EXOTIC VORTEX BEAM SHAPES FOR OPTICAL TRAPS
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Abstract: We experimentally demonstrate the generation of vortex traps with different shape and properties. We have done simulation to produce the phase mask for vortex traps. These phase masks are encoded on to the spatial light modulator (SLM). Intensity distribution at the focal plane for these novel optical traps of different shapes and properties are recorded. To increase the diffraction efficiency, the SLM is used in phase modulation mode.

1. INTRODUCTION

Optical beams carrying phase singularities (wavefront dislocations) have attracted much interest in recent years. There exist three types of wavefront dislocations, i.e., the screw dislocation or vortex with spiral phase, the edge dislocation with \( \pi \) phase shift located along the line in the transverse plane, and the mixed screw-edge dislocation [1]. An optical vortex is a spiral phase ramp around a point where phase of the wave is undefined and amplitude is zero. It is described by \( \exp(\text{im}\theta) \) where \( m \) is the topological charge. Optical vortices carry orbital angular momentum which is different from spin angular momentum arising due to polarization.

A vortex beam with the integer topological charge is characterized by a bright ring encircling the dark core generally called as doughnuts mode, where as fractional charge beam possesses a low intensity radial opening corresponding to the phase step in the bright ring. Light beams with nested vortices have wide-spread, far-reaching applications in fields as diverse as the biosciences, laser cooling and trapping, micromechanics and quantum information. The mechanical property of the vortex beam has been extensively used in rotation and manipulation of micro particle and these beams possess some advantages over Gaussian beams [2]. Fractional charge vortices have been used in the atom optics [3], quantum communication [4], where the low intensity gap in the doughnut structure gives extra advantage as compared to the perfect doughnut shape of integer charge vortices. Orbital angular momentum provides mechanical properties to the vortex beam. Optical beams possessing vortex with fractional charge can also be used for optical rotation and manipulation of microscopic particles by the transfer of orbital angular momentum.

Optical vortices can be generated in several different controllable ways for example by spiral phase plates [5], adaptive helical mirror [6], and computer generated holograms (CGH) [7]. The method of CGH is however most commonly used, because it permits precise control of the vortex position, topological charge and provides a possibility of generation of desired pattern of optical vortices.

In recent years array of vortices has generated an increased interest among many research groups. Vortex arrays are used in variety of applications which include multiple trap optical tweezers [8], spatial solitons [9], microfluidic sorting [10], and orbital angular momentum of periodic pattern [11].

Recent advances in the spatial light modulators enable a single laser beam to split into many beams. They are widely used for altering phase profile of laser beam. Arbitrary intensity pattern can be generated using SLM, acting as reconfigurable diffractive optical components. One of the methods to generate optical vortices is by using a phase mask with transmission function \( \exp(\text{im}\theta) \) where \( \theta \) are angular coordinate in the polar coordinate system. Diffraction pattern produced by a monochromatic beam in the focal volume of a lens has been widely studied. It is well known that size and shape of diffraction pattern depends on the property of focusing system.

In this paper we present a simple and effective method of generating exotic vortex beams which offer flexibility of position, number and topological charge of vortices present in the beam that can create new vortex beam traps. The method uses a single optical element to produce multiple vortices with good quality. A vortex beam of integer as well as fractional charge can be produced with it. These exotic beams with different shapes have been generated using vortex lens. For this purpose specially designed phase masks are produced, which are encoded on to the SLM. And intensity distributions at the focal plane for these lenses are recorded. Properties of new vortex beam shapes and their intensity distributions for the case of integer topological charge and fractional charge are discussed.

2. THEORY
Diffractive optics sculpts the propagation of light to generate complex intensity and phase structure. It is achieved by imposing a particular phase or intensity pattern on the incident beam. An SLM in phase modulation mode can imprint a phase term directly on the incident beam. We use computer-generated phase mask designed for this purpose. A plane wave of uniform intensity passing through the phase mask would simply have the phase structure of the desired phase variation. However, in practice the phase mask introduces phase delays over a significantly different range that depends on the SLM characteristics.

The transmission function for a computer generated phase mask for vortex generation is described by the equation as

\[ t(\rho, \theta) = \begin{cases} \exp(im\theta) & \text{for } 0 \leq \rho \leq 1 \\ 0 & \text{otherwise} \end{cases} \]  

(1)

\( \rho \) and \( \theta \) are polar coordinates in the input plane and \( m \) is the topological charge of vortex. A phase mask having this transmittance function transforms incident wave field into helicoidal structure. Presence of Fresnel lens factor in addition to \( e^{im\theta} \) gives desired curvature to the beam and the optical element is referred to as vortex lens [12, 13]. The transmittance function of the vortex lens is given by

\[ t(\rho, \theta) = \exp(im\theta)\exp\left(-\frac{i\pi\rho^2}{\lambda f}\right) \]  

(2)

where, \( f \) is the focal length of the lens and \( \lambda \) is the wavelength of light used. The first term gives the helical shape to the wavefront where as the second term gives the curvature to the wavefront. This specific transmittance imparts an on-axis vortex on the incident optical field. Multiple vortices can be embedded into the wavefront by using expression

\[ \theta = \sum_{i=1}^{N} n_i \theta_i(x_i, y_i) \]  

(3)

where \( n_i \) is the topological charge of \( i^{th} \) vortex and \( \theta_i = \arctan\left(\frac{y - y_i}{x - x_i}\right) \)

