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Spinning optical drills by dynamic high-order Bessel beam mixing

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ABSTRACT

Structured light is one of the frontiers of modern photonics. It refers to the generation of customized optical fields based on wave-front shaping methods. It is a topic of intense research activity due to the wide range of applications in imaging, nonlinear optics, biophotonics [1]. We propose, theoretically explore, and experimentally demonstrate "optical drill" beams presenting nonstationary intensity distributions that resemble the spinning mechanical drill. Optical drills appear as the spatiotemporal interference of two Bessel-vortex beams of different topological charges and different carrier frequencies. By mixing a pair of high-order Bessel beams, synthesized using a liquid crystal spatial light modulator, optical drills of tuned helicities were experimentally observed, and the simplest cases of light matter interaction (fluorescence) with such beams were demonstrated. The rotation in time was achieved by changing the offset of the hologram on the spatial light modulator. Optical drill beams could open new and revolutionary perspectives in dynamical material processing by light or in cell and particle manipulation in biomedical applications.

Keywords: Spatial light modulators, Bessel beams, helical beams, beam interference

1. INTRODUCTION

In 1987, Durnin introduced a novel class of exact solutions of the free space scalar Helmholtz equation, which is known as the zero-order Bessel beam. This type of beam has many unique characteristics, like non-diffraction and self-reconstruction [2]. High-order Bessel beams also have these characteristics as well as helical phases and orbital angular momentum (OAM). Due to these interesting properties and their potential use in various research areas, extensive research has been developed around Bessel beams. Such is the case of the superposition of higher-order Bessel beams. Superposition of Bessel beams with different helicities can lead to nontrivial interference patterns that can be further used in a wide range of applications such as optical tweezers and material processing. An example of superposition of higher-order BB is the so-called optical drills [3].

Higher-order Bessel beams can be formed by circular slits, conical lenses (axicons) [4], in addition to a spiral phase plates [5–7], or equivalently by the phase transmission masks [8–10] (holograms). Note these mechanisms have been demonstrated in acoustics, where curved surfaces can be also used [11,12]. If the phase mask contains a phase slip i.e., a phase change jump, dislocation of 2π, then the generated Bessel beam is helical. Phase mask in the simplest case reads: $\varphi=(\alpha_1 r)/\lambda+m_1\theta$, here α_1 is the radial phase slope, and $m_1=\pm 1\pm,2,\pm 3\ldots$ is the topological charge or helicity. If the topological charges of two Bessel beams are different by $|m_1-m_2|=1$ then the result is a single helix of the intensity pattern. Generally, the m-helical beam is obtained with $m=|m_1-m_2|$ (for instance, the corkscrew is a single helix, and DNA or typical mechanical drill is double-helix), by changing the signs of the topological charges the handedness (clockwise or counter-clockwise) of the intensity profile changes. Higher-order Bessel beams, in comparison with the zeroth-order beams, have helical phases and contain orbital angular momentum (OAM). OAM can provide phase gradient forces to guide and transport microscopic particles. High-order Bessel beams have been used to mechanically transfer their OAM to trapped particles in optical tweezers [13], they can also be used for information encoding/decoding in optical communications [14]. Moreover,

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because these types of beams carry OAM and at the same time are non-diffracting, they are widely used in industry for transparent material micro-processing purposes (cutting, drilling, etc.) [15].

2. METHOD AND RESULTS

2.1 Formation of the optical drill

Because most lasers that come out of the box are of a Gaussian shape, we have to find the correct spatial modifications to transform the beam into the wanted shape. The initial Gaussian beams phase front is modified by a single hologram comprised of two parts. The first part of the phase describes the axicon, while the second part describes the slip phase plate with the topological charge m. The intensity windings occur due to the interference of two constituent Bessel beams with different longitudinal propagation wavenumbers in their overlap area [Figure 1. a, b]. The period of winding is equal to the period the interference pattern is $d_{||} = 2\pi/(k_{1,||} - k_{2,||})$. The longitudinal wavevector components of Bessel beams depend on their ramp or cone angle. The axial overlap area extends from the distance the outer part starts to overlap the inner and reads explicitly $D_{||} = r_1(1/\alpha_1 - 1/\alpha_2)$.

