Optics and Laser Technology 107 (2018) 24–31

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Considerable diversity in generation light-arm beams using multi-twisted phase structure zone plate

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ARTICLE INFO

Article history:
Received 15 July 2017
Received in revised form 21 February 2018
Accepted 6 May 2018

Keywords:
Fresnel diffraction
Fresnel zone plate
Spiral zone plate
Light-arm beams
Optical vortex

ABSTRACT

We aim here to present a novel Fresnel zone plate- based element which is referred to as multi-twisted zone plate. This element is a zone plate whose phase structure is multi-spirally shifted. It is made of the binary combination of two radial phase shifted spiral zone plate. Given the produced structure, two various-charged vortices are generated prior to the focal plane and following it. Focusing and defocusing behaviors of the element are surveyed theoretically and verified by experiments. Depending on the total charge, a variety of light-arm beams is generated. Further studies elucidate that the charge of the prefocus-formed vortex gradually transforms to the charge of the post focus-formed vortex. Simulation predictions are verified by experiment in order to explore its feasibility.

1. Introduction

Rotating light beam carries angular momentum (AM) as it propagates in free space. Spin angular momentum (SAM) [1–3] and orbital angular momentum (OAM) [4–11] are known as two categories of AM. Vanishing circular or elliptic polarization results in the former whereas the latter relates to a screw dislocation of the phase structure. Optical vortices carry orbital angular momentum with screw phase dislocation of the form $exp(il\varphi)$ where φ is the azimuthal angle and l denotes the topological charge which specifies the number of twists of the wavefront in one wavelength, so that direction of the twisting depends on the sign of l. Owing to this property, these beams do not focus as a point but a form of a ring-shaped or series of rings that can impart optical angular momentum on particles [12,4]. These unique features give the optical vortex a great potential applications in many fields like optical trapping [13,14], quantum information [15–17], optical communication [18], global weather patterns [19], sensing tools [20,21], optical microscopy [22,23] and so on.

In the recent years, people are paying attention to another interesting light structures which some of the well-known beams are described as petal-like beams [24–28], optical ring lattice structures [29,30], and linear azimuthons [31]. In particular, the superposition of two vortex beams with different topological charges generates interesting light structures. These structures are known by various names such as Ferris wheels [30] and linear azimuthons [31].

A Fresnel zone plate containing spiral zones is referred to as spiral zone plate (SZP). An SZP is able to produce a phase front containing screw dislocation known as optical vortex [32]. However, radial phase shifted zone plate is a zone plate whose phase is radially shifted and results in an annular beam at the focal plane [33]. Combination both of the element results in interesting types of spirally and azimuthally modulated zone plates which have recently been presented [34,35]. Base on the method, we aim to report another interesting and novel modulated zone plate based element. Superimposing two radial shifted spiral zone plates with opposite topological charges allows us to create a novel modulated zone plate whose structure become multi-twisted and is called multi-twisted zone plate (MTZP). We demonstrate how MTZP is capable of generating a variety of light-arm beams. The effectiveness of topological charge of the two combined elements on the generated light-arm beams has been quite studied. Besides the impact of the so-called shifting parameter on the focused diffraction pattern is also examined. Theory, simulation, and experimental results are demonstrated and analyzed in detail.

2. Mathematical approach and numerical results

From the mathematical point of view, MTZP is based on the radially phase-shifted spiral zone plate (RP-SZP). So, by combining two RP-SZP with opposite phase shifting the element is constructed [33]. Therefore, transmittance of MTZP is given by [36]

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https://doi.org/10.1016/j.optlastec.2018.05.002
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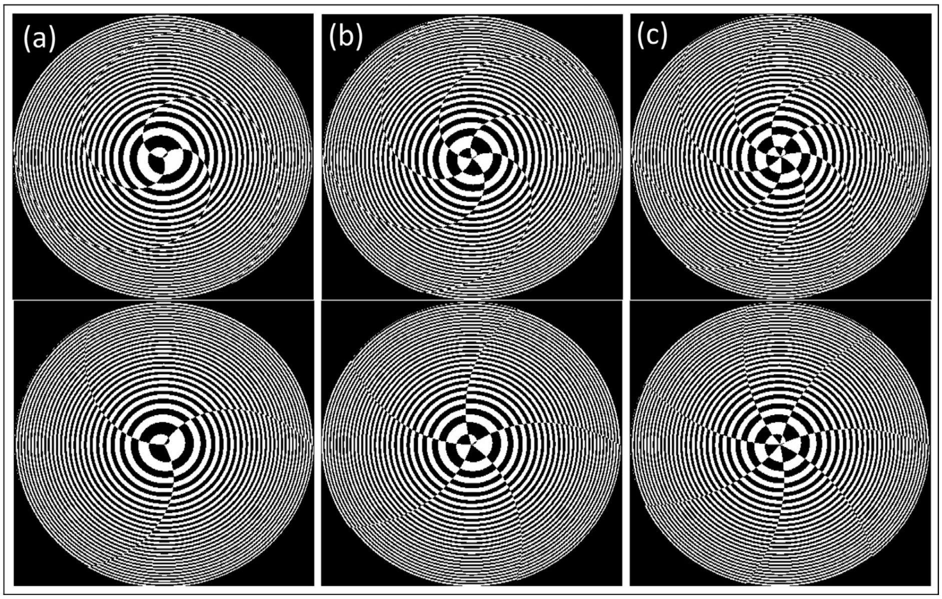

