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Remarkable ability of spiral orthogonal zone plate in generating various focused optical vortices

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A B S T R A C T

We propose an amplitude spiral orthogonal zone plate (ASOZP) as a Cartesian-based spiral zone plate for generating variety of optical vortices. The presented model is made by overlapping closely a vertical spiral one-dimensional zone plate and a horizontal one. We demonstrate that the element produces diversity of focused vortices, in a way that the vorticity and number of the produced vortices could be easily manipulated. In addition, the generated vortices show rotation features in the vicinity of the focal plane. Furthermore, it is demonstrated that diffraction efficiency of the model is much more higher than the previously introduced Cartesian-based elements. We finally verify numerical results by experimental studies.

1. Introduction

Light waves possessing a phase singularity are called optical vortices [1,2]. In an optical vortex, light beam is twisted in a corkscrew-like around its axis of propagation which brings it to an helically-shaped wavefront. Because of the twisting, the light beam finds an orbital angular momentum (OAM) that is associated with the azimuthal phase structure of the form $\exp(ip\varphi)$. Where φ is azimuthal angle and p denotes for topological charge of the field that may be any integer value, according to how many twists the light does in one wavelength. As well as, the number may be positive or negative depending on the direction of the twist.

Unique properties of optical vortices have made them attractive in many different fields like optical filtering in image processing [3,4], optical spanner [5], cold atom guide [6–8], optical tweezers [9–11], optical communications [12–14] and surface plasma excitation [15,16].

A vortex beam is generated by different diffractive elements. Spiral phase plates [17–21] can generate a vortex beam by using spiral phase in own their distribution. The other way for creating a vortex beam is Devil vortex lens which is a phase only Devil's lens modulated by an helical phase structure [22]. Recently, generation of vortex by Bragg reflector waveguide has also been reported [23]. Perhaps, the most important way to generate vortex beam is spiral phase plates, because they mainly provide high energy efficiency. Another interesting way to produce vortex beam is implementing square zone structures which opened up a new insight into generation of optical vortices using Cartesian-based spiral zone plate [24,25]. Herein, we introduce a new Cartesian-based diffractive element so called amplitude spiral orthogonal zone plate (ASOZP). The element is the same as orthogonal zone plate (OZP) except that an azimuthal phase with different topological charges is implemented over the symmetry axes of it. Nevertheless, the proposed element has two topological charges P_x and P_y along both of the orthogonal axes x and y to manipulate the produced optical vortices, unlike the spiral square zone plate which has one topological charge for manipulating the generated vortics. Furthermore, ASOZP is able to generate simultaneously one or more focused vortices along the axial coordinate whose the number of the vortices are specified by a given rule. Resultantly, this element may be implemented in trapping of multiple particles [25,26]. By further studies of defocusing properties of ASOZP, we showed that the generated vortex beam rotates in the vicinity of the focal plane which enable ASOZP to be considered for many interesting and potential applications, for example encoding the depth of a field in a 3D scene, image processing and auto focusing systems, as well [27,28]. We also demonstrate that diffraction efficiency of ASOZP is much more higher than spiral square zone plate (SSZP). Theory, simulation and experimental results are demonstrated and analyzed in detail.

2. Mathematical approach and numerical results

To generate an ASOZP, we implement the way of generation of orthogonal zone plate (OZP), in which an OZP is created by superpositioning of a vertical linear zone plate (LZP) with an

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horizontally one [29]. Having been azimuthally apodized the transmission functions of both of the two LZPs, they were binarized. Then, the final transmittance is acquired by multiplication of the two binarized functions, i.e. if t_x and t_y denote for the transmission functions of the two LZPs, then the azimuthally apodized transmissions are defined as

$$t_x = \exp\left\{-i\frac{kx^2}{2f} + iP_x\varphi\right\}$$
$$t_y = \exp\left\{-i\frac{ky^2}{2f} + iP_y\varphi\right\}, \tag{1}$$

where $k = \frac{2\pi}{\lambda}$ is the wave number with λ being the wavelength of the incident light, (x, y) are the Cartesian coordinate and f is the focal length. As well as, P_x and P_y are topological charges and φ is the azimuthal angle. Then, the transmission functions may be binarized as following:

$$\mathrm{Bin}_x[t_x] = \begin{cases} 1 & \text{if } \mathrm{imag}(t_x) > 0 \\ 0 & \text{if } \mathrm{imag}(t_x) < 0 \end{cases} \tag{2}$$

$$\mathrm{Bin}_y[t_y] = \begin{cases} 1 & \text{if } \mathrm{imag}(t_y) < 0 \\ 0 & \text{if } \mathrm{imag}(t_y) > 0, \end{cases} \tag{3}$$

subsequently, the transmittance of ASOZP is obtained as

$$t_{ASOZP} = \mathrm{Bin}_x[t(x)]\mathrm{Bin}_y[t(y)]. \tag{4}$$

These binarizations are in fact the same as Fourier expansion-based transmission function of the spiral orthogonal zone plate which takes the form

$$T(x, y) = \sum_{n,m} C_{m,n} \exp\left[\frac{-ik(mx^2 + ny^2)}{2f} + i(mP_x + nP_y)\varphi\right], \tag{5}$$

where the summation is over all possible integer pairs m and n which denote different diffraction orders. Therefore, concerning Eq. (5) zone plates have multiple focuses. But, at the main focus in which $m=n=1$ order is focused, the amplitude of $P_x + P_y$ vortex becomes large [30]. Intensity of a diffracted plane wave by an ASOZP may be simply calculated by Fresnel-Kirchhoff integral

