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Controlled interaction of the optical vortices generated by off-center spiral zone plates

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ABSTRACT

We report a simple, cost-effective, and scalable diffractive optical element named off-center spiral zone plates (OSZPs) to generate composite optical vortices (OVs) and control their interactions. By adjusting the parameters of OSZPs, the interaction process and performance of OVs, including fluid-like rotation, annihilation of vortex anti-twins, and creation or destruction of vortex anti-twins are investigated. Besides, the rotation between the two vortices with opposite TCs is observed. Furthermore, it is revealed that the common OVs interaction is based on the process of creation and destruction of vortex anti-twins, which helps us to understand the dynamics of the underlying interactions of composite OVs.

1. Introduction

Optical vortices (OVs), also called screw phase dislocations or phase singularities, have attracted much attention due to their broad range of potential applications, such as the optical manipulation [1,2], quantum information [3–5] and image processing [6]. The simplest optical vortex only contains one single phase dislocation, and the complex amplitude distribution contains the factor $\exp(jl\varphi)$, where φ is the polar angle and l is the topological charge (TC), respectively. The composite vortices are formed by the superposition of two or more vortices with different centroids in one beam [7,8], such as vortex twins are two adjacent vortices with same charge, while vortex anti-twins, or referred as vortex dipole, are two adjacent oppositely charged vortices.

The propagation dynamics of vortices play an important role in both linear and nonlinear regimes [7–10], and the intensity gradient and the phase gradient are believed to be two main reasons that control the propagation dynamics of the OVs. Owing to the complexity of the wavefronts produced by the composite OVs, twists, loops and knots are formed in the path of OVs propagation [11–13], and the interaction processes exhibit many intriguing properties, such as fluid-like rotation, transverse movement and annihilating with each other [14–18]. The study of interaction between vortices also offers new insights to the beam shaping [19–22], weakly interacting Bose–Einstein condensates (BEC′s) [23,24], and many other physic fields [25].

However, the optical tools for generating composite OVs and controlling their interactions are rather limited. And one often needs collinear superposition of different Laguerre–Gauss (LG) modes beams to generate the desired composite OVs, where spatial-light modulators (SLMs), lenses and beam splitters are used to control the interaction of OVs, which is complicated and the adjustment is also inconvenient.

In this work, by employing the “repetitive structures” method [26], we propose a simple, cost-effective, and scalable diffractive optical element named off-center spiral zone plate (OSZP) which can control the interaction by simply setting different parameters of OSZP. Using OSZP several different optical vortex interaction procedures are generated, and the creation and destruction of vortex anti-twins are observed, which acts as a basic process to ensure the conservation of TCs during the interaction process. In addition, this kind of elements also enables us to control the vortices interaction in more widely regimes, such as generating X-rays with a Berry Twist [27].

2. The concept of OSZP

We start with a conventional SZP which can be seen as a class of repetitive structures, namely, the coordinate transformed structures [26]. The transmission function associated with such structures can be written as $t(x,y) = p[g(x,y)]$, where $p(x')$ is a periodic function

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called the periodic profile which decides the focal length of the SZPs, and $x' = g(x, y)$ is a coordinate transformation map $h: \mathbb{R}^2 \mapsto \mathbb{R}$ which gives the geometric structures of the SZPs. For a conventional binary-phase SZP, the transmission function can be generated by combining the periodic function $p(x') = \text{sgn}(\cos 2\pi v x')$ with $g(x, y) = a(x^2 + y^2) + m\arg(x + iy)$. For our purposes, it is useful to rewrite g in polar coordinates (r, θ) as $g(r, \theta) = ar^2 + m\theta$, where m is the spiral charge which determine the vortex topological charge generated by the SZPs. The transmission function of OSZP has the form

$$t_{OSZP}(r, \theta) = \text{sgn}\,[\,\cos\,2\pi v(ar^2 + m\theta)] \quad (1)$$

Since $p(x')$ is a periodic function, it can be decomposed into Fourier series as $p(x') = \sum c_n \exp(i2\pi v n x')$. We take the condition $v = 1/2\pi$ and put the expression $x' = g(r, \theta)$ into Eq. (1), thus the transmission function of a SZP can be written as:

$$t_{OSZP}(r, \theta) = \sum_{n=-\infty}^{\infty} c_n \exp\,[jn(ar^2 + m\theta)] \quad (2)$$

Comparing the term $\exp(jnar^2)$ with the standard lens function $\exp(-jkr^2/2f)$, it can be seen that this term acts a lens with focal length equal $-k/2na$. Each term of Eq. (2) describes a beam with optical vortex passed through a series of lens. In practical, the $n = -1$ order is primarily used for focusing, because it acts like a positive lens and dominates the maximum diffraction efficiency. The focal length of 1st order can be expressed as $f = k/2a$, which also is the focal length of the SZPs.

