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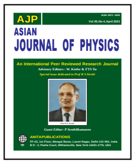

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Vortex beams and their mechanical properties

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This paper is dedicated to Padmashree Prof R S Sirohi

Light beams characterized by orbital angular momentum in the direction of propagation of the beam, often called phase singular or vortex beams, are described. Some of the important methods of generating vortex beams are discussed. We have developed a novel reflective device, an adaptive helical mirror (AHM) that can be used to generate vortex beams of both positive and negative topological charges. Topological charge of the vortex beam can be altered in magnitude and sign simply by varying the excitation voltage. Both computational and interferometric methods of detection of such beams are discussed. We have proposed a new technique of vortex detection based on lateral shear interferometer. Important properties and applications are also covered in the paper.

Keywords: Adaptive helical mirror, Optical vortices, Optical angular momentum. Vortex beams, Phase singularity.

1 Introduction

Electromagnetic radiation carries both energy and momentum [1]. The first observation about mechanical properties of light was made by Kepler who argued that tails of comets are due to the radiation pressure of the light from the sun [2]. The electromagnetic theory of Maxwell allowed the quantification of energy and momentum possessed by the electromagnetic radiation. Based on Maxwell theory, Poynting calculated the momentum and energy flux associated with the EM field. The momentum carried by EM radiation has both linear and angular contributions [3]. Beth experimentally demonstrated that circularly polarized light exert a torque on suspended birefringent wave plate by transfer of angular momentum [4]. A half wave plate transforms a right handed circular polarization to left handed circular polarization resulting in transfer of $2\hbar$ spin angular momentum per photon from light beam to the half wave plate, where $\hbar = h/2\pi$ and h is the Planck's constant. The angular momentum associated with circularly polarized light is due to spin of the individual photons and is called spin angular momentum. Apart from spin angular momentum, light beams also exhibit orbital angular momentum resulting from spatial distribution of light field. A light beam having helical wavefront characterized by azimuthal phase dependence $\exp(l, \theta)$, carry orbital angular momentum $l\hbar$ per photon in the direction of propagation, where l is the topological charge of the light beam [5]. Such a light beam is referred to as phase singular beam or a vortex beam. Besides mechanical properties, such beams also exhibit many other peculiar properties which have been exploited in a wide variety of applications.

In this article, we describe phase structure and other important properties of vortex beams. Various methods to generate these beams are also discussed. We have developed a novel reflective device, an adaptive helical mirror, which allows generation of vortex beam with variable topological charge. Methods of detection of such beams and some of the important applications are also covered in the paper.

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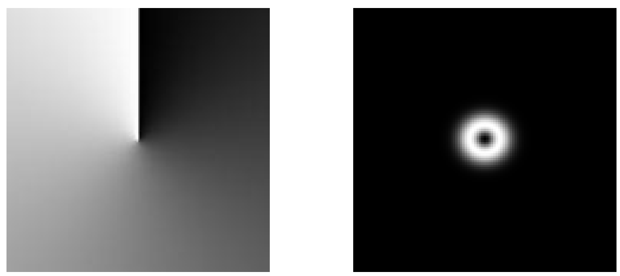
2 Phase singularity

An optical phase singularity also called optical vortex is characterized by azimuthal phase dependence of the form $\exp(il\theta)$, where l is the topological charge of the phase singular beam [6]. The magnitude of topological charge of the vortex field determines total phase, which the wavefront accumulates for one complete rotation around the vortex point. The sign of topological charge determines the direction of phase circulation, clockwise or anticlockwise, of the vortex beam. The phase gradient of the wave field having phase singularity is non-conservative in nature. The line integral of the phase gradient over any closed path surrounding the point of singularity is non zero. i.e., $\oint \nabla\phi . d\xi = 2\pi l$, where $\nabla\phi$ is the phase gradient and $d\xi$ is a line element. At isolated point, where phase singularity occurs, the phase is uncertain and amplitude is zero. Thus, there is an intensity null at the point of singularity. Intensity profile and phase variation of a phase singular beam with topological charge 1 are shown in Fig 1.



(a) (b)

Fig 1. Phase singular beam (a) intensity profile (b) Phase Profile.

