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Optical aberrations and vector beams as a tool for hollow structured light generation

Miroslav Sulc[1,2*], *Jean-Christophe* Gayde[3], and *Krystof* Polak[1,3]

[1]Technical University of Liberec, 46117 Liberec, Czech Republic
[2]Institute of Plasma Physics of the Czech Academy of Sciences, 182 00 Prague 8, Czech Republic
[3]CERN – European Organization for Nuclear Research, 1211 Geneva 23, Switzerland

Abstract. A method for the generation of structured laser beams (SLB) and hollow structured laser beams (HSLB) whose transverse profiles are invariant and can propagate to infinity is described. SLBs are formed after passing through an optical system that generates a special wavefront as a combination of rotationally symmetric optical aberrations. Transverse profile consists of concentric circles with a very bright central core and a bounding outer-ring. The divergence of the central core 0.01 mrad has been experimentally confirmed. When the system was illuminated with a special vector beam, a hollow SLB (HSLB) beam was generated. Its central part is very narrow and completely dark. Unlike conventional hollow beams, where the electric field is zero in the dark areas, an electromagnetic field with the zero Poynting vector is present in this part of the beam. By varying the illumination parameters of the vector beam, it is possible to obtain situations where there is a longitudinal component of the electric field or/and magnetic field in the central core. The simulation results are in good agreement with the SLB profile measurements using a polarization camera.

1 Introduction

Structured light has opened up a new field of both basic research and various technological applications. Due to the large number of degrees of freedom, such as amplitude, phase, polarization, frequency, and time waveform, the spatial structure of electromagnetic wave is now gaining significant attention. By tailoring the spatial and spatiotemporal structures of light waves, various special light beams can be generated, including Bessel beams, vector beams, Airy beams, helically phased beams, and spatiotemporal beams [1,2]. These structured light beams have become a key area of research, with applications in optical communications, sensing, micromanipulation, quantum information processing, and super-resolution imaging [3,4]. In recent years, the need for structured light beams with distinct spatial and spatiotemporal structures has increased, driving advancements in the generation and detection of such beams by different ways.

A number of different methods have been used to generate structured light including axicons, computer-generated holography, diffractive optical elements, and spatial light modulators [5]. Despite the success of traditional methods for generating structured light, challenges remain in maintaining beam integrity over long distances [6,7].

In this paper, we propose a novel approach utilizing optical aberrations to create Structured Laser Beams (SLBs) that exhibit enhanced long-distance propagation capabilities [8] while preserving the desired intensity pattern. By intentionally exploiting aberrations, we demonstrate the potential of this new method through experimental results, simulations, and theoretical analysis. Our findings suggest that optical aberrations hold promise for advancing structured light generation and expanding its potential applications.

Additionally, we explore the transformation of vector beams into hollow structured beams using optical system with aberrations. This type of Hollow Structured Laser Beams (HSLB), in contrast to hollow gaussian beams, has a generally non-zero amplitude of electric or magnetic field in the dark region. As the electric or magnetic fields here have only a longitudinal polarization component, the Poynting vector is zero at this point.

2 SLB generated by optical aberrations

Through theoretical analysis and a series of simulations and experiments, it has been shown that it is possible to create an SLB by exploiting combination of defocus aberration and primary or higher-order spherical aberrations made by an optical system. Such a wave has a wavefront similar to a "Mexican hat". As it propagates, this wave interpenetrates, creating a new wavefront in which different locations are characterized by different polarization distributions (in the same way as in the case of an infinite axicon, for which a conical wavefront creates a planar wavefront). Electric and magnetic fields at different locations oscillate along different ellipses, whose ellipticity, orientation, and initial phase generally depend on position.

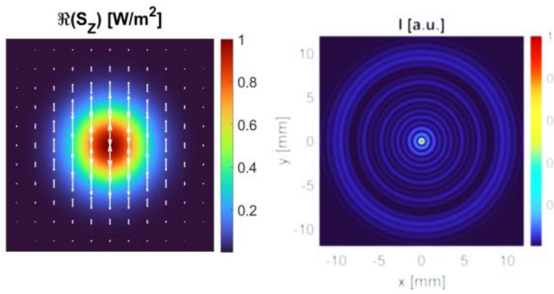

Fig. 1. Left) The input Gaussian beam cross-section with linear polarization. Right) The output SLB (after passing through the generator system) with very bright centre and characteristic outer-ring.

