Nondiffractive polarization feature of optical vortices

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Optical vortices have been extensively researched in recent years for applications in optical manipulation, orbital angular momentum, optical mode multiplexing, and quantum information.[1] When the polarizations (spin angular momentum) encounter the phase singularity (orbital angular momentum) of an optical vortex, spin-orbit interaction occurs, leading to the discovery of even more fascinating features such as optical skyrmions[2] and polarization robustness.[3] Optical vortices are like a rich goldmine with many more fascinating features yet to be revealed.

Recently, in *Advanced Photonics Nexus*, Andrei Afanasev from George Washington University, USA, in collaboration with the research group of Anatoly V. Zayats from King's College London, UK, demonstrated through theoretical analysis and simulation that certain polarization features of vortex beams maintain constant transverse spatial dimensions, independent of beam diffraction.[4] These polarization features appear near phase singularities and are related to the presence of longitudinal electric fields.

Traditionally, research on nondiffracting beams has mainly focused on their intensity distributions, which enable them to travel in free space without significant spreading over distances far exceeding the normal Rayleigh length. Examples of such beams include the nondiffracting Bessel beam and Airy beam.[5–7] Typically, these nondiffracting beams originated from the pursuit of packet-like solutions to Maxwell's free space wave equation, resulting in nondiffractive features limited to the intensity of the electromagnetic fields or the energy flow, with polarization properties being neglected. However, when polarization is taken into consideration, the nondiffractive character is still accompanied by intensity divergence of these beams. In other words, when intensity is diffractive, polarization is also diffractive.

In their report, A. Afanasev and A. V. Zayats demonstrate, both theoretically and numerically, that the transverse dimension of the partial polarization feature of an optical vortex beam remains unaffected by beam diffraction (see Fig. 1). This remarkable effect is attributed to the phase singularity of the beam cross-section, resulting from the interaction of the longitudinal and transverse electromagnetic fields in the vector vortex. The nondiffraction behavior in the three-dimensional polarization of vortex beams is analyzed using a paraxial simplified analytical model and nonparaxial numerical simulation. It is important to note that the longitudinal field of the vortex beam cannot be ignored, as it may affect the accuracy of the simulation study. The existence of the longitudinal field in a 3D vortex field makes the conventional 2D polarization description of Stokes parameters incomplete. Therefore, the authors have adopted the convention description of polarization for spin-1 particles, which includes matrices of the spin vector and the quadrupolar tensor.[8]

Typically, the p_y, p_{zz}, and p_{xx}-p_{yy} parameters are required to fully describe the polarization structure in a tightly focusing beam that is highly divergent. The authors investigated the 3D polarization parameters near the singularity of a tightly focused optical vortex beam with respect to the incident linear and circular polarizations.

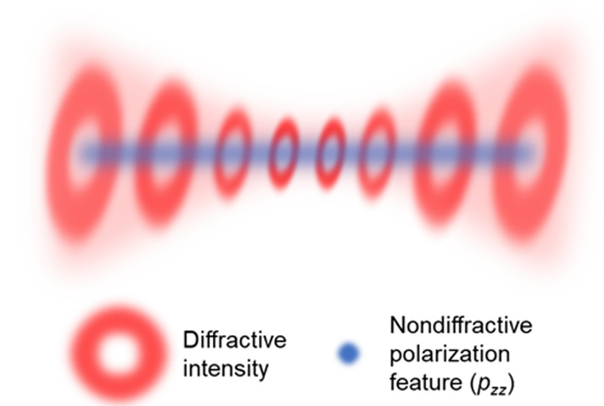

Fig. 1 Nondiffractive polarization feature of optical vortex beam unaffected by beam diffraction.

They demonstrated that the polarization structures remain invariant and extend far beyond the focal plane. Additionally, the authors confirmed through numerical simulations that the numerical aperture of the focusing system and the imperfections beam or aberrations in the actual experiment will not affect the non-diffractive nature of these polarization features. The predicted nondiffractive polarization features have relatively small transverse dimensions, on the order of a fraction of a wavelength at low l, and are centered on a low-intensity region of the optical vortex wavefront. As a result, high resolution and sensitivity are required for accurate measurement.

This work represents an important step towards fully understanding the nondiffractive nature of optical vortex polarization features and investigating the intrinsic nature of spin-orbital interaction. In terms of applications, the study sheds new light on optical metrology, optical communications, optical networking, laser sensing, and radar operations. Additionally, investigating these nondiffractive 3D polarization features can benefit research in photonic quasiparticles and spatiotemporal optical vortices, among other areas.

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