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Low Divergence Structured Beam In View Of Precise Long-Range Alignment

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Abstract. A new method of generation of a Structured Laser Beam (SLB) with non-diverging central core was proposed and is promising for creating long distance multipoint alignment systems. This beam is generated by a set-up consisting of two convex lenses in Kepler telescope arrangement. The first one is a high refractive index ball lens, second one is a standard lens. The beam, in cross-section consisting of light and dark concentric circles, propagates over a large distance. The central core of the SLB has a very small divergence which can be tuned. A divergence of 10 µrad was proven experimentally. In this experiment, the small initial beam core diameter of 10 µm, and its diameter of 1.5 mm at a distance of 150 m, show its ability for use as a multipoint fiducial reference line. This small beam divergence seemingly lies beyond the diffraction limit for laser beams.

1 Introduction

The use of very well collimated laser beams to alignment is a common and precise part of many optical methods in metrology. Efforts to obtain very precise data on the position of objects have recently attracted interest in the use of so-called quasi-Bessel beams. These beams are often made up by different kinds of axicons, also used together with other optical elements. A characteristic feature of such beams is their structure, which is manifested in the cross-section of the beam by a symmetric distribution of light intensity, well approximated by the Bessel function. The central bright core of the beam is surrounded by a set of dark and light circles. Since the visibility of such circles is close to one and the diameter of the centre can be very small and comparable to the wavelength of light, it is possible to determine the position of the beam centre with significantly higher accuracy than is the case for laser beams with a Gaussian intensity distribution.
Such laser beams have been used as a fiducial line for high precision alignment system [1]–[3]. A limiting factor for the use of such beams in long-range meteorology is that their length does not exceed 20 m under standard conditions.
An almost nondivergent light beam that propagates across a long range with a narrow beam width was generated by a Galilean transmitting telescope with an eyepiece that has a spherical aberration [4]. The beam width was narrower than that of the diffraction limit of normal optics [5]. Additionally, the presented experimental results showed that such a type of beam can be much less influenced by atmospheric turbulence than laser Gaussian beams [6].
Discussions are underway at CERN, the European Organization for Nuclear Research, to build a new high-energy accelerator. During the first analysis of the requirements for a number of its properties, it became clear that the magnets and detectors must be prealigned with an accuracy at one sigma level which is typically of 10 - 100 µm along 200 m long sliding window section. Theoretical analysis and practical experiments showed that it is very difficult to create a reference line by conventional Gaussian beam on which multiple point positions can be measured at different distances with such an accuracy.
A new way of generating long-distance structured laser beams (SLB) with a transverse intensity profile, partly similar to quasi-Bessel beams, has been proposed [7]. It can be efficiently used for a development of long-distance alignment systems for accelerators and other applications. These types of SLB are under study and the beam propagation was already tested in the range from some centimetres up to a distance of 150 meters showing promising results. It would be a precise and elegant optical alternative to the currently used WPS and HLS alignment systems based on stretched wire and hydrostatic levels measured by capacitive sensors.

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2 Generation of Structured laser beam

In the search for the optimal method of generation of non-divergent optical beams for alignment, we have drawn on our experience with Bessel beams formed by axicon. These beams have a conical wavefront shape in the initial phase. The rays from the beam (perpendicular to the wavefront) form a Bessel beams by superposition of rays from opposite parts of the wavefront. If they intersect at points where the phase is the same, they form light rings, and in the opposite phase they form dark rings. The larger the angle between the rays, the narrower (but also shorter) the central part of the beam is.

The disadvantage of the limited range of the beam from the axicon can be overcome by using a different shape of the primary wavefront, where the beams from different opposite parts of the wavefront would meet at successively increasing distances. They could propagate to infinity for rays from parallel parts of the wavefront. The simplest form of such a wavefront is a wavefront with a spherical abberation and a defocus. This type of distorted concave spherical wave was generated by a Galilean transmitting telescope with an eyepiece concave lens with spherical aberration [4].

We designed and tested a different set-up. This new type of generator is similar to a Kepler telescope with both convex lenses. The input lens of the structured light generator is a 10 mm sphere with a high refractive index of 1.9938 for 632 nm. Second lens was standard lens with focal length 25 mm and 1 inch aperture. The system has strong spherical and defocus aberrations, see Fig.1.

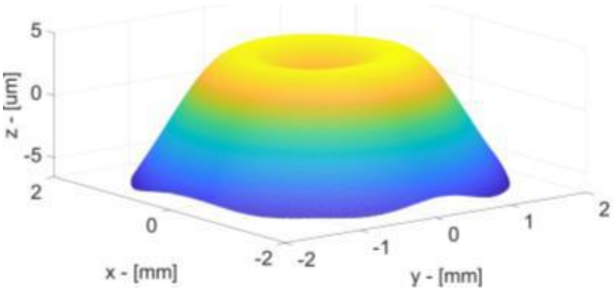

Fig. 1. Measured shape of the wavefront of the SLB, combined spherical and defocus aberrations

The beam generated in this arrangement, unlike the Bessel beam, has a distinct outer ring see Fig.2. Small amount of the light propagates outside this ring too. By changing the relative position of the lenses, the defocus aberration is changed and the outer beam can expand more or less. As it expands, the central core of the beam narrows to a certain limit. The central core of the beam remains very narrow and its diameter increases linearly with distance from approximately 10 μm at a distance of 2 m from the generator to 1.5 mm at a distance of 150 m. The core of the beam therefore has a significantly smaller divergence than that of a Gaussian beam. If we consider only the divergence of the beam core, we would be several orders of magnitude beyond the diffraction limit for light propagation.

The significant optical aberrations shown in Fig. 1 can be achieved with optical elements other than those described here as examples. Thus, beam parameters such as the divergence of the outer ring, the relative intensity of the light and dark rings, relative distances of both light and dark rings, and the diameter of the central core can be well varied. A number of simulations and experiments have been performed to optimize the beam for the specified requirements.

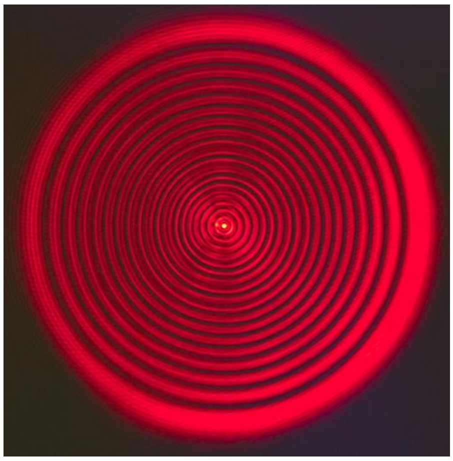

Fig. 2. Typical intensity distribution at transverse cross-section of SLB measured at 5 m from the SLB generator. Diameter of outer ring is 12.6 mm.

3 Conclusions

A new method of generation of pseudo-non-diverging structured laser beams is described in this paper. These beams can propagate with a very low divergence of the central core, which is an order of magnitude lower than the divergence of classical Gaussian laser beams. These beams are foreseen to be used as reference for very precise alignment and positioning of optical elements, or objects such as physics detectors, particle accelerator parts, etc. It would be a precise and elegant optical alternative to the currently used WPS and HLS alignment systems based on stretched wire and hydrostatic levels measured by capacitive sensors.

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