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Optical properties of polarization-dependent geometric phase elements with partially polarized light

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Abstract

The behavior of geometric phase elements illuminated with partially polarized monochromatic beams is investigated both theoretically and experimentally. The element discussed in this paper is composed of wave plates with π-retardation and a space-variant orientation angle. We found that a beam emerging from such an element comprises two polarization orders; right-and left-handed circularly polarized states with conjugate geometric phase modification. This phase equals twice the orientation angle of the space-variant wave plate comprising the element. Apart from the two polarization orders, the emerging beam coherence polarization matrix includes a "vectorial interference matrix" which contains information concerning the correlation between the two orthogonal, circularly polarized portions of the incident beam. In this paper we measure this correlation by a simple interference experiment. In addition, we found that the equivalent mutual intensity of the emerging beam is modulated according to the geometric phase induced by the element. Other interesting phenomena concerning propagation will be discussed theoretically and demonstrated experimentally. The experiment made use of a spherical geometric phase element that was realized by use of a space-variant subwavelength grating illuminated with CO_2 laser radiation of 10.6 μm wavelength.

Keywords: Subwavelength gratings; Partial polarization; Polarization-dependent lens; Geometric phase

1. Introduction

When the polarization state of a beam traverses a close loop on the Poincaré sphere, the beam acquires a phase equal to half the area enclosed by the loop. This phase modification, which is described as a geometric phase, was investigated by Pancharatnam in the 1950s [1–3] and later on by Berry in the 1980s in the context of quantum systems [3,4]. Most of the papers which investigated the geometric phase considered the evolution of the phase over time [1–5]. The phase was initially generated by placing polarization elements, such as wave plates or polarizers, in sequence; the phase was then detected by the interference of the resulting beam with the incident beam. However, the polarization state of the manipulated beam is considered to be space-invariant. Geometric phase in the space domain has been theoretically investigated. Bhandari, for example, proposed the formation of a quadratic geometric phase by use of spatially rotating wave plates [6]. This phase was also demonstrated experimentally using different realization methods. Frins et al. and Zhen et al. proposed forming space-variant geometric phase elements by joining birefringent plates in different spatial orientations [7,8]. Such elements were also designed utilizing polarization recording media (e.g., bacteriorhodopsin) [9]. Recently, we proposed generating a geometric phase front based on a space-variant subwavelength dielectric grating [1,10–18]. Subwavelength gratings have opened new methods for forming beams with sophisticated phase and polarization distributions [19–21]. Using the above methods, elements with spatially varying wave plate orientations and of constant retardation were realized [22–24]. These elements form space-variant polarization state manipulation, which eventually leads to the geometric phase modification. Such elements are referred to as Pancharatnam–Berry phase optical

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elements (PBOEs). PBOEs have been exploited for near-field and far-field polarimetry [12,13], beam-splitting [14], encryption [15], polarization-dependant lenses [16], and have also been used in the formation of vectorial vortices [17,18]. In another application, space-domain geometric phase was used for nulling interferometry to detect a faint light source near a bright one [25].

The above mentioned studies were limited to the case of fully polarized illumination [1–11,14–18]. This naturally leads one to ask how a partially polarized beam behaves when transmitted through a geometric phase-induced element (PBOE), and what the propagation properties of this beam are when it emerges from such an element? Specifically, how do the intensity, the degree of polarization and the coherence of the beam depend on the transmission through the PBOE, and how are they affected afterwards on propagation through free space?

In this paper we investigate the optical properties of polarization-dependent geometric phase elements with partially polarized light. The analysis of a partially polarized monochromatic beam is performed using the beam coherence polarization (BCP) matrix formalism [13,26–28]. The ensuing propagation of the partially polarized beam in free space is analyzed by use of the extended van-Cittert Zernike integral [13,28]. By using the above formalism, we found that when a partially polarized beam is incident upon a π-retardation PBOE, the emerging beam comprises two polarization orders; right- and left-handed circularly polarized states with conjugate geometric phase modification. This phase equals twice the orientation angle of the space-variant wave plates comprising the PBOE. The intensity of the right (left)-handed circularly polarized order, RCP (LCP), equals the amount of the left (right)-handed circularly polarized portion of the incident beam. Apart from the BCPs of the two polarization orders, the emerging BCP comprises another matrix, which we term the "vectorial interference matrix". This matrix contains the information concerning the correlation between the RCP and LCP portions of the incident beam. The matrix distinguishes, for example, between an incident beam with a linearly polarized state versus an unpolarized state. In this paper we measure this correlation by transmitting the beam emerging from the PBOE through a polarizer-analyzer.

