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SPECIAL TOPIC — Optical field manipulation

Dynamic shaping of vectorial optical fields based on two-dimensional blazed holographic grating*

Xinyi Wang(王心怡)[1], Yuan Gao(高源)[1], Zhaozhong Chen(陈召忠)[1], Jianping Ding(丁剑平)[1,2,3,†], and Hui-Tian Wang(王慧田)[1,2]

[1] National Laboratory of Solid State Microstructures and School of Physics, Nanjing University, Nanjing 210093, China
[2] Collaborative Innovation Center of Advanced Microstructures, Nanjing University, Nanjing 210093, China
[3] Collaborative Innovation Center of Solid-State Lighting and Energy-Saving Electronics, Nanjing University, Nanjing 210093, China

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We propose a vectorial optical field generation system based on two-dimensional blazed grating to high-efficiently generate structured optical fields with prescribed amplitude, phase, and polarization. In this system, an optimized blazed grating hologram is written on a spatial light modulator (SLM) and can diffract the majority of the incident light into the first-order diffractions of the x and y directions, which then serve as base vectors for synthesizing desired vector beams. Compared with the conventional cosine grating used in the previous work, the proposed two-dimensional, blazed grating has a much higher efficiency. Both computer simulation and optical experiment validate that a conversion efficiency up to 5 times that of the former work is achieved. Our method can facilitate applications of the optical field manipulation.

Keywords: diffraction, polarization, holographic gratings, liquid-crystal devices

PACS: 42.25.Fx, 42.25.Ja, 42.40.Eq, 42.79.Kr **DOI:** 10.1088/1674-1056/ab5a3b

1. Introduction

The information of light relies on the distribution of the elements including amplitude, phase, and polarization, which are often required to be steerable in a variety of applications. Therefore, the complete control of light is of great significance for optical science and engineering research. In recent years, beams with inhomogeneous polarization states have attracted much attention due to the unique feature and a wide range of applications compared with homogeneously polarized beams.[1] These peculiar properties are useful for many applications such as laser processing,[2] plasmon excitation,[3] focus shaping,[4,5] and optical trapping.[6,7] A large number of schemes to generate vectorial optical fields have been proposed, among which spatial light modulators (SLMs) are widely used because of their advantage of enabling programmable and dynamic modulations.[8–11] Complete control of an optical field requires four independent modulation degrees of freedom, one for the amplitude, one for the phase retardation, and two for the polarization, which can be represented by a point on the surface of the Poincaré sphere (PS). However, methods which could control all these four parameters independently and simultaneously often result in low efficiency or make any optical adjustment complicated.[12–14] In a 4-f system for generating vectorial optical fields, a designed holographic grating (HG) displayed at the SLM is used to diffract the incident beam into different orders, but only the first-orders are allowed to pass through.[15] This leads to a low efficiency, especially when using a two-dimensional (2D) HG.

In this work, we propose a high-efficiency method to generate vectorial optical fields with an optimized 2D HG. The designed high-efficiency HG endowed with a blazed phase structure is used to diffract the incident light as much as possible into two first-orders along the x and y directions, which are subsequently recombined to produce any desired vectorial optical fields.

2. Principle

The general experimental arrangement is shown in Fig. 1.[16] A 532 nm collimated laser beam illuminates a SLM with 1920×1080 pixels (Holoeye PLUTO with 8 μm pixel pitch). A 4-f system composed of a pair of lenses (L_1 and L_2) is placed behind the SLM locating at the front focal plane of L_1. In order to obtain four independent modulation degrees of freedom needed for the complete shaping of vectorial optical fields, a specially designed 2D HG is needed. The HG to be displayed on the SLM diffracts the incoming beam into different orders, among which the first x- and y-directional orders (i.e., the (1, 0)-th order and (0, 1)-th order in the x–y plane) are required to have the highest intensity. 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, and then are converted by two wave plates

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†Corresponding author. E-mail: jpding@nju.edu.cn

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into two mutually orthogonal polarization components, which serve as a pair of base vector beams for the subsequent superposition process. Then the base vector beams are recombined by a Ronchi grating which is placed in the rear focal plane of L_2. At the end of this system, the optical field can be observed by a charge-coupled device (CCD). We measure the efficiency on the Fourier plane (after filter) and CCD recording plane with a dynamometer (Ophir PD300-3W).