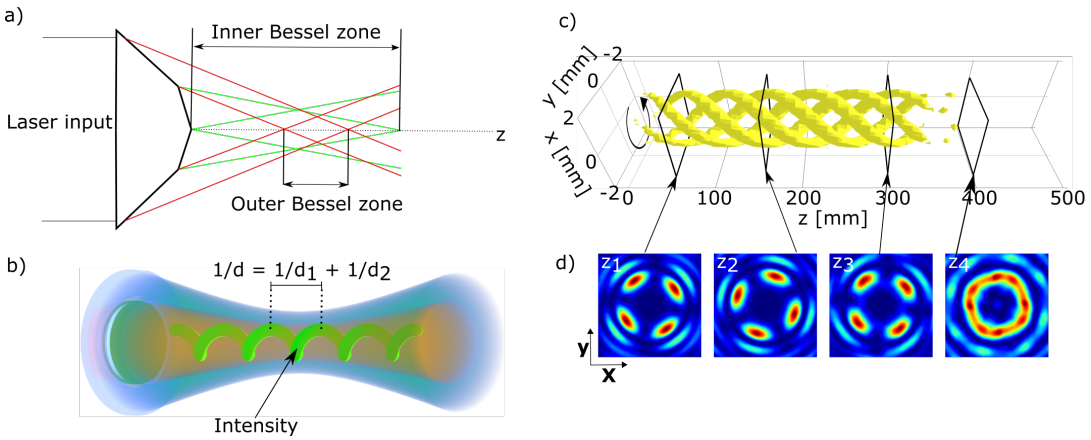


Figure 1. The principal scheme of generating optical drills with a single composite element. a) Schematic demonstration of the overlap of two Bessel regions in which interference occurs. The overlap is made possible by a composite element with two different axicon angles. b) 3D illustration of the formed intensity spiral with the corresponding winding pitch. c) 3D iso-surface model of the interference of two Bessel-Gauss beams creating the spiral intensity structure - optical drill, 4-arm optical drill formed by two Bessel-Gauss beams of topological charges 4 and 8. d) Simulated x-y cross-section intensity distributions at different planes.

2.2 Experimental generation

To experimentally generate such a beam a Liquid Crystal Spatial Light Modulator (SLM) was used [Figure 2.]. The entire beam was generated by a single hologram comprised of two parts. Each part generates one of the two interfering Bessel beams. In addition, the hologram has a diffraction grating added to separate the zero-diffraction order from the wanted Bessel structures. Of course, such a method has drawbacks, as the length of the drill is determined not only by the initial beam size but also by the central parts size, and you must tune the energies of each of the Bessel in proportion to the incoming Gaussian beam to not have a dominant Bessel beam, that still creates a visible ring. Because the SLM is a dynamical element, we can induce rotation of the entire beam in time. In doing so, the apparent forward and backward motion of the entire structure appears. In the present work, a 4f telescope was chosen since it proved to generate a better image of the optical drills. The lenses had different focal distances: $f1 = 150mm$ and $f2 = 30mm$, and therefore the magnification factor is $M = f2/f1 = 1/3$. Between the lenses, right at the Fourier plane, a low pass filter was positioned to select only the zeroth-diffraction order. Finally, a screen is positioned at the focal distance of the second lens. The

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screen is a WinCamD DataRay CCD camera with a 4.4μm pixel pitch and was positioned in a motorized stage to have better control of the visualization plane position.

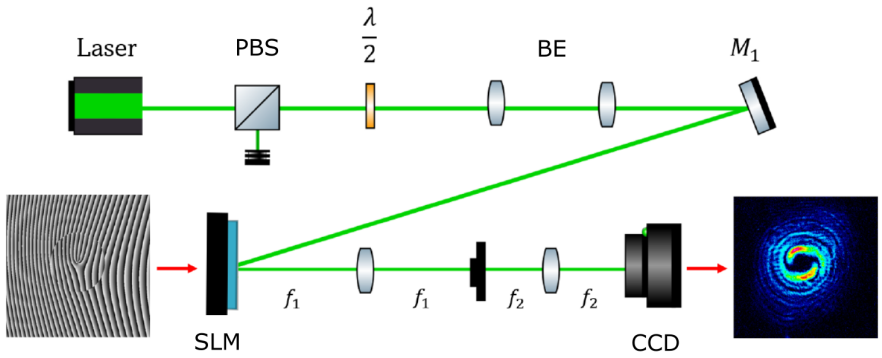


Figure 2. Experimental optical scheme for generating and measuring the optical drill. The initial beam has to be set up for the SLM by filtering the correct linear polarization, expanding the beam to get the most use of the SLM screen. A subsequent spatial filter is used to remove all other orders and the beam is registered by a CCD.

By changing the topological charge difference between the interfering Bessel-Gauss beams, the resultant interference pattern has the number of windings equal to the topological charge difference. Also, because each of the Higher-order Bessel propagates as rings with ever larger diameters, the interference occurs at ever greater radial distances [Figure 3.].

