Transverse Polarization Structure of an Optical Vortex Beam around the Unfolding Point in a Birefringent Crystal

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1 Introduction

Recently, there has been considerable work in studying the natural singularities of scalar optics, namely, optical vortices. The vortices are rotational phase structures, with a singularity at center where phase is undefined. Study on such structures has become a new topic in modern optics called *singular optics* [1]. The concept has been extended to vector optics as polarization singularities, where the geometric polarization parameters of coherent fields cannot be defined [2]. The two types of polarization singularities are the C-points where the major axis of the polarization ellipse is not defined and the L-lines where the polarization handedness is not defined. These structures have been observed in the transverse plane of different fields [3-5]. The polarization singularities have significant importance in understanding the fine details of beams with complex polarization structure.

The investigations on connection between the singularities of scalar optics and vector optics using birefringent crystals [6-8] have become a current interest. Propagation within a birefringent crystal produces a lateral shift between the two mutually orthogonal eigen-polarizations. Combination of this lateral shift and the intensity and phase variations associated with an optical vortex (OV) results in a complex polarization distribution. A detailed study of the spatial variation of polarization due to a circularly polarized input beam with Gaussian and Laguerre-Gaussian envelopes propagating through a birefringent crystal along and at an angle to its optic axis is presented in Ref. [6]. The formation of a complicated network of polarization singularities at the output of a birefringent crystal due to unfolding of a diagonally polarized OV beam have been studied [7, 8] to show the topological interplay between scalar and vector optics.

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However, in these previous works, the polarization structures were studied at the output of a finite-length crystal where centers of the two eigen-beams are well separated. The spatial polarization structure near the unfolding point where the beam initially enters the crystal and splits into two eigen-beams has not been studied experimentally.

In this work we present a novel experimental setup to investigate the transverse polarization structure of an OV beam near the unfolding point, where the two eigen-beams separate inside a birefringent crystal. Results obtained with the initial setup as well as our ongoing experiment with the modified design are reported. Our main purpose is to understand the effect of the rotational phase structure of the OV beam on the transverse polarization structure near the unfolding point in the vicinity of OV.

2 Birefringent Interferometer

Here we present the balanced birefringent Mach-Zehnder interferometer (BR-MZI) setup, which reconstructs the unfolding point at the crystal output and allows us to study the polarization structure near the unfolding point of a uniformly polarized OV beam [9]. Using this novel setup, we have obtained for the first time the polarization structure very near the unfolding/refolding point in a birefringent crystal. It has also been demonstrated that the separation between the two eigen-beams can be controlled, allowing observation of the beam structure further from the unfolding point.

The interferometer consists of two identical birefringent crystals, with a half wave plate (HWP) in between. The first crystal splits the incoming beam horizontally into two orthogonally polarized eigen-beams, namely, ordinary ray (O-ray) and extraordinary ray (E-ray). The HWP interchanges the polarization states of the two beams, so that propagation through the second crystal brings back the two beams together again. This recreates the unfolding point at the output of the second crystal, allowing us to observe the polarization distribution in detail. Rotating the second crystal around the vertical axis adjusts the horizontal separation between the two eigen-beams at the output, so that polarization distributions slightly before and after the unfolding point can also be observed.

In our initial investigation [9] the interferometer was built with two 30-mm long yttrium vanadate (YVO_4) crystals and a diagonally polarized OV beam with wavelength 632.8 nm as input. Observation of polarization distribution at 1.7% separation (relative to beam diameter) between the two eigen-beams was achieved. We also demonstrated control of beam separation from 30% to -7.2%.

However as we approached the unfolding point various imperfections in the setup became apparent. The wave front curvature coupled with the beam separation resulted in relative tilt between the two beams. Residual 2.5% beam separation in the (uncontrolled) vertical direction was also observed. While the relatively long crystal contributed to the large range of control for the beam separation, it also caused distortion in beam profile as we increased the beam diameter. To deal with these issues a redesign of the setup was necessary.

3 Modified Experimental Design

The main point of the redesign is to place the BR-MZI well within the Rayleigh range of the beam to alleviate the curvature issue. This needs to be balanced with the need to keep the beam profile small compared to the 12 mm (horizontal) × 10 mm (vertical) cross-section of the crystals. The crystal lengths have been shortened to 10 mm to suppress beam distortions. The BR-MZI should also be placed in the far field of the hologram generating the OV. To observe the polarization distribution in detail, magnification between the BR-MZI output and the CCD camera is desirable.