For a conventional SZP, the spiral structure is located at the central axis of the zone plate, as shown in Fig. 1(a1), which means in the transmission function the parameters $\theta = \arctan(y/x)$ and $m = 1$. To obtain the 20 mm focal length, the parameter a is set to $a = k/2f = 44.2$ with a 355 nm wavelength. In Fig. 1(a), the white areas give phase shift 0 while the black areas give phase shift π. The corresponding intensity and phase profile at the focal plane are shown in Fig. 1(b) and (c), respectively, indicating that the center of the phase singularity also lies in the optical axis. Next we will introduce the off-center spiral structures by change the expression of θ in the $g(r, \theta)$. The new expression of θ can be written as $\theta_k = \arctan[(y - y_k)/(x - x_k)]$, where (x_k, y_k) is the location of the spiral center. For multi-vortex focusing, we can embed multiple spiral structures into one OSZP. An n-OSZP is the OSZP that has n spiral structures in it, and the layout generation function can be expressed as:

$$g(r, \theta) = ar^2 - \sum_{k=1}^{n} m_k \theta_k, \quad (3)$$

where m_k is a parameter which determines the vortex topological charge produced by the kth spiral structures, and it can be a positive or a negative integer. Combine Eqs. (3) and (2) and only reserve $n = -1$ order, the transmission function of the n-OSZPs can be seen as:

$$c_{-1} \exp\,(-jar^2)\ \exp\left(j \sum_{k=1}^{n} m_k \theta_k\right) \quad (4)$$

This is a multi-vortex beam with expression $\Pi_k \exp[(jm_k\theta_k)$ passing through a lens. According to the image theory, the center of the vortices imaged by the off-center vortex beams will also be displaced off the central axis at the focal plane. The structure with one off-center spiral structure can generate one optical vortex located off-center at the focal plane of the OSZPs, as shown in Fig. 1(a2). The spiral structure lies above the central axis. The corresponding intensity distribution and phase profiles generated by 1-OSZP are shown in Fig. 1(b2) and (c2), respectively. One can clearly see that the vortex center is also located above the central axis and the intensity is zero in the vortex center, and the phase increases 2π every loop around the central singularity. This is because we set the parameter $m_1 = 1$ here, and the corresponding vortex topological charge equals 1.

To generate vortex twins or anti-twins, we can choose a 2-OSZP which has two same sign or opposite sign m parameters. Fig. 1(a3)

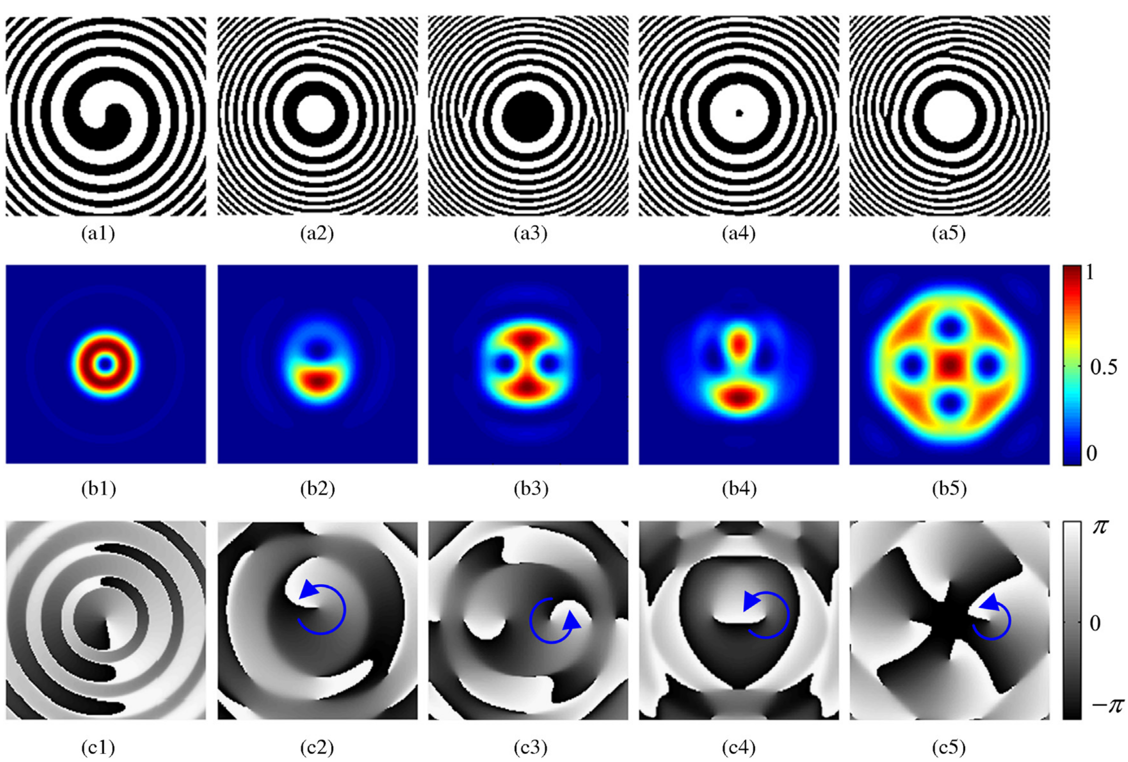

Fig. 1. Layout structures of conventional SZPs and OSZPs: (a1) a conventional SZP, (a2) a 1-OSZP, (a3) a 2-OSZP for generating vortex twins, (a4) a 2-OSZP for generating vortex anti-twins, (a5) a 4-OSZP. (b) Intensity distributions of the OVs generated by the OSZPs shown in (a). (c) The corresponding phase profiles of (b). The arrows show the direction of phases increase.