The vortex beams can be best described in terms of Laguerre-Gause polynomials and hence these are also known as Laguerre-Gaussian (LG) beams. An important example of such a beam is well known TEM_{01}^{*} doughnut mode of a laser.

3 Properties of optical vortices

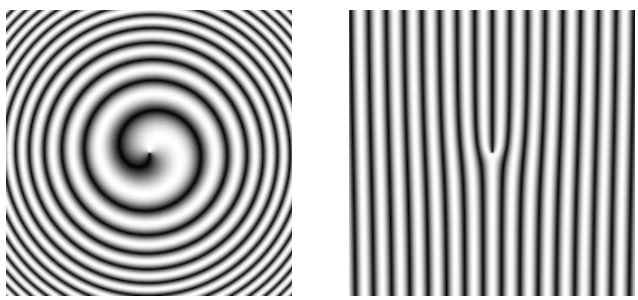
Optical vortices, as morphological objects, are robust with respect to perturbation [7]. For instance, the addition of a small coherent background does not destroy a vortex but only shifts its position to another place, where the field amplitude has a zero value. For vortices with higher topological charges, this operation will convert an optical vortex of topological charge m into m vortices, each having charge 1. It has been established that optical vortices with same topological charge rotate about each other during propagation [8]. Neither the presence nor the position of one vortex affects the propagation dynamics of the other vortex. On the contrary, propagation dynamics of a vortex is affected due to the presence of another vortex of opposite topological charge. Thus, vortices with equal magnitude but opposite polarity of the topological charges do not gyrate around each other but drift away from each other. When wavefronts are allowed to converge or interfere, bipolar vortex pairs are created and annihilated. Vortices with small cores, called vortex filaments exhibit fluid like rotation similar to the vortices in the liquids [9].

4 Generation of vortex beam

Vortex beams can be generated by both intra-cavity and extra-cavity methods. In intra-cavity approach, a TEM_{01}^{*} doughnut mode of laser is created by frequency locking of TEM_{01} and TEM_{10} modes in phase quadrature [10]. Other intra-cavity methods of vortex beam generation involve insertion of a linear or a non linear element inside the laser resonator to have sustained oscillations of LG modes. In the extra-cavity approach, an azimuthal phase profile is imprinted on an otherwise plane or spherical wavefront. Some of the commonly used devices for generation of a vortex beam using this approach include spiral phase plate

(SPP) [11], computer generated hologram (CGH) [12], spatial light modulator [13], mode converter [14], lithographically etched mirror [15] and segmented mirror [16]. Spiral phase plate is an optical element that generates phase singularity by introducing azimuthal dependent phase retardation on the optical field. It is a transparent, circular plate, whose thickness (or thickness of the optical coating) is proportional to azimuthal angle. When the SPP is inserted in the path of a uniform plane wavefront or in the waist region of a Gaussian beam, it results in azimuthal dependent optical phase retardation thereby transforming a plane wavefront to a helical wavefront of vortex beam.

A phase mask or a computer generated hologram (CGH), used for generation of vortex beam, carries an interferogram recorded by interfering a vortex beam and a plane or a spherical beam. Figure 2 depicts fork and spiral type interferograms obtained by interfering a vortex beam with plane and spherical wave, respectively. A vortex beam can be reconstructed by illuminating the CGH with the reference beam. A lithographically etched mirror (LEM) works on the same principle as that of a phase mask or CGH but operates in reflective mode. A mode converter uses a pair of cylindrical lenses for transforming a rectangular symmetric mode often referred to as Hermite Gaussian (HG) mode to its equivalent LG mode. Recently, a new technique for generating and emitting vortex beams from a reconfigurable and scalable silicon photonic chip has been reported [17]. The method may enable large-scale integration of optical vortex emitters on CMOS compatible silicon chips [17]. Ultra-short (femto-sec) optical-vortex pulses in few-cycle regime have been generated by optical parametric amplification [18].



