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# Computational analysis of higher order optical vortex

P. Upadhaya [a], D. Prakash [b,*]

[a] Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
[b] School of Computer Science & Engineering, SMVD University, Kakryal, Katra 182320, J&K, India

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ABSTRACT

This paper presents computational analysis on higher order optical vortex lattices. Tunability of higher order topological charge can be done by tuning the predetermined phase of phase engineered beams. Simultaneously we report the symmetrical annular intensity profile around the higher order topological charge. It is also presented that generated topological rings around the higher order topological charge used in trapping of low index particle varies with topological charge at the center of vortex lattice. Laguerre–Gaussian modes are also defined using the interference method.



## 1. Introduction

From the last two decade the optical phenomena related to dislocations of wave fronts has a great interest of research. The phenomena of dislocation has been noticed by Nye and Berry [1]. Wavefront is a surface of constant phase which can contain dislocation. When two dislocated wave fronts are added, both wave fronts try to cancel the dislocation of each other's and new dislocation is created. The waves containing dislocation need not be plane [1]. Wavefront dislocation exists in 2D. There are edge dislocations, screw and edge-screw dislocations exist. A screw dislocation wave front has tendency of helicity $p$ which is topological charge or it is also known as order of dislocation. The phase between two topological charges varies from 0 to $2\pi$ and within a wavelength it varies as $2p\pi$ where $p$ can be positive or negative. On the axis of screw dislocation, amplitude of wave is zero and phase is indeterminate, it is called phase singularity or optical vortex which carries orbital angular momentum. In this paper we have represented higher order screw dislocation, it is interference of several first order screw dislocation. After introducing the plane wave we get changed form of screw dislocation of charge $p$ and splitted into $p$ first order screw dislocation [2]. $TEM_{01}$ mode with the shape of doughnut is known as first order screw dislocation. The first order screw dislocation can be found in scattered laser light by the diffuser, it shows complex structure as speckle pattern [3].

## 2. Related work

An optical vortex is a point phase defect at which amplitude is null and phase is indeterminate. It is also called Phase singularity and array of optical vortices is known as optical vortex lattices [1]. There are lots of methods defined by which light beams containing Optical vortex can be generated. The most common methods which used for generating OVs with computer generated hologram [4], spiral phase plate [5] and dielectric wedge [6]. One of most famous method of generation of optical vortex is interference of three and multiple plane waves. Various interferometric configurations have been used for generating optical vortex lattices such as Multiple Michelson and Machzender interferometer [7]. The interference fields play an important role in the various branches of optics. These interference fields can be recorded to make hologram and photonic lattices. To generate the optical vortex, the minimum three homogenous plane waves are required which should be non-coplanar and amplitude of each wave should be equal [8,9]. 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. An optical vortex possesses the property of orbital angular momentum $p\hbar$, where $\hbar$ is Planck's constant h divided by $2\pi$ [10]. As the topological charge $p$ increases, orbital angular momentum is also increased. Not only Laguerre–Gaussian beam (LG) but Bessel beam and Mathieu beam are also the example of containing orbital angular momentum. Application of Optical vortex lattices has been reported in various fields such as holographic optical tweezers, transferring their angular momentum to micro-particle or nanoparticle to spin them around axis of beam in the field of biomedical, optical communication and quantum communication and information, optical trapping and optical manipulation of ultra cold atoms

* Corresponding author. Tel.: +91 9760997092.
*E-mail address:* dp.prfl@gmail.com (D. Prakash).

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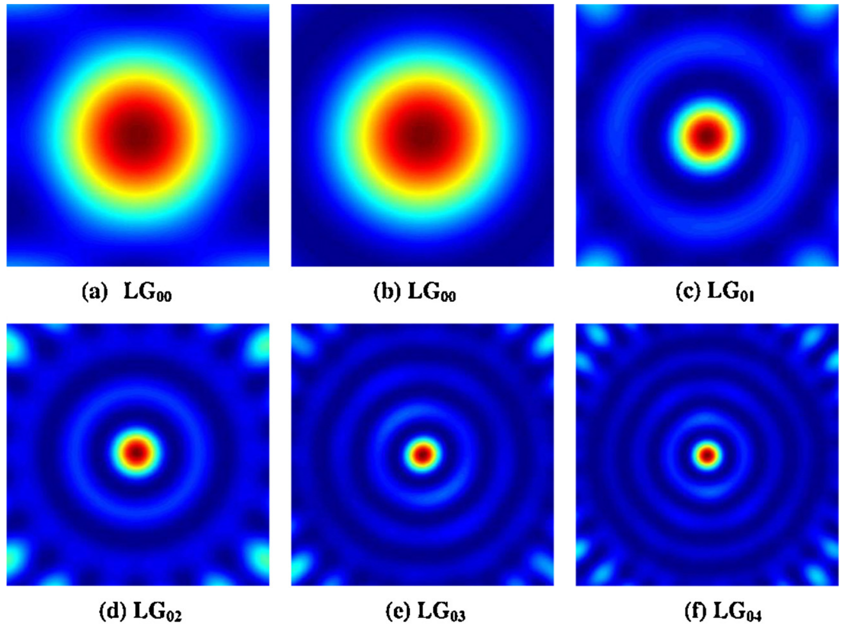