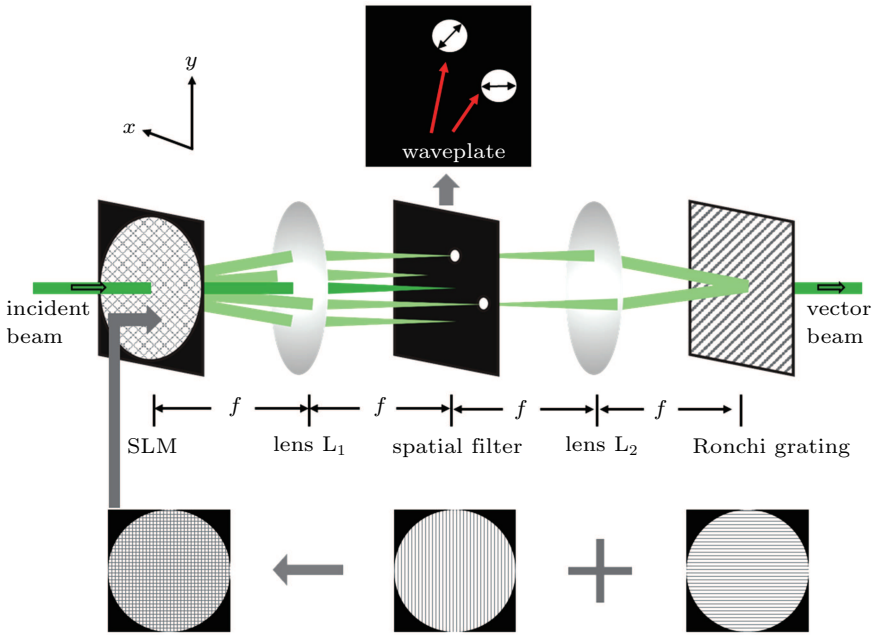


Fig. 1. Schematic of experimental setup.

A cosine HG is normally used in this scheme for generating vector beams.[10,15–17] However, the cosine grating diffracts the incident light beam into several orders, resulting in an energy loss after the filter, and the energy loss becomes more serious when the grating is in the 2D format. Therefore, we use a blazed grating instead of the cosine one so that the majority of light will be blazed to a certain order. The transmission function of a one-dimensional (1D) blazed HG is represented by $t_\xi(x,y) = \exp\left[\mathrm{i}\varphi_\xi(x,y)\right]$, where $\xi = x$ or y and $\varphi_\xi(x,y) = 2\pi f_0 \xi + \delta_\xi(x,y)$. In addition to a linear phase with spatial frequency f_0 in the ξ-direction, the HG also incorporates a phase $\delta_\xi(x,y)$ to be imposed on the diffracted light at the first-order of the ξ-direction, which is needed for synthesizing vector beams. Since we use a phase-only SLM, we are trying to figure out different generation methods of a 2D blazed HG that can regulate two independent phase functions $\delta_x(x, y)$ and $\delta_y(x, y)$. We assume a 2D phase-only HG grating expressed by $t(x,y) = \exp[\mathrm{i}\theta(x,y)]$ that will diffract an incoming beam mainly into the first x- and y-directional orders, and investigate four types of HG functions, which are denoted by type-1, type-2, type-3, and type-4 as follows.

The first one (type-1) is formed by multiplying two 1D blazed grating functions, i.e., by setting $\theta(x,y) = \varphi_x(x,y) + \varphi_x(x,y)$. The second one (type-2) is formed by multiplying the phase functions of two 1D blazed gratings, i.e., by setting $\theta(x,y) = \varphi_x(x,y) \times \varphi_x(x,y)$. The third one (type-3) is synthesized from the sum of two 1D blazed grating functions in terms of least square optimization by minimizing the following error function:

$$\varepsilon = \iint \left| \exp[\mathrm{i}\varphi_x(x,y)] + \exp[\mathrm{i}\varphi_y(x,y)] - \exp[\mathrm{i}\theta(x,y)] \right|^2 \mathrm{d}x\mathrm{d}y. \quad (1)$$

It follows by setting $\partial\varepsilon/\partial\theta = 0$ that the optimal phase $\theta(x, y)$ must satisfies the following relation:

$$\exp[\mathrm{i}2\theta(x,y)] = \frac{\exp[\mathrm{i}\varphi_x(x,y)] + \exp[\mathrm{i}\varphi_y(x,y)]}{\exp[-\mathrm{i}\varphi_x(x,y)] + \exp[-\mathrm{i}\varphi_y(x,y)]}. \quad (2)$$