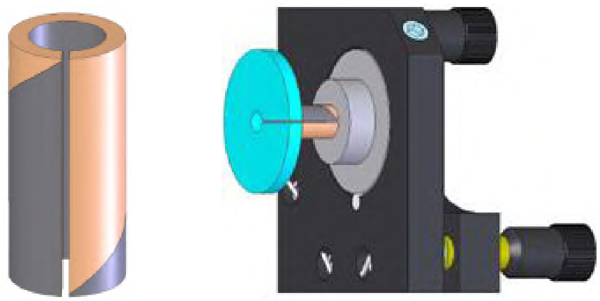
(a) (b)

Fig 2. CGH with (a) Fork (b) spiral type fringes.

5 Adaptive helical mirror

An adaptive helical mirror [19] is a reflective device which can be used to generate a vortex beam with continuous phase variation along azimuthal direction. It is primarily a thin, circular mirror with a narrow hole at its center and a cut along the radius. On the non-reflecting side of the mirror, a hollow piezo-ceramic (PZT) tube is glued in such a way that the inner diameter of the tube aligns exactly with hole in the center of the mirror. The PZT tube has a cut along its length which aligns itself with the slit in the mirrors. The PZT tube is provided with electrodes on its inner and outer surfaces. The length of the outer electrode varies linearly with azimuthal angle, being minimum on one side of the longitudinal cut and maximum on the other side. The PZT tube is poled along the radial direction. The open end of the AHM is glued to a ceramic ring and the whole assembly is held in a XY tilt mount. The CAD model of tubular PZT actuator and mounted AHM is depicted in Fig 3.

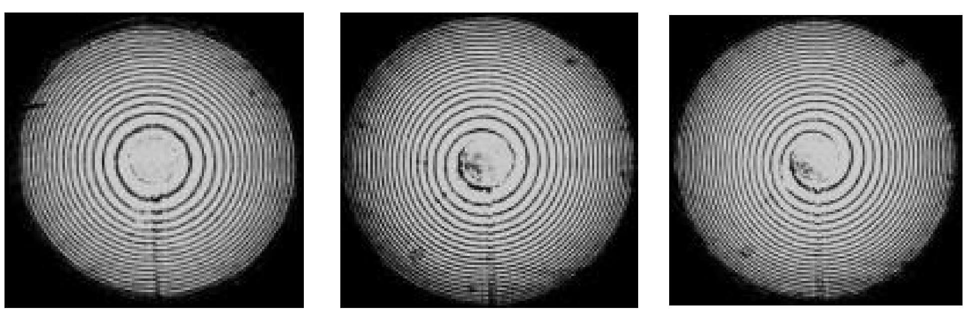
When a voltage is applied between the two electrodes of the PZT tube, its length undergoes expansion or contraction depending upon polarity of applied voltage. Because of helical outer electrode, the effective length of PZT tube and hence expansion/ contraction varies along the azimuthal direction. Therefore, AHM under actuation exhibits out-of-plane displacements that vary along azimuthal direction. The out-of-plane displacements of AHM is maximum on one side of the radial cut and minimum on the other side, such that there is discontinuity or a step height across the radial cut. For a particular value of the excitation voltage, this step height can be made equal to half the wave length of operation i.e. $\lambda/2$ (λ, being wave length of operation). Under this condition, a plane wave after reflection from AHM will accumulate maximum path length variation equal to λ or phase change of 2π. This results in the generation of a vortex beam of topological charge 1. By increasing the excitation voltage, vortex beams of higher topological charges can be generated. For generation of vortex beam of negative topological charge, excitation voltage needs to be reversed in sign.



(a) (b)

Fig 3. CAD model of (a) Tubular piezoelectric actuator (b) Assembled AHM

Generation of vortex beam with the use of adaptive helical mirror can be tested with the help of Michelson interferometer. One arm of the Michelson interferometer carries AHM, while a reference spherical (concave) mirror is placed in the other arm. The light waves reflected from the AHM and the reference spherical mirror are recombined to generate interference pattern. When AHM is not actuated, the plane wave reflected from it, interferes with the reference spherical wavefront to form circular fringes, as shown in Fig 4(a). On actuation, the AHM transforms the plane wave incident on it to a vortex beam. The interference of vortex beam and the spherical wave results in the formation of single or multi-start spiral fringes in the interference pattern. Figures 4(b) and 4(c) depict fringe patterns with single and double start spiral fringes corresponding to optical vortices of charge 1 and 2, respectively.



