Optik 127 (2016) 5757–5760

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Realization and computational analysis of splitting in higher order optical vortices

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ARTICLE INFO

Article history:
Received 3 February 2016
Accepted 16 March 2016

Keywords:
Computational analysis
Optical vortices
Vortex splitting
Topological charge

ABSTRACT

Control on spacing between splitted topological charges is a matter of concern in optical phenomenon. Splitting of higher order topological charge has been done by the interference with three plane waves at smaller angle than the one which phase engineered beam makes with the axis. Splitting has been realized by introducing additional phase in three plane waves. It is observed that the spacing between splitted topological charges can be controlled by controlling the introduced additional phase in these three plane waves.

1. Introduction

Recently, optical vortices have captured great attention. The optical vortex is an isolated point singularity with a screw dislocation, which was first noticed by Nye and Berry [1]. There are other types of dislocation, such as; edge dislocation and edge-screw dislocation. When two dislocated wave fronts are added, they give a new dislocation. At the point of screw dislocation or optical vortex, the amplitude is null and the phase is indeterminate. Optical vortex wave front has the tendency of helicity which is also a topological charge (positive or negative) of the order of screw dislocation. The phase varies in the form of $2p\pi$ within the wavelength. An array of the optical vortex is called optical vortex lattices.

There are lots of methods to generate the optical vortex; one of the most famous methods is the interference method, where minimum three non-coplanar plane waves with equal amplitude are required. Various optical interferometric setups have been implemented for the generation of optical vortex array. Computer generated hologram method has also been used to generate the light beams containing optical vortex [2]. Other methods, including; dielectric wedge plate [3], spiral phase plate [4], wave front division [5], interference of three, four and five plane waves [6], coupled Wollaston prisms [7] and lateral shearing interferometer [8] have been reported for the generation of optical vortex.

Optical vortex contains orbital angular momentum, which has great deal of interest. Optical vortex plays significant role in the area of optical tweezers [9], by transferring their orbital angular momentum to the micro and nano- particles to rotate them around the propagation axis. Application of optical vortex in singular optics, bio-medical, optical communication, quantum communication and information, optical trapping and optical manipulation of ultra-cold atoms [10–12] have been reported. The singular or optical vortex beam can be defined by $e^{ip\emptyset}$ where $\emptyset$ is the phase of the singular beam and p is the topological charge of optical vortex.

Higher order optical vortices are not stable, as they have tendency to split into unit charge vortices. There are lots of methods

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http://dx.doi.org/10.1016/j.ijleo.2016.03.051
0030-4026/

that have been introduced to split the higher order optical vortices. It has been observed that interference of higher order vortex beam and axially introduced plane waves give the splitted pattern [13]. In the presence of non-singular beam, the higher order vortices of charge p split into the singly charged p number of vortex. This analogy is called unfolding, where p folded pattern change into unfolded. The tilting of SLM during the generation of higher order vortices also lead to asymmetry in the generation of vortices. With larger tilting, the higher order vortices can be separated into unit charge [14]. By using SLM, the superposition of multiple fork holograms gives vortex beam and compensates the vortex splitting [15]. Mamaev et al. reported the splitting of higher order optical vortices into unit charge array, in a media with anisotropic nonlocal nonlinearity [16]. So higher order optical vortex decays into low order or unit charge vortex, but the overall topological charge remains conserved in the lattice [17,18].

We aim to introduce a general method to split the higher order optical vortex into low order. Further, we noticed the tunability of spacing between splitted low order optical vortex by varying the angle between central axis and interfering side beams and by introducing the additional phase in three interfering beams.

2. Results and discussion

In this paper, we have introduced a new method to split the higher order optical vortex into unit charges. In generation of vortices, combinations of axially equidistant non-coplanar side phase engineered plane waves have been used. To split the higher order vortices, we introduced equidistant three plane waves which are at different angle from the axis, than phase engineered planes waves, as shown in Fig. 1. The tips of the wave vectors lie on the projected ring in the transverse Fourier plane. The complex field distribution of three plane waves is given by the Eq. (1).

$$u(r) = A\sum_{i=1}^{3}\exp\left[-i(k_i.r)\right] \tag{1}$$

where, A is amplitude of each wave and k is wave vector. Amplitude is taken as unity. Wave vector of these beams can be defined as:

$$k_i = \left[k\sin\theta_1\cos\emptyset_i,\quad k\sin\theta_1\sin\emptyset_i,\quad k\cos\theta_1\right] \tag{2}$$

where, θ_1 is the angle between beams and z-axis, and $\emptyset_i = 2\pi i/3$.