From Eq. (2), it is easily seen that the optimal phase should be

$$\theta(x,y) = \arg\left\{\exp[\mathrm{i}\varphi_x(x,y)] + \exp[\mathrm{i}\varphi_y(x,y)]\right\}. \quad (3)$$

Furthermore, if one wants to impose a complex amplitude (denoted by $A_\xi(x,y)\exp\left[\mathrm{i}\delta_\xi(x,y)\right]$ with $\xi = x$ or y) instead of phase-only modulation on the diffracted light in the respective direction, the above optimal phase turns out to be

$$\theta(x,y) = \arg\left\{A_x(x,y)\exp[\mathrm{i}\varphi_x(x,y)] + A_y(x,y)\exp[\mathrm{i}\varphi_y(x,y)]\right\}. \quad (4)$$

Finally, we also propose the type-4 HG, which is based on a complementary chessboard encoding method. In this method, we consider the pixelated structure nature of SLMs and divide the modulation region into two complementary parts M_1 and M_2, either of which is in charge of phase in one direction, as

shown in Fig. 2, where M_1 and M_2 represent two binary masks whose values at the cell (m, n) are

$$M_1(m,n) = \begin{cases} 1, & \text{if } (m+n) \text{ is even}, \\ 0, & \text{if } (m+n) \text{ is odd}, \end{cases} \quad (5)$$

$$M_2(m,n) = \begin{cases} 0, & \text{if } (m+n) \text{ is even}, \\ 1, & \text{if } (m+n) \text{ is odd}. \end{cases} \quad (6)$$

The phase pattern to be written on the SLM now becomes

$$\theta(x,y) = [2\pi f_0 x + \delta_x(x,y)]M_1 + [2\pi f_0 y + \delta_y(x,y)]M_2. \quad (7)$$

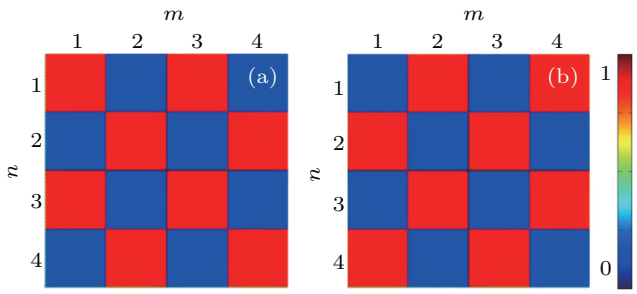


Fig. 2. Patterns (a) M_1 and (b) M_2 are responsible for blazing the light into the first order in the x and y directions, respectively.

We carry out numerical simulation to demonstrate the diffraction efficiency of the above 4 types of 2D HGs. Assuming a plane light wave normally incident on the HGs, we calculate the light distribution in the Fourier plane and evaluate the energy percentage of the incident light diffracted into the first order in the x and y directions (i.e., the (1, 0)-th and (0, 1)-th orders). The intensity distribution in the Fourier plane is shown in Fig. 3. It is found that the type-1 HG has the lowest efficiency since most of light is blazed to the (1, 1)-th order in the 45° direction rather than the (1, 0)-th and (0, 1)-th orders in the x and y directions. The poor efficiency of the type-2 HG is caused by the multiplication of two 1D blazed gratings that results in a strong zero-order and multiple higher orders. The type-3 HG achieves the highest efficiency of 73%, while the type-4 HG results in an efficiency of 46%, both of which are substantially higher than that of the ideal cosine grating $\left(0.5\left[1+2\cos\left\{2\pi f_0 x+\delta_x(x,y)+2\pi f_0 y+\delta_y(x,y)\right\}\right]\right)$ with an efficiency of 15%. We therefore chose the type-3 method to create the 2D phase-only HG needed for synthesizing fully vectorial optical fields in the subsequent section.

