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Geometrical-phase lens based optical system for the spin-splitting of vector beams

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A R T I C L E I N F O

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A B S T R A C T

In this work, we present a new optical lens system based on a polarization directed flat lens (geometric phase lens) designed to provide circular polarization split focusing in two real foci located at two different axial planes. We find the conditions to obtain two real back focal planes of the system, and the same focal length of opposite sign. In this situation, the system acts as a bifocal SAM split system with equal scale for both real foci. We experimentally demonstrate the optical spin dependent dual focus effect of the system. Then, we illuminate the system with vortex and vector beams generated by a q-plate and provide theoretical explanation within the Jones matrix formalism for the different orbital angular momentum (OAM) and spin angular momentum (SAM) states experimentally observed at the two focal planes. Finally, we show the interference of the two split focused components of the vector beam at the intermediate plane between the two focal planes. The resulting spiral interference pattern indicates the sign and value of the vector beam's topological charge. It can also be used to identify the vector beam of a given charge by the shift on the interference fringes. Therefore, the optical system can be useful as a new tool for analyzing OAM and SAM beams.

1. Introduction

In recent times there has been a great interest in developing geometric phase (also known as Pancharatnam-Berry phase) diffractive optical elements (GP-DOE). These thin optical elements allow reducing the size of the optical systems, while maintaining high efficiency [1,2]. These GP-DOEs are basically half-wave retarders (HWR) where the angle of the fast (or slow) axis follows a given spatial pattern $\phi(\mathbf{r})$, where $\mathbf{r}$ denotes the spatial coordinate in the plane of the GP-DOE. When the GP element is illuminated with right circularly polarized (RCP) light, the output beam is left circularly polarized (LCP), and gains a phase $2\phi(\mathbf{r})$. When illuminated with the opposite circular polarization (LCP), the output is RCP and the opposite phase $-2\phi(\mathbf{r})$ is acquired. More complex designs involve not only controlling the orientation of the spatial retarder at each position, but also the spatial variation of an additional phase, thus allowing to encode two independent phase functions onto the two circular polarizations [3].

Such GP-DOE can be fabricated following two main techniques: 1) via nanostructuring metasurfaces [4,5], and 2) via photo-aligning liquid-crystal materials [1]. Whilst the first technique provides optical devices with structured birefringence and much higher light intensity tolerance, thus making possible the use of high power lasers, the second technique provides material birefringence and much more cost effective. In addition, liquid-crystal based GP elements can be made tunable with voltage and therefore useful for operation at different wavelengths [6,7].

In general, compact thin optical GP elements such as lenses, gratings, and holograms have been reported. In this work we will deal with standard GP-DOEs with π retardance at the operating wavelength (HWR plates). One such popular GP-DOE is the q-plate [8]. In this case the optical axis space distribution follows $\phi(x,y)=q\theta$, where θ is the azimuthal angle, $\tan(\theta)=y/x$. GP-DOE q-plates have become very popular since they transfer orbital angular momentum (OAM) of charge $\pm 2q\hbar$ per photon to circularly polarized light (the sign depends whether input light is RCP or LCP). This is an additional angular momentum added to the spin angular momentum (SAM) of $\sigma\hbar$ per photon that is associated to circularly polarized states ($\sigma=\pm 1$ depending on the helicity of the circular polarization). Q-plates can also be used to generate higher-order cylindrically polarized light (vector beams). When they are illuminated with a uniform polarization state, the output is a vector beam with the same ellipticity as the input beam, but with an orientation that follows the azimuth angle [7,9]. Since q-plates are flat elements, they allow the

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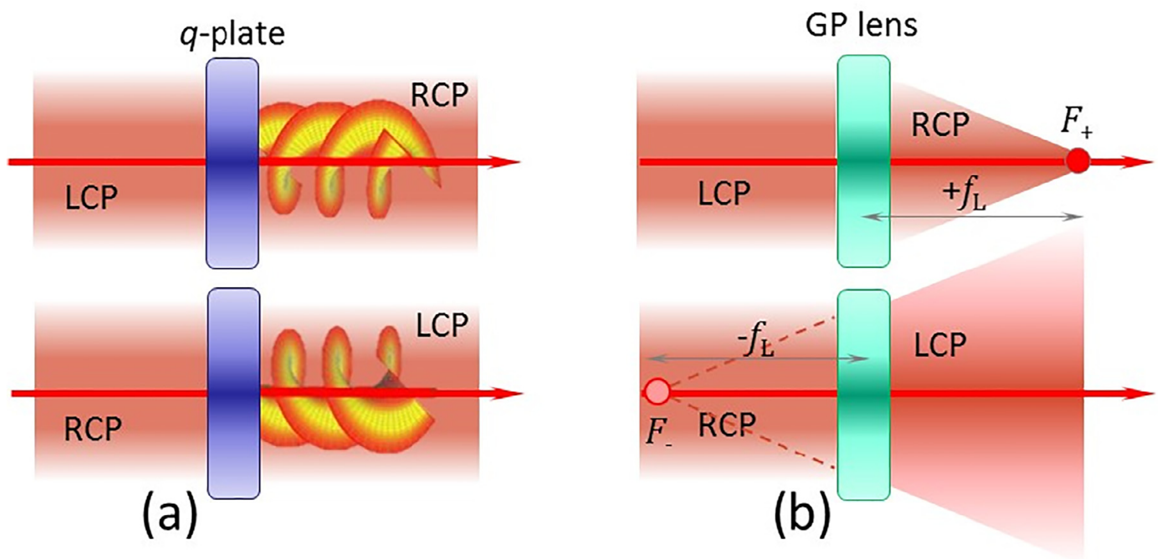

Fig. 1. Action of the two GP elements used in this work. RCP and LCP stand for left and right circularly polarized light. (a) A q-plate transfers OAM with charge of opposite sign for RCP/LCP light. (b) A GP lens converges (diverges) for RCP (LCP) light.

generation of vector beams in very compact systems, thus being an advantage over other approaches that require SLMs [10], double-wedge birefringent prisms [11], or axicon elements [12]. Nowadays, *q*-plates are actually commercially available at various suppliers, like Edmund Optics, Altechna, Thorlabs or Arcoptix.

