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Generation of vector beams using a Wollaston prism and a spatial light modulator

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ABSTRACT

We propose a method based on a 4-f system that mainly consists of a spatial light modulator (SLM) and a Wollaston prism, to generate arbitrary vector beams with specifically designed amplitude, phase, and polarization. The incident beam is divided by a computer-generated hologram written on the SLM into two beams, each of which is encoded with a prescribed complex field and then are combined efficiently into a single beam by the Wollaston prism. Combining capability of the Wollaston prism can be tuned through the prism's rotation. We achieve a conversion efficiency that is three-fold higher than that of using a Ronchi grating for the beam combination.

1. Introduction

Recently, beams with inhomogeneous polarization states have drawn considerable attention owing to their unique properties [1–4]. These properties have fostered their use in a wide range of applications such as focus engineering [5,6], high-resolution microscopy [7], plasmon excitation [8,9] and optical micro-manipulation [10,11]. Several approaches [12–22] have been proposed for the generation of vector beams, among which SLMs are widely used because they have the advantage of supporting programmable and dynamic modulations. In order to obtain complete control of a vector optical field, four degrees of freedom are required: one for amplitude, one for phase, and two for states of polarization (SoP). Methods that could control these four parameters usually result in low energy efficiency or make any optical adjustment complicated. The method in Ref. [20] utilizes a Ronchi grating for beam combination, which leads to an energy efficiency of approximately 2%. Methods in Refs. [21,22] utilize two SLMs, making it sensitive to optical misalignment.

In this paper, we propose an efficient and practical method to generate vector beams using a Wollaston prism. In general, the Wollaston prism is used to split a light beam into lineally polarized components. For the generation of vector beams, it is inverted to combine two beams. Its combination ability is extended by rotation. The principles utilized in the experiment and the procedure for beam combination using a Wollaston prism are explained below.

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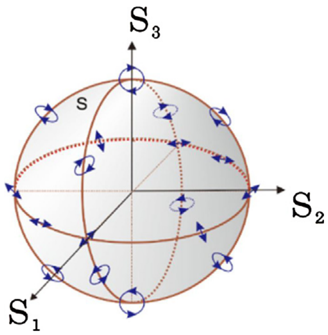

Fig. 1. Geometrical representation of SoP on the Poincaré sphere (PS) formed by the three Stokes parameters (S_1, S_2, S_3). The equator and the poles of the PS represent the linear and circular SoPs, and other points on the PS represent elliptical SoPs.

2. Principal

2.1. Generation of vector beams

In a plane (x, y) transverse to the direction z of propagation, a vector optical beam $\vec{E}(x, y)$ can always be expressed in the form of Jones vector by two orthogonal components as below

$$\vec{\boldsymbol{E}}(x,y)=\begin{pmatrix}a_1(x,y)\exp[i\phi_1(x,y)]\\a_2(x,y)\exp[i\phi_2(x,y)]\end{pmatrix}=A(x,y)\exp[i\varphi(x,y)]\begin{bmatrix}\cos\alpha(x,y)\\\sin\alpha(x,y)\exp[i\delta(x,y)]\end{bmatrix},\tag{1}$$

where $a_j(x,y)$ and $\phi_j(x,y)$ represent the amplitude and phase distribution of the j-th component (j = 1,2). In the second equality above, $A(x,y)=\sqrt{a_1^2(x,y)+a_2^2(x,y)}$ is the amplitude of vector optical beam, $\varphi(x,y)(=\phi_1(x,y))$ is the overall phase, and both $\delta(x,y)=\phi_2(x,y)-\phi_1(x,y)$ and $\alpha(x,y)=\tan^{-1}\left(a_2(x,y)/a_1(x,y)\right)$ determine the SoP of beam. A SoP can also be geometrically represented as a point on the surface of the Poincaré sphere (PS), as shown in Fig. 1,whose center is at the center of a Cartesian coordinate system defined by the Stokes parameters (S_1, S_2, S_3) as below

$$\begin{aligned}S_1&=a_1^2-a_2^2,\\S_2&=2a_1a_2\cos\ \delta,\\S_3&=2a_1a_2\sin\ \delta,\end{aligned}\tag{2}$$

The set of all SoPs are one-to-one mapped to points on the PS. It can be seen from Eq. (1) that four free parameters are needed to fully describe the vector beams, i.e. two for specifying the overall amplitude and phase and two for the SoP. Consequently, the complete manipulation of a vector beam requires an independent and simultaneous control over the four parameters. On the other hand, and perhaps more importantly, their control should be dynamic and space-variant for many applications. This requirement naturally invokes the use of liquid-crystal SLMs, which, working in a pixilated form, are the most prominent building blocks of many of today's state-of-the-art electro-optical systems. However, to date commercial SLMs usually afford one modulation parameter (phase or amplitude, depending on its modulation mode) [19–21] In order to obtain complete control of the amplitude, phase, and SoP, we need to generate the optical field defined by Eq. (1).

The experiment setup is as shown in Fig. 2. A SLM and a Wollaston prism are placed at the input and output planes of the 4-f system, respectively. The collimated beam is incident onto the SLM with a two-dimensional computer-generated grating function [20] given by

$$t(x,y)=0.5+0.25a_1(x,y)\cos[kx+\phi_1(x,y)]+0.25a_2(x,y)\cos[ky+\phi_2(x,y)],\tag{3}$$

where a_1, a_2, ϕ_1 and ϕ_2 correspond to the parameters in Eq. (1). The index k is responsible for splitting the incident beam into x- and y-directions and should be carefully chosen so that it matches the combination property (viz. splitting angle) of the Wollaston prism. The SLM grating yields the 1st x- and y-direction diffraction orders with complex amplitudes of $a_1(x,y)\exp\{i[kx+\phi_1(x,y)]\}$ and $a_2(x,y)\exp\{i[ky+\phi_2(x,y)]\}$. The two +1st orders are allowed to pass through a spatial filter located at the focal plane of the first lens. Two wave plates (half wave plate – HWP orienting at 22.5° and 67.5° with respect to the x-axis) covert the two passing orders into two mutually orthogonal linear polarization components, which serve as a pair of base vector beams for the subsequent superposition process. The two base vector beams are collinearly recombined at the rear focal plane of the second lens by the Wollaston prism. After the Wollaston prism the resultant optical field is obtained as

$$\vec{\boldsymbol{E}}(x,y)=\exp\left[i\left(\frac{kx+ky}{2}\right)\right]\begin{pmatrix}a_1(x,y)\exp[i\phi_1(x,y)]\\a_2(x,y)\exp[i\phi_2(x,y)]\end{pmatrix}\tag{4}$$