. It is shown both experimentally and numerically that although the initially diffracted wave does not contain any angular momentum, the wave starts shrinking to a focal hotspot during free-space propagation. This is very different from previous patterned structures that are usually phase-modulated [1–3,10,11], involving a curved phase for focusing the waves. We note that the diffraction of waves through a single aperture has been well-known [21,22], and it has also been recognized that the optical waves would diffract in all directions and become expanding after passing through the diffractive apertures. This work will present

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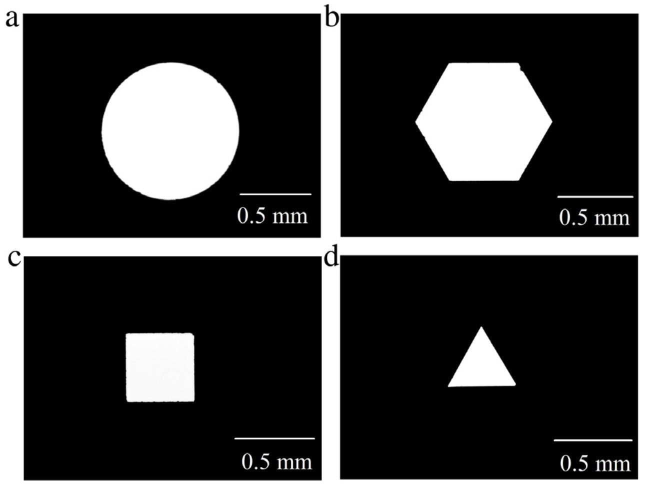

Fig. 1. The microscopic photographs of the fabricated samples: (a) the circular aperture; (b) the regular hexagonal aperture; (c) the square aperture; and (d) the regular triangular aperture.

an interpretation for the observed focusing phenomenon with the SEA that has rotational symmetry, and also discuss the effect of aperture's thickness on the wave focusing. In addition, it is worth mentioning that the intensity of the focal hotspot as well as the corresponding focal length could be controlled by the rotational symmetry C_n of the SEA. This is nice since the diffracted wave by a single slit (C_2) only has a fixed value (1.8) of the intensity-enhanced ratio at the focal hotspot, and the recently reported focusing is limited to the early stage of wave propagation (a little bit far beyond the near field) [23–25].

2. Model and methodology

We start by considering an optical plane wave diffracted by a SEA structure. We assume that the aperture size is much larger than the considered wavelength, in which case it is expected that the focusing phenomenon would occur at propagation distance that is far beyond the near field [25]. Therefore, the propagation dynamics of the diffracted waves beyond the aperture can be governed by the paraxial Helmholtz equation

$$i\frac{\partial E}{\partial z}+\frac{1}{2k}\left(\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}\right)=0, \tag{1}$$

where E denotes the complex diffracted field, and $k = 2\pi/\lambda$ is wavenumber in vacuum with λ being the injected wavelength. z represents the propagation distance, while x and y are the transverse coordinates respectively. i is the imaginary unit. We assume that our introduced aperture is of negligible thickness, and located in the x–y plane at $z = 0$. Therefore, the transmission function of the SEA can be approximately written as

$$T(x,y)=\begin{cases}1, & \text{inside the SEA}\\ 0, & \text{outside the SEA.}\end{cases} \tag{2}$$

In this case, the diffracted light field at $z = 0$ can be written as $E(x, y, z = 0) = E_0T(x, y)$, where E_0 is amplitude of the incident plane wave. We emphasize again that the SEA is only amplitude-modulated, and hence such an initially diffracted wave has zero angular momentum but with sharp edges in its amplitude distribution, evolving along the propagation distance. To seek for solution of the diffracted waves beyond the aperture, we integrate Eq. (1) with this initial condition, and find

$$\begin{aligned}E(x,y,z)=E_0\iint &\tilde{T}(u,v)\\ &\times\exp\left[-i\frac{2\pi^2 z}{k}(u^2+v^2)\right]\exp\left[i2\pi(ux+vy)\right]du\,dv,\end{aligned} \tag{3}$$