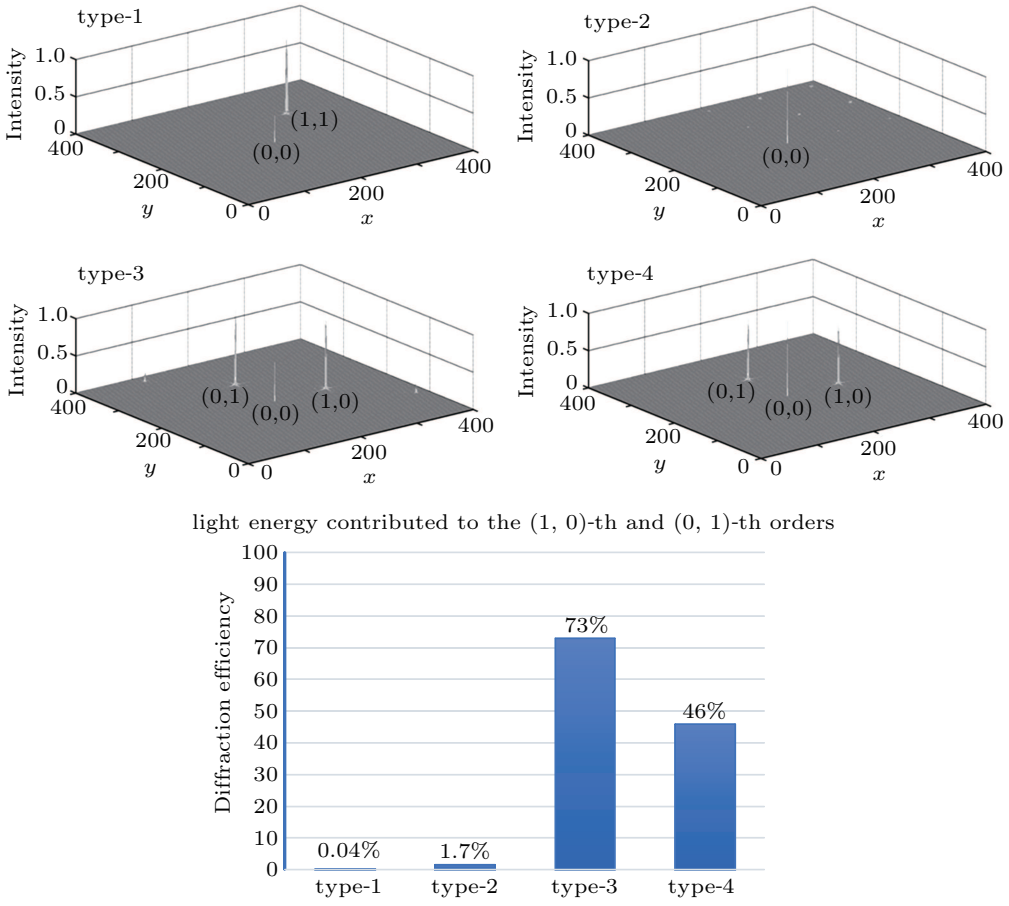


Fig. 3. Simulation results of the diffraction intensity in the Fourier plane of HGs. All intensities are normalized at the incident light intensity.

3. Experimental results

As a validation of the feasibility of the proposed method to generate fully vectorial optical fields, we present examples demonstrating the capability of manipulating the amplitude, phase, and polarization of optical fields. The experimental arrangement for creating arbitrary vector beams is similar to

that of previous works in our lab,[15,16] which is shown in Fig. 1. The first example is a PS beam, whose polarization states within the beam cross-section span the surface of the PS. The polarization states of the beam is designed as being distributed in a pattern shown in Fig. 4, wherein two regions marked by A and B correspond to the northern and southern hemisphere surfaces of the PS, respectively. The measured Stokes parameters of the generated vectorial beam are shown in Fig. 5.

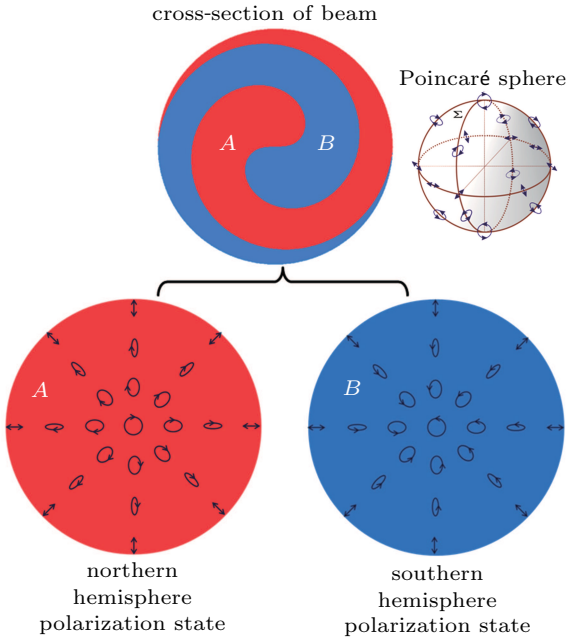


Fig. 4. A designed PS beam with space-variant polarization states distributed within its cross-section comprising two regions marked by A and B. Polarization states in the regions A and B span the northern and southern hemispheres of the PS, respectively.