On the Fourier plane, interference of three plane waves and multiple phase engineered plane waves give unfolded or perturbed pattern, in which p higher order vortices are splitted into p unit

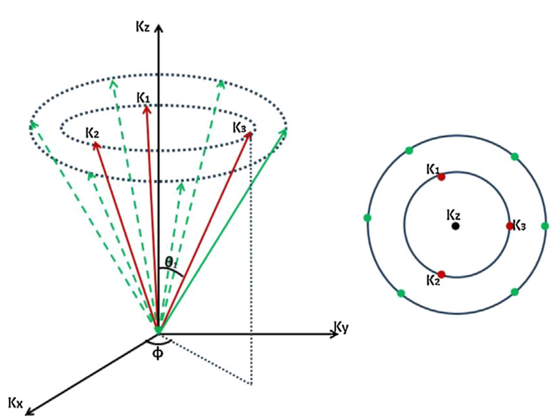

Fig. 1. Schematic representation of interference of three plane waves of wave vectors k_1, k_2, k_3 subtended at angle θ_1 from the central axis and multiple phase engineered plane waves in the Fourier plane $k_x - k_y$..

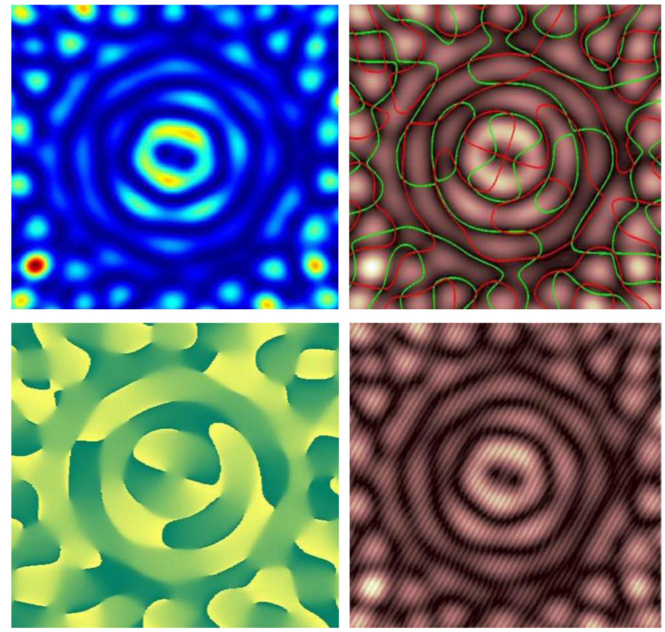

Fig. 2. Splitting of higher order topological charge at the center of optical vortex lattice (a) intensity of splitted vortices, (b) phase representation, (c) detection of vortices by zero crossing plot, and (d) fork pattern of splitted vortices.

charge vortices. In Fig. 2, the splitting of topological charges at the center of vortex lattice has been shown. Zero crossing plot and fork pattern is the signature of the optical vortices as shown in the figure.

The spacing between the topological charges can be tuned by the two ways.

First, by controlling the angle θ_1 between central axis and three plane waves, the spacing between unit charges can be controlled. As the angle increases, the spacing between charges decreases, and the unit charge vortices shift from their previous position, as shown in Fig. 3.

Second way is the interference of phase engineered three plane waves at the angle θ_1 and multiple phase engineered beams at different angle. It can be concluded that if we introduce additional phase γ_i in three plane waves and get interfere with multiple phase engineered beams, splitted topological charges at the centre of lattices are observed. Here the complex field distribution of three plane waves is:

$$u(r) = A\sum_{i=1}^{3}\exp\left[-i(k_i.r+\gamma_i)\right] \tag{3}$$

where, γ_i is the additional phase introduced in three plane waves and

$$\gamma_i = \delta(i-1) \tag{4}$$

where, i will vary from 1 to 3 and δ is angle. If $\delta = 2\pi/3$ then additional phase would be $0, 2\pi/3, 4\pi/3$. When γ decreases, the spacing between splitted topological charge increases. The observed results are shown in Fig. 4. The final complex field distribution of interference at focal plane is given by the following equation:

$$U_f(r) = \left[\sum_{j=1}^{q}\exp(-i(k_j.r+\varepsilon_j))\right] + \left[\sum_{i=1}^{3}\exp\left(-i(k_i.r+\gamma_i)\right)\right] \tag{5}$$

where, q, k_j, and r are the total number of multiple phase engineered waves, wave vector and position vector, respectively. Here amplitude of waves is unity. $\varepsilon_j = 2\pi j/(q/p)$ is additional predetermined phase and p is higher order topological charge.