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Simultaneous tailoring of complete polarization, amplitude and phase of vector beams

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ABSTRACT

We propose and experimentally demonstrate the complete and simultaneous modulation of the amplitude, phase and arbitrary state of polarization spanning the entire surface of the Poincaré sphere. By using a single spatial light modulator (SLM), we can create vector beams from a coaxial superposition of *x*- and *y*-linearly polarized light, each carrying the structured amplitude profile and phase distribution, which result from a two-dimensional holographic grating pattern that is imposed on the SLM. By manipulating four free modulation parameters imbedded in the SLM grating we can realize the independent and simultaneous tailoring of the amplitude, phase and polarization distribution of vector beams.

1. Introduction

The behavior of light relies on the distribution of its parameters including amplitude, phase and polarization, which are often required to be controllable and tailored in variety of applications. Thus, full control of the shape of light is the everlasting quest for optical science and engineering research. Much effort has been devoted to modify the wavefront of light by engineering its amplitude, phase and polarization in a desired manner. Spatially shaping one or more parameters of light beams has been used in wide range of applications such as high-resolution microscopy [1,2], polarimetry [3], laser microfabrication [4,5], focus engineering [6,7] and optical micromanipulation [8,9]. Complete control of an optical vector field requires four independent modulation degrees of freedom, one for the amplitude, one for the phase retardation, and two for the state of polarization (SoP), which can be represented by a point on the surface of the Poincaré sphere (PS). Up to now, however, almost all methods for generating vector beams are limited to no more than three free parameters of optical field [10–17]. A recent study utilized two spatial light modulators (SLMs) in series to achieve four degrees of modulation freedom [17]. Note that this approach employed two cascaded 4-f systems and four SLM sections, thus being complicated and more sensitive to optic misalignments.

In this work, we propose an approach that, with help of a single SLM, enables the complete and simultaneous control of an optical beam over the amplitude, phase and arbitrary SoP. The SoP of generated beams can sweep across the entire surface of the PS. Based on a 4-f system including the SLM, the vector beams with space-variant shape are created from a coaxial superposition of the *x*- and *y*-linearly polarized components. Each polarized component carries structured amplitude profile and phase distributions which are produced from the SLM that imprints an amplitude-modulated holographic grating (HG) pattern onto the diffracted light. The HG contains four free modulation parameters. By doing so, the amplitude, phase and polarization distributions of vector beams with space-variant shape can be tailored independently and simultaneously by electrically adjusting the computer-generated pattern on the SLM. The benefits of our scheme include the great flexibility in terms of the controllability over the space-variant amplitude, phase as well as SoP that can span the entire surface of the Poincaré sphere, and the capability of dynamic modulation. Therefore, our approach is promising in expanding the functionality of vector beams as well as in exploring their new applications.

2. Principle

Consider a vector beam assumed to propagate along the *z* direction. The cross-sectional field of such a vector beam can in

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general be expressed in the form of Jones vector as

$$\vec{E}(x, y) = A(x, y)e^{i\beta(x,y)}\begin{pmatrix} \cos\alpha(x, y) \\ \sin\alpha(x, y)e^{i\gamma(x,y)} \end{pmatrix} \quad (1)$$

where $A(x, y)$ is the amplitude profile, $\beta(x, y)$ is the global phase, $\gamma(x, y)$ is the relative phase difference between the x- and y-linear polarization components, and $\alpha(x, y)$ determines the relative ratio of the two components. The Jones vector defines a SoP by the relative amplitude and phase of the two constituent polarization components, and can be represented as a point on the surface of the unit Poincaré sphere. It is obvious as shown in Eq. (1) that four free parameters are needed to fully describe the vector field, 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. 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, a commercial SLM usually afford one modulation parameter (phase or amplitude, depending on its modulation mode) [18–20]. A means to overcome this issue is to employ the diffraction property of the SLM, as outlined below.

Our approach is based on the principle of superimposing orthogonally polarized beams with spatially varying phase distributions. The general experimental arrangement is shown in Fig. 1. The collimated linearly polarized light is incident onto the SLM that is encoded with a two dimensional HG pattern, then coming into a 4-f system composed of a pair of identical lenses with the focal length of f. The computer-generated HG diffracts the incoming light into various diffraction orders. The grid-like amplitude transmission function of SLM with a HG written on is

$$t(x, y) = \left\{\frac{1}{2} + \frac{1}{4}\left[A_1(x, y)\cos(2\pi f_0 x + \phi_1(x, y)) + A_2(x, y)\cos(2\pi f_0 y + \phi_2(x, y))\right]\right\} \quad (2)$$