* Corresponding author: miroslav.sulc@tul.cz

This combination of aberrations can be achieved using a set of optical lenses, with at least one lens displaying huge spherical aberration. By adjusting the positions of the lenses, the defocus aberration can be fine-tuned to expand or contract the outer ring of the resulting beam. We commonly utilize ball lenses with a refractive index close to 2.0 in conjunction with conventional converging lenses having a focal length of 25 mm to create this unique beam profile, as shown in the simulation in Fig. 1. The resulting beam displays an outer ring distinct from a Bessel beam, with a small amount of light propagating outside of this ring. The central part of the SLB has a very small divergence 0.01 mrad, as it has been confirmed by experiments.

3 Hollow SLB

In the SLBs described above, opposite parts of the wave with the same phase meet at the beam axis, due to the rotational symmetry of the aberrations. Therefore, the central part is very bright. If we illuminate the generator with a vector beam having, for example, a radial polarization, opposite parts of the wave with a phase shift π meet there. The central core will be dark, and very narrow, see Fig.2. However, there is a continuously distributed wave inside, with a non-zero amplitude electric field and a longitudinal polarization component.

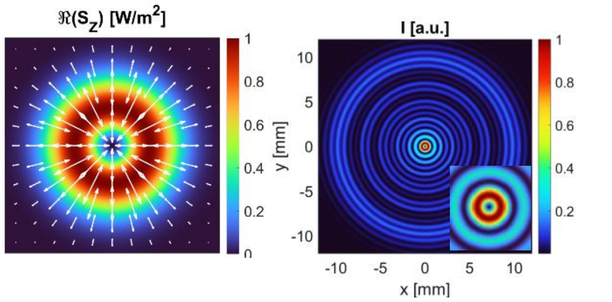

Fig. 2. Left) The input vector beam cross-section with radial polarization. Right) The output HSLB (after passing through the generator system) characterised by a narrow dark centre and typical outer-ring.

If the generator is illuminated at the input of the optical system by a beam with azimuthal polarization, there will be a zero electric field and a non-zero longitudinal magnetic field at the central core. The resulting hollow SLB differs by a non-zero field amplitude in the central core from the input vector beams, which have a singularity in the center and therefore a zero electromagnetic field. In the case of illumination of the HSLB generation optical system with an incoming vortex beam with general spiral polarization, there may be longitudinal parallel electric and magnetic fields in the central core of the HSLB, in phase or opposite phase, see Fig. 3. In the circles where the light intensity is high, the transverse components of the electromagnetic wave are dominant. In addition, the phases in even and odd circles are shifted by π from each other for both HSLBs and SLBs. This has been demonstrated by creating interferences between structured beams and plane wave. The distribution of the light intensity and transverse polarization components in the beam cross-sections was experimentally verified using a polarization camera. Measurements were also performed at distances greater than 100 m. A very accurate agreement was obtained.

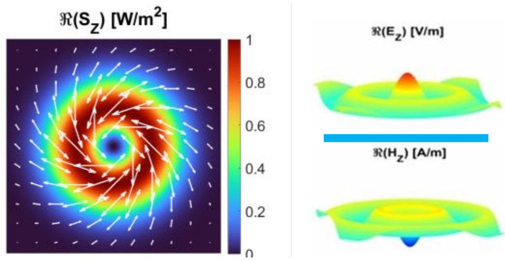

Fig. 3. Left) The intensity cross-section of input vector beam with spiral polarization. Right) The output HSLB (after passing through the generator system), cross-section of both electric and magnetic fields around central dark part, longitudinal components of fields are anti-parallel.

4 Conclusion

A number of other similar results were also obtained for input vector beams created by using s-plates with ½ charge, Poincaré beams, and vortex beams with different topological charges. The combination of the use of optical systems with large optical aberrations, and optical system illumination by different vector and vortex beams, allows the creation of very interesting structured light beams such as the SLBs and HSLBs which can propagate to infinity with an invariant profile and a small divergence of the central core.

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