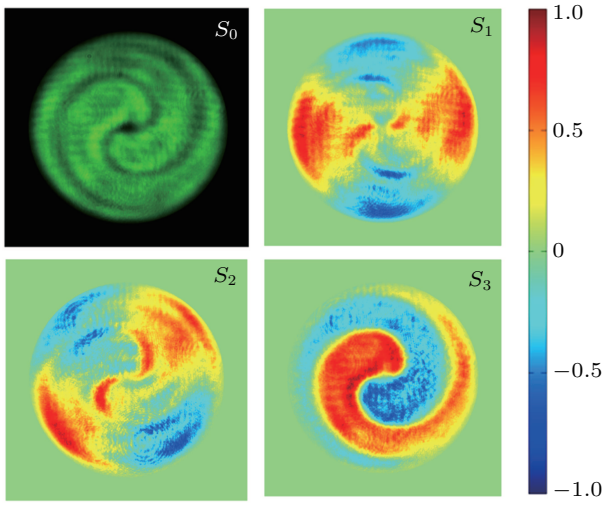


Fig. 5. The measured Stokes parameters (S_0, S_1, S_2, S_3) of the experimentally generated PS beam field with space-variant polarization distribution described in Fig. 4.

The second example is a hybrid PS beam.[18] A polarization state on the hybrid PS can be expressed by the combination of a pair of orthogonal basis vectors as follows:

$$\boldsymbol{E} = A_L \widehat{\boldsymbol{L}}_l + A_R \widehat{\boldsymbol{R}}_m, \tag{8}$$

where A_L and A_R are the amplitude factors of orthogonal basis vectors $\hat{\boldsymbol{L}}_l$ and $\hat{\boldsymbol{R}}_m$, each of which is a handed circular polarization carrying a specific helical phase and is defined by

$$\begin{cases} \widehat{\boldsymbol{L}}_l = \dfrac{1}{\sqrt{2}} \mathrm{e}^{\mathrm{i}l\varphi} \begin{bmatrix} 1 \\ -\mathrm{i} \end{bmatrix}, \\ \widehat{\boldsymbol{R}}_m = \dfrac{1}{\sqrt{2}} \mathrm{e}^{\mathrm{i}m\varphi} \begin{bmatrix} 1 \\ \mathrm{i} \end{bmatrix}, \end{cases} \tag{9}$$

with l and m representing the topological charge of the respective helical phase. Figure 6 depicts the phase and polarization states of three typical points (A, B, and C) on a hybrid PS with $l = 1$ and $m = -3$; the points A and C locate at the north and south poles of the hybrid PS, respectively, and the point B locates at the equator of the sphere. The generated optical field represented by the point B is shown in Fig. 7. The first and second rows of Fig. 7 present the theoretical and experimentally measured distributions of the Stokes parameters (S_0, S_1, S_2, S_3) for the hybrid PS beam. Figure 7(m) shows the experimentally recorded interference pattern produced by a reference wave with plain phase and the left circular basis vector $\hat{\boldsymbol{L}}_l$ with helical phase of topological charge $l = 1$, and figure 7(n) shows the theoretical phase distribution of the left circular basis vector. Likewise, figures 7(o) and 7(p) give the experimental and theoretical results of the right circular basis vector with topological charge $m = -3$.