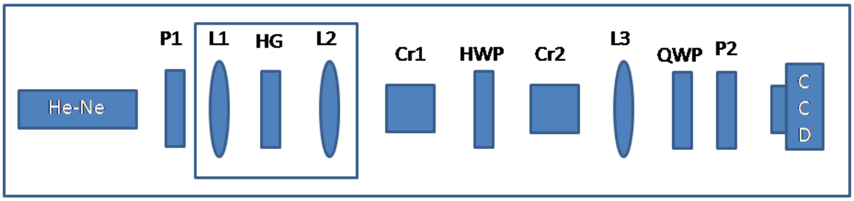

Fig. 1 Experimental Setup; P1, P2: Polarizers; L1, L2, L3: Lenses; HG: Hologram (OV generator); Cr1, Cr2: YVO4 Crystals; HWP: Half Wave Plate; QWP: Quarter Wave Plate; CCD: Charge Coupled Device

The schematic of the experimental setup is shown in Fig. 1. In the present experimental design, we place the OV generator in the Fourier plane of a telescopic system to obtain a collimated far field of the OV beam after the second lens. The focal lengths of the lenses used in the telescopic system are 300 mm (L1) and 400 mm (L2). After the telescopic system, a fully developed and collimated OV beam with 2.4 mm beam diameter is illuminated on to the balanced birefringent Mach-Zehnder interferometer, which creates the unfolding point of the OV beam at its output. As before, the horizontal separation between the two eigen-beams is controlled by rotating the second crystal of the interferometer. The output of the interferometer is magnified by lens L3 (focal length 100 mm) onto the CCD camera so that the beam diameter on the CCD is around 9.6 mm.

To address the issue of residual separation in the vertical direction, we have measured the horizontal and vertical separations of the two eigen-beams as functions of the tilt of the crystal around a horizontal axis orthogonal to the beam incidence direction. Fig. 2 shows a preliminary result with the tilt of the crystal represented by the translation distance of the reflection beam from the front surface of the crystal. It can be observed that the variation of the horizontal separation is almost negligible whereas the vertical separation varies linearly with the tilt of the crystal with a slope of -0.00238. By adjusting the tilt of the two crystals in the interferometer, we were able to reduce the vertical separation to less than 0.6% of the beam diameter.

At each value of horizontal separation, the output polarization is measured by recording spatial intensity variations for different combinations of quarter wave plate and polarizer. Experiments are now underway to represent the transverse polarization distribution around the unfolding point in the vicinity of OV as a function of the separation between the eigen-beams. Interesting results are expected due to rapid variation of the phase structure in the vicinity of OV.

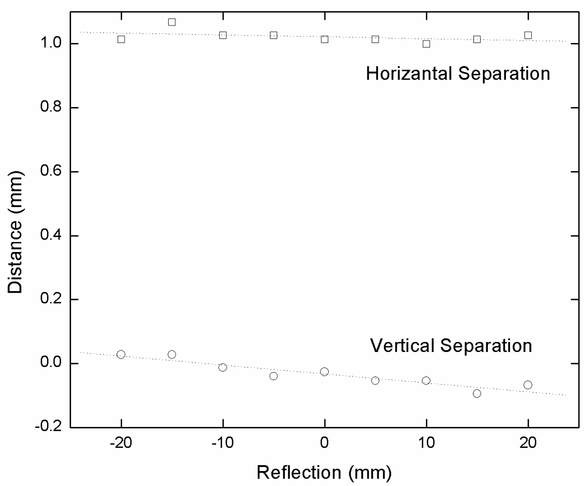

Fig. 2 Horizontal and vertical separations of the two eigen-beams at the output of the crystal vs. the tilt of the crystal as represented by the translation distance of the reflected beam

4 Conclusion

We presented and demonstrated a novel experimental setup to investigate the transverse polarization structure of an OV beam near the unfolding point, where the two eigen-beams separate inside a birefringent crystal. Observation of polarization distribution at 1.7% separation as well as control of beam separation from 30% to -7.2% was achieved. A modified design to address the shortcomings of the initial setup is presented.

These studies can be useful to generate and control spatially varying polarization structure. As the birefringent interferometer is stable and compact, the interferometer itself can be used for various metrological applications.

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