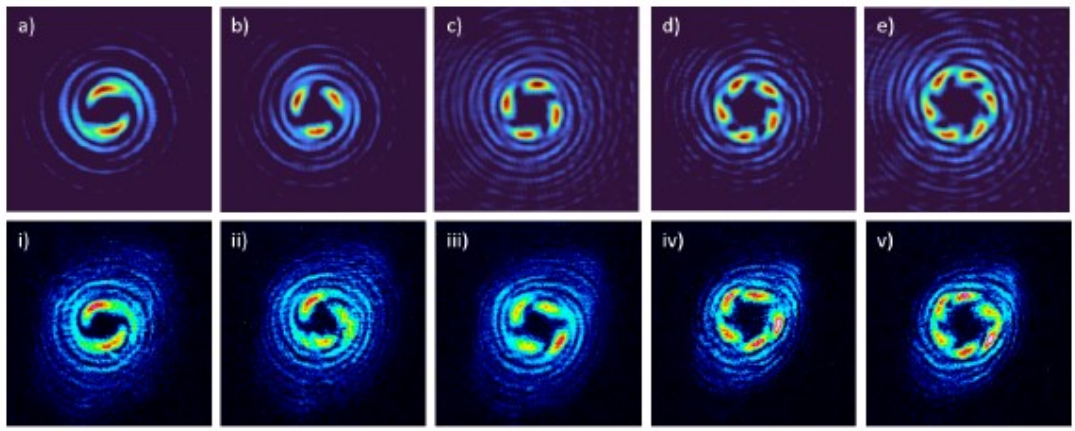


Figure 3. Comparison between the numerical simulation (top row) and the experimental results (bottom row) of the transverse intensity distribution of two interfered High-order Bessel beams. The inner beam has a constant topological charge of $m2 = 4$ while the outer beam changes from $m_2 = 6$ to $m_2 = 10$. The number of helices in the resulting beam corresponds to the difference between the topological charges of the inner and outer beams.

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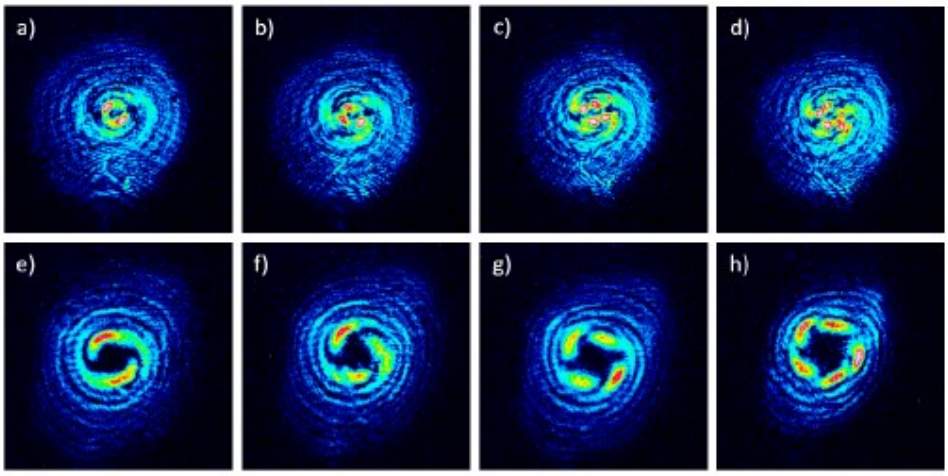


Figure 4. Experimental results for the superposition of higher-order Bessel Beams with different topological charges and axicon angles. The top row has half the axicon angle used in the bottom column.

This result shows that by decreasing the axicon angle is possible to decrease the diameter of the optical drills. Nevertheless, the helices seen in the top row are not as well defined as the ones shown at the bottom since there is a considerable amount of diffracted light around them. In [Figure 4. a-c], the helices are still distinguishable, but for d) the 5 helices have lost their symmetry and are almost overlapping.

3. CONCLUSIONS

Structured beams with rotating helical intensity distribution emerge as the spatiotemporal interference of high-order Bessel beams with different axicon angles, different topological charges, and different carrier frequencies. The principle of generating such beams by using a single dynamic optical element has been explained. The parameters of the optical drills, i.e., their length, radius, winding period, and the order of helical structure, have been shown to be highly tunable. While the rotation of the SLM hologram is sufficient to demonstrate the principle, the rotation frequency must be strongly increased for technologically relevant applications. Optical drill beams could open new and revolutionary perspectives in dynamical material processing by light or in cell and particle manipulation in biomedical applications. Further work must be done to explore the achievable feature sizes of the optical drills. Moreover, improvements can be made to the setup to increase the quality of the beams, this includes changing the SLM used in the present work with higher resolution SLM, or their generation with other types of modulators.

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