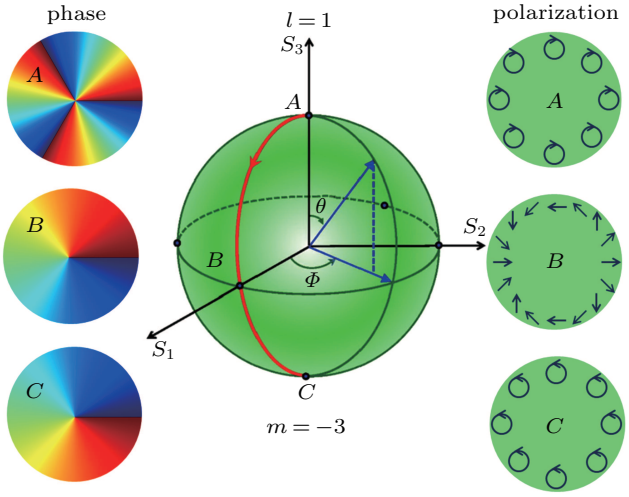


Fig. 6. States of phase (left) and polarization (right) on surface of hybrid PS. The north and south poles of this hybrid PS represent right and left circular polarizations with phase vortices of the topological charge 1 and −3, respectively.

It should be known that the main energy loss in optical fields generating lies in splitting and combining processes. Our method can greatly decrease the energy loss during the splitting process. In our experimental system, the output suffers from an array of elements, which are outlined here: the diffraction efficiency of the SLM used in this system is about 70%; the diffraction efficiency of blazed grating on the Fourier

plane is 73% as aforementioned; the transmission efficiency of the quarter wave plate (QWP) is 90%; the combining efficiency of the Ronchi grating is 40%. By also taking into account other elements such as the lenses in this system, the conversion efficiency at the output plane (CCD plane) turns out to be about 10%, which is validated by the actual measurement result shown in Fig. 8 and is 5 times higher than that of previously reported methods that employed cosine gratings.[15–17] It should also be noted that the conversion efficiency can be further increased if the combining process is improved, for example, the Ronchi grating combination is replaced by a polarization beam splitter.[19]

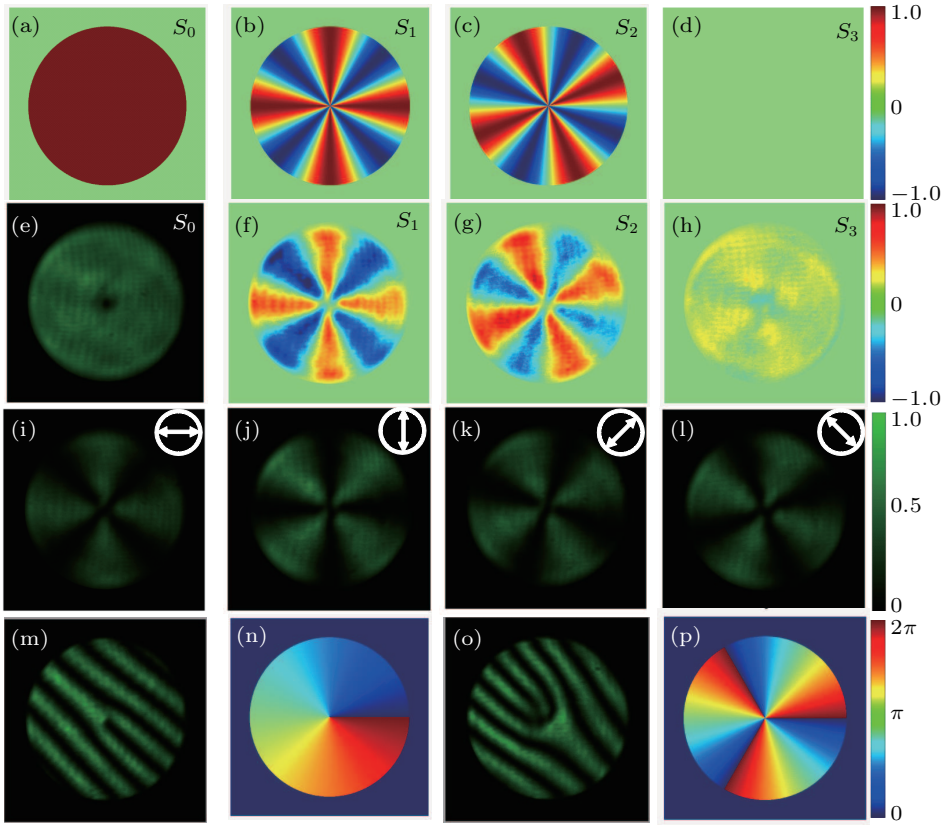


Fig. 7. Theoretical and experimental results of the point B on the hybrid PS depicted in Fig. 6. (a)–(d) Simulated Stokes parameters (S_0, S_1, S_2, S_3). (e)–(h) Measured Stokes parameters. (i)–(l) Intensity behind polarization analyzer of four directions indicated by white double arrows. (m), (n) Experimental and theoretical results of left circular basis vector, (o), (p) experimental and theoretical results of right circular basis vector.