**Fig. 1.** Computational analysis of Laguerre–Gaussian modes.

[11,12]. Optical vortex is very important for free space communication as shown in Influence of topological charges on random wandering of optical vortex propagating through turbulent atmosphere [13]. The optical vortex can be transmitted over significant distance in the presence of atmospheric turbulence and there is no loss in signal. It is well known that Laguerre beam carries orbital angular momentum which is used in free space communication. They used $LG_{0P}$ modes in analysis for communication where $p = 1$, 5, 10, 15.

A large number of methods have been noticed for generation of optical vortex but recently some methods have been reported to generate higher order topological charges. Using asymmetric pinhole plate we can produce higher order optical vortex with plane waves and wave vector's tips lie in a spiral [14]. For generation of 3D vortex lattices containing higher order topological charge at the center, three and multiple of three phase engineered plane waves are used. Phase engineered plane waves can be defined as predetermined phase has introduced in each and every plane wave [15]. This higher order topological charge generated at the center of vortex lattice has been defined by the phasor approach and all phasors must be form a closed polygon to ensure complete cancelation of the complex amplitude at the position of vortex [16]. Zhenhua Li et al. introduced a method by using six pinholes interferometer to generate second order optical array [17]. They used two set of concentric and symmetric three pinhole interferometer with different radial distances and pinhole distributed at an angle $\pi/3$. It realizes the topological charge 2.

In this paper we reported the tunability of higher order topological charge at the center of optical vortex lattices which is generated by the multiple of three and non-multiple of three phase engineered plane waves. It is also found that interference of plane waves gererate Laguerre–Gaussian modes.

## 3. Critical analysis

### 3.1. Laguerre–Gaussian modes

Laguerre–Gaussian modes or beam has widely used in optical micro-manipulation. Circularly symmetric Laguerre–Gaussian modes form a complete orthonormal basis set for paraxial light beams. A LG mode is defined by the $LG_{pl}$, where $l$ stands for radial modes and $p$ stands for azimuthal index which is referred as topological charge of optical vortex. The azimuthal term of LG mode is $e^{ip\emptyset}$. There are several methods to generate LG modes. A well known method is interference of plane waves. Currently programmable spatial light modulator are widely used in generation of LG beam which is an array of liquid crystal droplets. The orbital angular momentum of this light field of helical wave front leads to a Poynting vector. Because of rotation tendency the torque acts on the body. There are two ways to produce torque one is spin angular momentum mechanism and other is orbital angular momentum mechanism. The orbital angular momentum of light is useful in micro-manipulation. Studies have reported that interference of non-coplanar plane waves give LG modes which contain orbital angular momentum [12].

**Table 1**
LG modes by interference of plane waves.

| Number of interfering plane waves | LG modes |
|---|---|
| 3 or 5 | $LG_{00}$ |
| 7 | $LG_{01}$ |
| 9 | $LG_{02}$ |
| 13 | $LG_{03}$ |
| 15 | $LG_{04}$ |

$$I(r) = \sum_{i=1}^{q} \left|E_i\right|^2 + \sum_{i=1}^{q} \sum_{\substack{j=1 \\ j \neq i}}^{q} E_i E_j^{*} \exp[ik_{ij}.r]$$

In Fig. 1 Laguerre–Gaussian modes $LG_{00}$, $LG_{01}$, $LG_{02}$, $LG_{03}$ and $LG_{04}$ are obtained by the interference of 5, 7, 9, 13 and 15 plane waves, respectively. It is observed that by the interference of plane waves we got $LG_{0l}$ modes only. If predetermined phase is introduced in each plane wave then we get higher order LG modes as shown in Table 1.