Furthermore, we find that while the intensity and degree of polarization are invariant upon transmission through a PBOE, the equivalent mutual intensity of the emerging beam is modulated according to the geometric phase induced by the PBOE. Other interesting phenomena regarding propagation will be discussed theoretically and experimentally demonstrated.

The theoretical analysis as well as the experimental results are investigated on a polarization-dependent PBOE lens. This lens focuses incoming light at different distances, depending on the polarization state as can be seen in Fig. 1(a) [16]. The intensities of the focal spots depend on the incident polarization state as will be shown experimentally for fully and partially polarized incident beams. The analysis of partially polarized illumination upon a geometric phase element is elaborated in Section 2. In Section 3 we describe the design and realization procedures for a PBOE using space-variant subwavelength dielectric gratings. In Section 4 we present the experimental results for the geometric phase multi-focal lens achieved by a PBOE. Section 5 is devoted to concluding remarks.

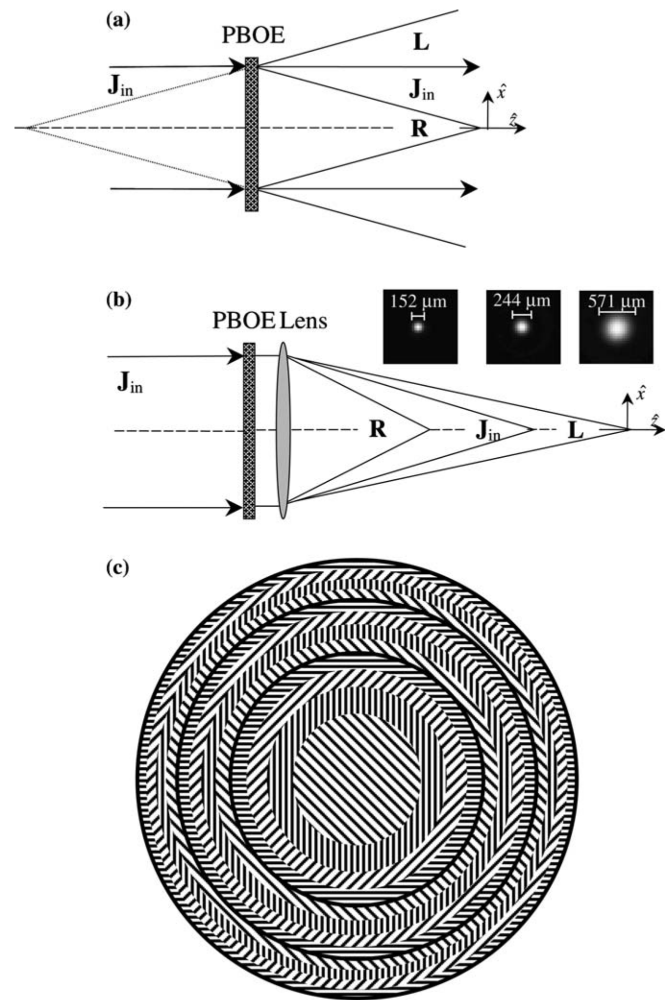

Fig. 1. Schematic presentation of a geometric phase element illuminated by a beam with a BCP matrix $\mathbf{J}_{in}$. The three emerging polarization orders are denoted by **L**, **R**, $\mathbf{J}_{in}$. (b) Concept of the multi-focal polarization-dependant lens achieved by combining the PBOE with a positive refractive lens. Insets show measured diffraction-limited spots for each focal plane. (c) Illustration of a magnified geometry of a PBOE lens mask with 4 discrete levels ($N = 4$).

2. Theoretical analysis

The analysis of partially polarized, quasi-monochromatic beams is conveniently performed by use of the BCP matrix calculus [13,26–28]. This formalism is derived from the more general case, the unified theory of coherence and polarization, which was developed by Wolf [29–34]. Assuming a beam propagating along the $\hat{z}$ axis, the 2×2 BCP matrix for a plane at constant z is defined as,