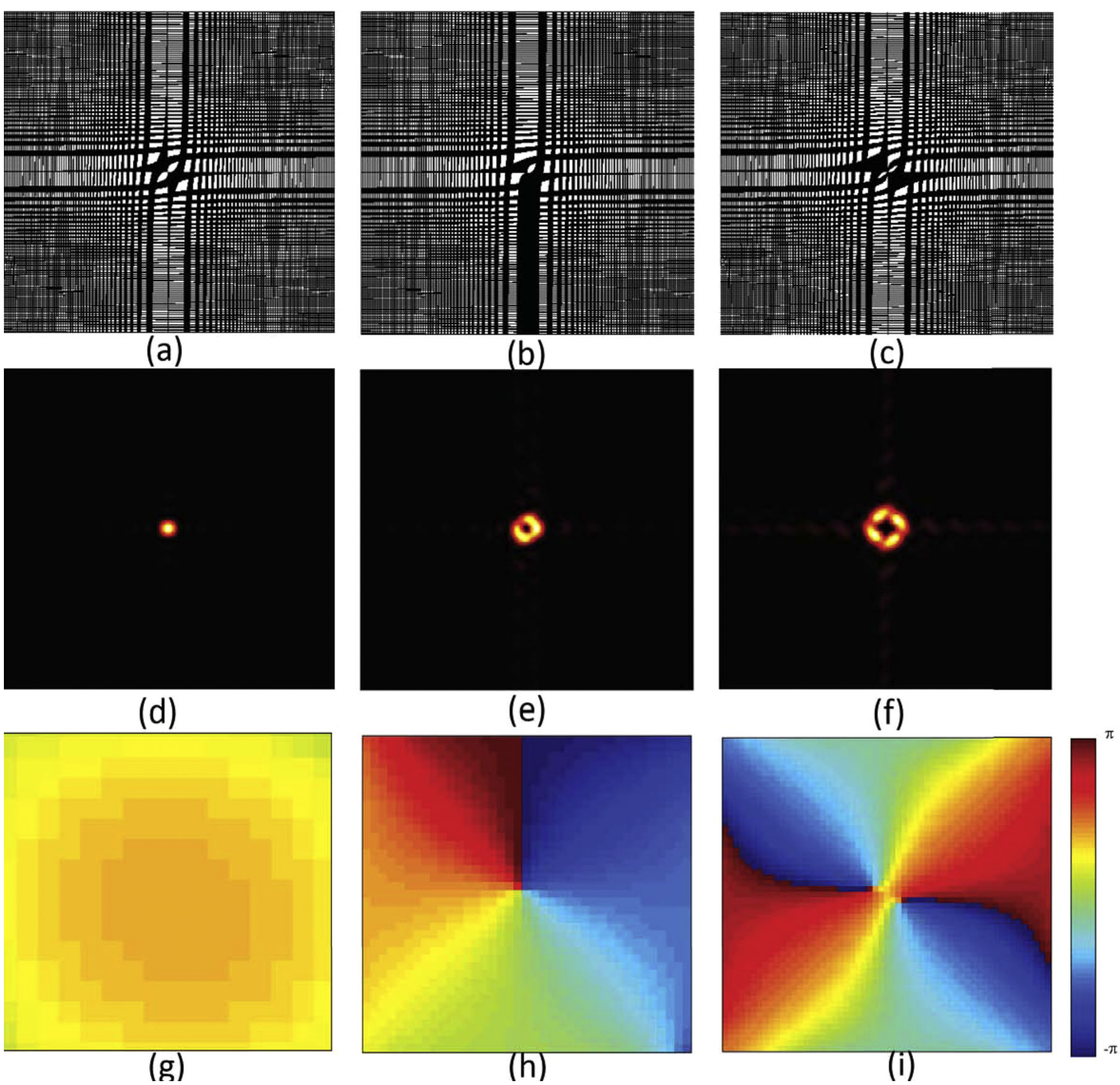

Fig. 1. Typical samples of ASOZP with the same specifications side length $R=6$ mm, focal length $f=500$ mm, but different topological charge and the corresponding diffraction patterns and the phase distribution in the focal plane are shown in this figure. Topological charges for samples (a)–(c) are $P_x = 2$, $P_y = -2$, $P_x = -1$, $P_y = 2$ and $P_x = -2$, $P_y = 4$, respectively.