(a) (b) (c)

Fig 4. AHM test Results (a) Circular fringes when AHM is not actuated; (b-c) Single and double start spiral fringes confirming generation of vortex beam with charge 1 and 2, respectively

6 Vortex detection

Detection of vortices in an optical field is possible using computational or interferometric techniques. The important computational methods include zero crossing method, line integral method and phase contour method [20]. The zero crossing method is based on the fact that wave function of the vortex field comprises of real and imaginary parts, both of which vanish simultaneously at the vortex point. The presence of vortices can be found by locating the intersection of contours of real and imaginary zeroes. In the line integral method, the presence of vortex in an optical field is ascertained by finding the accumulated phase changes around closed path encircling each dark point in the field. The phase contour method is based on the fundamental fact that equi-phase contours, terminate on point of singularity. Intersection of phase contours occurs only when vortices are present. Hence, by drawing phase contours in a complex field, one can infer the presence of vortices.

The interferometric techniques use two-beam interference, in which a vortex beam is made to interfere with a plane or spherical beam resulting in the formation of fork or spiral fringes, respectively [21]. A lateral shear interferometer can also be used for the effective detection of an isolated vortex as well as randomly distributed vortices in a scattered optical field [22]. Lateral shearing is achieved by the use of a thick glass plate. Light reflected from front and back surface of the plate interfere to give interference fringes in region of overlap of two beams. One of the major advantages of this technique is that it eliminates the need of the reference wavefront because the original wavefront interferes with the sheared copy of itself. This reduces the alignment complexities and the technique is insensitive to vibrations.

7 Applications of vortex beams

Orbital angular momentum of vortex beams has been extensively exploited in a wide variety of applications. Unlike conventional traps, vortex beams can trap both low and high index particles [23]. Further, highly reflective (metallic) particles cannot be trapped by normal optical tweezers. Optical traps with vortex beams hold such particles effectively in their annular region, where radiation pressure is small. Another major limitation of conventional particle traps is that the particles are trapped near high intensity focal region of the beam and thus are susceptible to optical damage due to absorptive heating. With phase singular beams, the damage to the trapped particles is minimized due to presence of dark core at the centre of the phase singular beam. Trapping of atoms is useful in laser cooling to obtain nano-scale temperatures. Trapping of micron or nano sized particles is useful in biology for sorting of bio-cells, stacking them and in isolating healthy cells from the cancerous ones. Besides trapping the microscopic particles, phase singular beams can also cause rotation of the trapped particles [24]. The rotation of the trapped particles is due to the partial transfer of angular momentum of vortex beam to the absorptive particles.

Besides maneuvering of atoms and micro-particles, vortex beams find variety of other applications. Spiral interferometry [25], where a spiral phase element is used as a spatial filter, removes the ambiguity between elevation and depression in the optical thickness of a sample. Spatial filtering with a spiral phase element results in interference fringes which are spiral in shape. Sense of rotation of these spirals makes a distinction between elevation or depression in surface height of the object. A vortex beam having a dark core at the centre can be used as a filter for viewing a weak terrestrial object hidden in the background of a bright coherent star [26]. Vortex phase mask can be used for image processing and pattern recognization applications [27]. The entanglement between various spatial modes of phase singular beam has potential applications in data encryption for free space information transfer [28]. The data encrypted using orbital angular momentum states of phase singular beam have been found to offer better security to a communication system [29]. Vortex beams also find applications in quantum computation [30], optical data storage [31] and study of cold atoms [32].

8 Conclusions

Vortex beams characterized by their mechanical properties i.e. orbital angular momentum in the direction of propagation are described. Peculiar phase structure and related properties of the vortex beams are also discussed. Important methods of generating vortex beams including the one devised by us are covered in the article. A special feature of the device developed by us is that the topological charge of the vortex beam can be changed simply by varying the excitation voltage given to the device. Methods of detection of vortex beams / fields are also described. We have developed a novel technique of vortex detection which is simple, rugged and insensitive to vibrations. Important applications of vortex beams are also discussed.

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