A second type of commercially available GP-DOEs are known as metalenses (when made of metamaterials) or polarization directed flat lenses (when fabricated with liquid crystals). In this case, the optical axis orientation follows the characteristic phase of a lens; namely, proportional to the square of the radial coordinate and inversely proportional to the focal length. For these lenses, one input circular polarization results in a converging beam, while the orthogonal circular polarization results in a diverging beam [13]. The encoded focal length in each case is $\pm f$, thus acting as a polarization beam splitter, separating the circular states. Such lenses were demonstrated in Refs. [13–15], and they have been applied to create novel optical systems such as new spectrometers [16], or new polarized-based zoom lenses [17].

In this work, we combine and make the most of the properties of these two kinds of GP-DOEs described above. We use a GP lens to build an optical system that splits the circularly polarization components (or SAM components) of the input beam onto two different foci located at different axial distances. This system is composed of the GP-DOE lens followed by a telescopic system. The purpose of the telescopic system is to image the two back focal planes provided by the GP lens (one real and the other virtual) onto two real foci, both with the same magnification. In some cases, before the GP lens we place a *q*-plate to generate vector beams that will impinge on the GP lens.

Since the flat lens splits the circular polarization components of the input beam, this optical system directly allows the analysis of the incoming beam in the basis of circular states. This is very interesting for analysing cylindrically polarized beams, since these beams are the superposition of RCP and LCP vortex beams with opposite OAM. The two foci of the flat-lens based optical system directly show the content of the incoming beam in this basis. In addition, the intermediate planes between the two foci reveal a spiral interference pattern when a linear polarizer analyzer is added to the system, which serves to identify the sense of rotation of the input vector beam.

These spin splitting properties could be exploited in OAM-based optical communications [18], and in beyond OAM optical communications using vector beams where the information is encoded in the polarization distribution [19,20]. Hence, these spin-splitting properties could be used in building decoding schemes similar to that in [21]. Also, the proposed optical set-up could benefit the research on the spin-Hall effect of light, which has been proposed for optical manipulation and trapping [22] and where a longitudinal spin splitting using a spatial light modulator was recently reported [23].

The paper is organized as follows: after this introduction, Section 2 describes the GP-DOE properties, and the proposed optical set-up is explained in Section 3. Experimental results are provided in Section 4 for different input beams: beam with different uniform polarizations, but also vector beams generated by *q*-plates. Finally, the conclusions of the work are given in Section 5.

2. Geometric-phase diffractive optical elements

A standard GP-DOE is basically a HWR whose fast axis orientation follows a given function $\phi(\mathbf{r})$ of the space coordinates in the retarder's section. According to the Jones matrix formalism, the Jones matrix describing this element is given by [8]:

$$\mathbf{M}_{\mathrm{GP}}[\phi(\mathbf{r})] = \mathbf{R}(-\phi)\cdot\mathbf{HWR}\cdot\mathbf{R}(+\phi) = \begin{pmatrix}\cos(2\phi) & \sin(2\phi)\\ \sin(2\phi) & -\cos(2\phi)\end{pmatrix} \quad (1)$$

where $\mathbf{R}(\phi) = [\cos(\phi), \sin(\phi); -\sin(\phi), \cos(\phi)]$ stands for the 2×2 rotation matrix, and $\mathbf{HWR} = \mathrm{diag}[1, -1]$ is the Jones matrix for the aligned HWR. Note that in this relation ϕ is a spatially variant function $\phi(\mathbf{r})$.

When such a GP-DOE is illuminated with circularly polarized light, the output beam is given by:

$$\mathbf{M}_{\mathrm{GP}}(x, y)\cdot\mathbf{C}_{\sigma} = \exp(2i\sigma\phi)\mathbf{C}_{-\sigma} \quad (2)$$

where the normalized Jones vectors for the circular states are written following the convention in [24] as:

$$\mathbf{C}_{\sigma} = \frac{1}{\sqrt{2}}\begin{pmatrix}1\\ \sigma i\end{pmatrix} \quad (3)$$

with $\sigma = +1$ for RCP polarization and $\sigma = -1$ for LCP polarization.

Eq. (2) shows that a GP-DOE flips the circular polarization (as expected of a HWR), but also imparts a phase term $\exp(2i\sigma\phi)$ whose sign depends on the helicity of the input circular polarization. If the GP-DOE is a *q*-plate, the axis orientation pattern follows a helical phase $\phi = q\theta$, q being the *q*-value and θ the azimuthal coordinate, while for a GP lens the axis orientation pattern follows a quadratic phase function, $\phi = \pi r^2/\lambda f$, with f denoting the lens focal length, λ the wavelength, and r the radial coordinate.