The position of \( i^{th} \) vortex in wavefront can be changed by changing \((x_i, y_i)\). The complex amplitude at the focal plane can be evaluated by using the Fresnel-Kirchhoff diffraction integral which can be written, [14] as

\[ E(r, \phi, f) = \frac{1}{\lambda f} \int_{0}^{\infty} \int_{0}^{\pi} E(\rho, \theta, z = 0) \times \exp\left[-\frac{2\pi a}{\lambda f} r \rho \cos(\theta - \phi)\right] \rho d\rho d\theta \]

\[ c_i = \frac{a^2}{i\lambda f} e^{ikf} \exp\left(i\pi r^2 / \lambda f\right) \]  

(4)

where \((\rho, \theta, z)\) and \((r, \phi, f)\) corresponds to object and the diffracted field planes respectively expressed in cylindrical coordinates. The phase factor in the multiplicative factor \( c_i \) does not play any role in intensity and hence can be ignored. The amplitude factor \( \frac{a^2}{i\lambda f} \) in \( c_i \) is only a scale factor and hence is ignored. The field at the focal plane is proportional to the Fourier transform of the transmittance function given in Eq. (2). Intensity distribution at the observation plane is then given by

\[ I(r, \phi, f) = |E(r, \phi, f)|^2 \]  

(5)

Here the intensity distribution refers to the far-field image of a point object. The vortex lens has low numerical aperture as the SLM has finite pixels and so Eq. (4) can be applied to find the field \( E(r, \phi, f) \).

3. EXPERIMENTAL

A phase only SLM can impose an azimuthal phase term directly on the incident beam converting it into a helical beam. But this requires the SLM to possess a precise phase modulation from \( 0 \) to \( 2\pi \). The method of generating optical vortices using phase mask is more versatile because it allows precise control over vortex parameters and the possibility of generating specific patterns of optical vortices. Furthermore a phase mask displayed on the SLM gives the dynamic control over the vortex.
Fig. 1 Experimental arrangement

The experimental arrangement is shown in Fig. 1. Linearly polarized light from a He-Ne laser at \( \lambda = 632.8 \text{ nm} \) is spatially filtered, expanded and collimated to form a plane wave. The collimated beam of light is directed on the SLM (Holoeye LC-2002 with 832X624 of pixels and pixel pitch 32 \( \mu \text{m} \)). Our SLM produces phase shift of \( 1.5 \pi \) at \( \lambda = 532 \text{ nm} \). By using properly oriented linear polarizer or by generating appropriate elliptically polarized light one can modulate, mainly the phase while keeping the amplitude constant. We have used elliptically polarized light to achieve phase only modulation for the SLM by the use of combination of two-polarizers and two quarter wave plates as shown in Fig. 1. This architecture consists of a combination of an input polarizer (P1) and a quarter wave plate (QW1) in front of the SLM and an output quarter wave plate (QW2) and polarizer (P2) behind the SLM. We adjust the polarizers and quarter wave plates such that the SLM modulates phase only and keeping the intensity of light beam constant. A gray scale phase mask corresponding to the transmittance of a lens embedded with an array of vortices is displayed on the and the corresponding intensity distribution is recorded on CCD.

The phase mask for vortex lens that can generate different beam shapes has been made using Virtual lab software. In the phase profile shown in Fig. 2 (a, b) phase is shown on the continues gray scale where white representing a phase of zero and black representing \( 2\pi \).

Fig. 2. Phase mask for vortex lens (a) Four vortices each with \( m=4 \) (b) two vortices each with \( m=4.5 \)

4. RESULTS AND DISCUSSION

Fig. 3. Spatial distribution of intensity at the focal plane (a) corresponding to the phase mask shown in the Fig. 2 (a), (b) corresponding to the phase mask shown in the Fig. 2 (b)

Generally a lens produces a single bright spot at its focal plane but when phase singularity is added into it then it produces a ring instead of the bright spot at the focus. If multiple singularities are presented in the beam then it can produce many intensity nulls in the beam. An arbitrary distribution of the vortices can be produced with this optical element. Multiple vortices can be embedded into the same mask by placing them at different positions. For example we have shown in Fig.2 (a) four vortices with \( m=4 \) which are kept in the square geometry vortices. Bifurcation of the phase contours occurs at the point of singularity. The number of bifurcation depends upon the topological charge of the vortex. This bifurcation produces corresponding dark spots in the intensity profile as shown in Fig. 3 (a). Various combinations and positions of vortices are possible in the beam profile.

Fractional charge is known to produce a radial opening in the doughnut structure of the vortices. Fractional charge vortices are also known as the mixed screw edge dislocation. They produce two types of phase singularity one corresponding to a point (screw dislocation) that produces a intensity null and the other a line singularity (edge dislocation) that produces intensity void in the beam profile. The advantage of mixed edge-screw dislocation is recently reported in the field of quantum communication and atom optics where the orientation of edge-dislocation present in the fractional charge vortices gives extra degree of freedom.

A new type of optical trap is possible when two fractional vortices with alternating sign are kept near as shown in Fig. 2 (b). They produce spatial intensity distribution in which two rings are joined with a narrow opening between them. Intensity distribution in the far field is shown in Fig. 3 (b). In case of the two same fractional charge vortices the ring still joins with the intensity nulls but has doubled shape intensity distribution.

5. CONCLUSION

We have experimentally demonstrated the generation of symmetric structure of optical vortices with different shapes and topological charge using vortex lens. Intensity distributions for different vortex beams are recorded at the focal plane. Since
the phase masks created for vortex lens are computer generated, they offer great flexibility of design and controlled vortex parameter like position in wavefront, topological charge and the focal length. They can produce multiple point and line singularity with different shapes. The method presented here is useful in research areas where good quality multiple hollow beams are required. It can also find applications in areas of laser beam array, optical trapping, atom optics, and in quantum communication.

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REFERENCES