Fig. 1. Typical samples of MTZPs with different topological charges are shown in this figure. For the first column through the third one topological charges are $(\ell_1 = 2, \ell_2 = 1)$, $(\ell_1 = 3, \ell_2 = 2)$ and $(\ell_1 = 4, \ell_2 = 3)$, respectively. Besides, the shifting parameter for the upper and lower rows are $\alpha = 0.02$ and 0.005, respectively.

$$T = Bin(T_1 + T_2), \quad (1)$$

where *Bin* is defined as

$$Bin[T] = \begin{cases} 1 & \text{if imag}(T) < 0 \\ 0 & \text{if imag}(T) > 0, \end{cases} \quad (2)$$

and T_1 and T_2 denote transmittances of the two radially shifted spiral zone plates

$$\begin{aligned} T_1 &= exp\left[-i\frac{k(r-\alpha R)^2}{2f} - i\ell_1\theta\right] \\ T_2 &= exp\left[-i\frac{k(r+\alpha R)^2}{2f} + i\ell_2\theta\right] \end{aligned} \quad (3)$$

where $k = \frac{2\pi}{\lambda}$ is the wave number with λ being the wavelength of the incident light, (r) is the radial coordinate and f is the focal length. ℓ_1 and ℓ_2 are referred to as topological charges of the two elements and θ is the azimuthal angle. As well as, R is the radius of the element and α may be considered as the shifting parameter.

Fresnel-Kirchhoff integral can be directly employed to numerical study diffraction behavior of the proposed models [37]

$$U(\vec{r}; z) = \frac{-i}{\lambda z} exp\left[ik\left(z + \frac{r^2}{2z}\right)\right] \int exp\left(\frac{ikr'^2}{2z}\right) T(\vec{r'}, 0) exp\left(\frac{-ik}{z}\vec{r}.\vec{r'}\right) d\vec{r'}, \quad (4)$$

in which $(\vec{r})$ and $(\vec{r'})$ are coordinates of observation and aperture planes, respectively. It should be mentioned in mind that all of the considered samples for simulations and experiments have the same radius $R = 4$ mm and focal length $f = 500$ mm. First of all, the impact of topological charges P_1 and P_2, as well as the shifting parameter on the structure of MTZP are considered. To this end, columns (a) through (c) in Fig. 1 show typical samples of MTZPs constructed with three different values of $(\ell_1 = 2, \ell_2 = 1)$, $(\ell_1 = 3, \ell_2 = 2)$ and $(\ell_1 = 4, \ell_2 = 3)$, respectively. Besides, the value of $\alpha = 0.02$ and 0.005 for the first and second row, respectively. Resultantly, it is clearly evident that the phase of the zone plates are multi-twisted so that the number of the arms equals to $\ell_1 + \ell_2$. FFT-based Fresnel-Kirchhoff integral has been used to numerical calculate the focused intensity pattern of an MTZP [38]

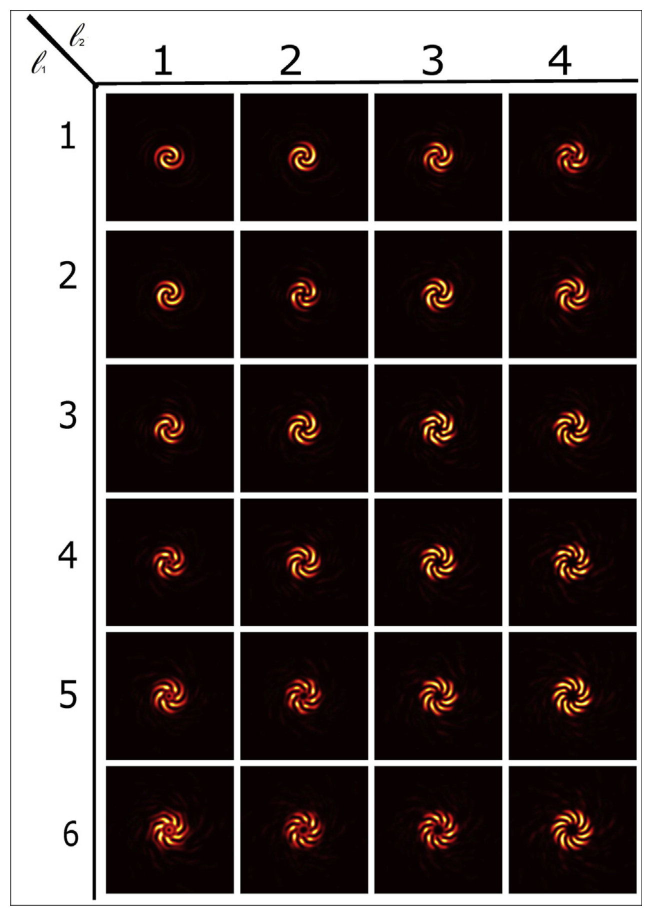

Fig. 2. Focused intensity patterns for typical samples of MTZPs with $\alpha = 0.02$ but different topological charges which are clearly shown in the figure.

$$I(r,z) = \left|FT^{-1}[FT(T)FT(h)]\right|^2, \quad (5)$$