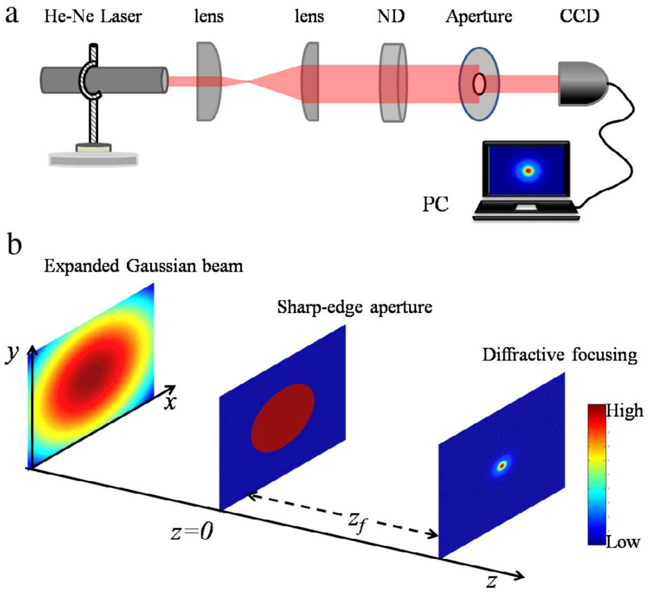

Fig. 2. The experimental setup (a) and the schematic illustration (b) of the two-dimensional (2D) diffractive focusing by a single sharp-edge aperture.

where $\tilde{T}(u, v)$ is the Fourier spectrum of the transmission function of the SEA, with u and v being the spatial frequency with respect to the x and y coordinates, respectively. Eq. (3) shows two-dimensional (2D) complex diffracted light field propagating in free space along the z direction. The diffracted light field beyond the aperture is inverse Fourier transform of the transmission spectrum which is modulated by a propagating phase factor. With a convolution of the aperture illuminated with the phase factor, i.e., the Fresnel propagator, we can rewrite Eq. (3) in the form of

$$\begin{aligned}E(x,y,z)=\frac{E_0k}{2\pi z}\iint &T(x',y')\\ &\exp\left[i\frac{k}{2z}[(x-x')^2+(y-y')^2]\right]dx'dy'.\end{aligned} \tag{4}$$

In order to observe the propagation dynamics of the diffracted waves beyond the aperture, we fabricated these planar apertures based on a circular copper film. The diameter and the thickness of the metallic film are 25 mm and 30 μm (±5 μm), respectively. The apertures having different regular polygons can be fabricated with femtosecond laser processing technology. Fig. 1 shows the microscopic photographs of the fabricated samples. In the experiments, we used a linearly polarized He–Ne laser working at the wavelength of 632.8 nm to generate a monochromatic fundamental Gaussian beam. The output laser light is expanded and then collimated to a width of nearly 1 cm, as illustrated in Fig. 2(a) and (b). After propagating through a neutral density (ND) filter, the expanded laser beam illuminates the fabricated sharp-edge aperture, and the intensity distribution of the diffracted waves along the propagation distance ($z > 0$) is recorded using a CCD camera.

3. Results and discussion

We firstly investigate the counterintuitive focusing phenomenon of an optical plane wave diffracted by a circular SEA, having the highest rotational symmetry C_∞. The transmission function of the C_∞ SEA has a form of $T(x, y) = \mathrm{circ}(r/r_c)$, where $r = \sqrt{x^2 + y^2}$, circ(·) represents circle function and r_c is the radius. In experiment, the radius was set as $r_c = 0.5$ mm. The intensity distributions of the diffracted light field at three different distances of $z = 22$ mm, 214 mm and 400 mm were measured, as shown in Fig. 3(a), (c), and (e) respectively. From these results, it is interesting to find that, instead of expanding, the diffracted waves exhibit significant behavior of concentration. Specifically, the

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