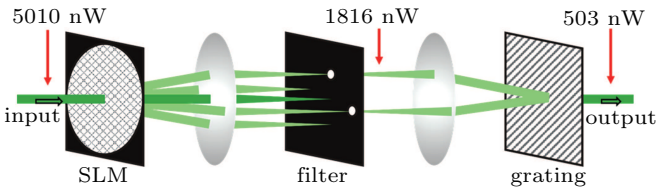


Fig. 8. Experimentally measured power of the light at different planes in our system.

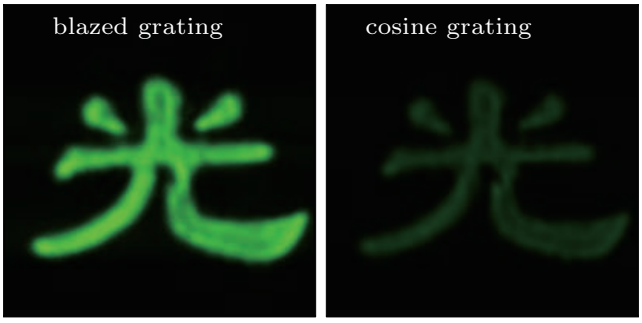


Fig. 9. Intensity map of optical fields generated by the blazed (left) and cosine (right) gratings.

To show the efficiency of two different gratings clearly, we present a group of recording pictures for visual comparison. Figure 9 shows CCD recording results by two methods under the same experiment condition. Apparently, the optical field generated by the blazed grating has a much stronger light intensity than that by the cosine grating.

4. Conclusions

We propose an efficient and practical method to generate fully vectorial optical fields with a two-dimensional blazed holographic grating. A significant advance made in this work is the 5 times higher efficiency compared with the former work. The simplicity, higher efficiency, and complete control of the optical field make this method suitable for a range of applications involving vector beams, such as focus shaping and optical tweezers.

References

[1] Zhan Q 2009 *Adv. Opt. Photon.* **1** 1

[2] Lou K, Qian S X, Ren Z C, Tu C, Li Y and Wang H T 2013 *Sci. Rep.* **3** 2281

[3] Moh K J, Yuan X C, Bu J, Zhu S W and Gao B Z 2009 *Opt. Lett.* **34** 971

[4] Kenny F, Lara D, Rodríguez-Herrera O G and Dainty C 2012 *Opt. Express* **20** 14015

[5] Chen W and Zhan Q 2010 *J. Opt.* **12** 045707

[6] Kozawa Y and Sato S 2010 *Opt. Express* **18** 10828

[7] Zhang L, Qiu X, Zeng L and Chen L 2019 *Chin. Phys. B* **28** 094202

[8] Arrizón V, Méndez G and Sánchez-de-La-Llave D 2005 *Opt. Express* **13** 7913

[9] van Putten E G, Vellekoop I M and Mosk A P 2008 *Appl. Opt.* **47** 2076

[10] Chen H, Hao J, Zhang B, Xu J, Ding J and Wang H T 2011 *Opt. Lett.* **36** 3179

[11] Han W, Yang Y, Cheng W and Zhan Q 2013 *Opt. Express* **21** 20692

[12] Chen H, Ling X H, Chen Z H, Li Q G, Lv H, Yu H Q and Yi X N 2016 *Chin. Phys. B* **25** 074201

[13] Waller E H and von Freymann G 2013 *Opt. Express* **21** 28167

[14] Moreno I, Davis J A, Hernandez T M, Cottrell D M and Sand D 2012 *Opt. Express* **20** 364

[15] Wang X L, Ding J, Ni W J, Guo C S and Wang H T 2007 *Opt. Lett.* **32** 3549

[16] Yu Z, Chen H, Chen Z, Hao J and Ding J 2015 *Opt. Commun.* **345** 135

[17] Chen Z, Zeng T, Qian B and Ding J 2015 *Opt. Express* **23** 17701

[18] Yi X, Liu Y, Ling X, Zhou X, Ke Y, Luo H, Wen S and Fan D 2015 *Phys. Rev. A* **91** 023801

[19] Gao Y, Chen Z , Ding J and Wang H T 2019 *Appl. Opt.* **58** 6591