where $\phi_1(x, y)$ and $\phi_2(x, y)$ are the additional phase distribution imposed on the vertical and horizontal HG, respectively, and f_0 is the spatial frequency of the HG. $A_1(x, y)$ and $A_2(x, y)$ are the modulation depth functions of the HG along the vertical and horizontal directions, respectively, and are defined as $0 \le A_1(x, y) \le 1$ and $0 \le A_2(x, y) \le 1$. If we control the modulation depth distributions $A_1(x, y)$ and $A_2(x, y)$, we can manipulate the spatially varying diffraction efficiency on the first order of the HG so that it yield the prescribed amplitude distribution in the two first diffraction orders in the orthogonal direction of the Fourier plane, respectively. Normally the designed HG displayed at the SLM diffracts the incoming light into different diffraction orders. In our system only the first-orders are allowed to pass through a spatial filter (with two separate open apertures) placed at the Fourier plane of the 4-f system so that the transmitted light waves are expressed by $FT\left\{A_1(x, y)\exp\left(i\phi_1(x, y)\right)\right\} \otimes \delta\left(f_x - f_0, f_y\right)$ and $FT\left\{A_2(x, y)\exp\left(i\phi_2(x, y)\right)\right\} \otimes \delta\left(f_x, f_y - f_0\right)$ with $FT\{\cdot\}$ and $\otimes$ denoting the two-dimensional Fourier transform and the convolution operation, respectively. Here f_x and f_y represent the spatial frequencies of x- and y-direction, respectively. The filtered lights are then converted by two half-wave plates (HWPs) into the x- and y-linearly polarized beams, respectively, which act as a pair of orthogonal polarization components. After being Fourier transformed by the second converging lens, the two waves turn to $A_1(x, y)\exp\left(i\phi_1(x, y)\right)[1, 0]^T$ and $A_2(x, y)\exp\left(i\phi_2(x, y)\right)[0, 1]^T$ (the superscript T denotes the transpose of matrix), and are collinearly recombined at the output plane of the 4f system by a Ronchi grating whose period matches with that of the HG. The output beam can be expressed by the superposition of x- and y-linear polarization components as

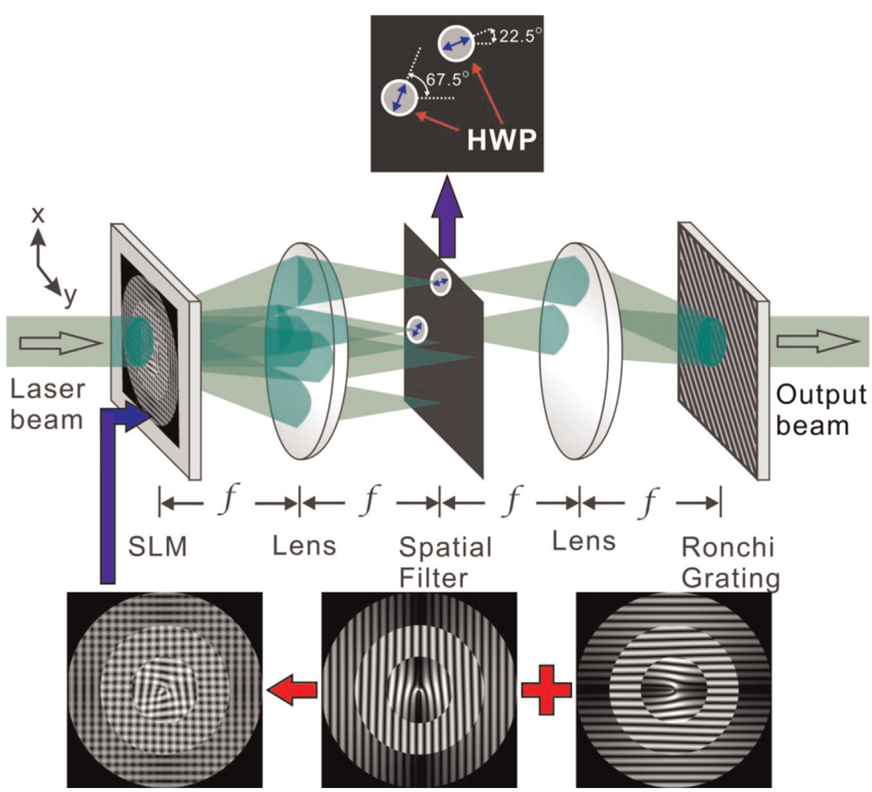

Fig. 1. Schematic of experimental setup.