An efficient dynamic control method of light polarization using single phase-only liquid-crystal-on-silicon spatial light modulators (LCOS SLMs) for optical data storage

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The technology of five-dimensional (5D) optical data storage in transparent materials paves a promising way to unlimited lifetime data storage for future cloud. Phase-only liquid-crystal-on-silicon spatial light modulator (LCOS SLM) has already exhibited its potential for this application in tailoring ultrafast laser writing beams for 5D optical data storage. A phase-only LCOS SLM can generate arbitrary data patterns by using diffractive holographic imaging for the data writing light beam generation. However, the polarization control of the output holographic image is still achieved by using an external polarization modulator, which leads to complications, bulkiness, and large delays in current methods. In this paper, we presented an efficient phase and polarization modulation method through a compact system based on a single phase-only LCOS SLM to simultaneously control both the holographic image and its polarization state. The proposed method utilizes two-polarization-components coding in conjunction with a polarization components rotation technique in a compact system. Using this polarization rotation technique, two light components can be independently coded by separately using two holograms on two halves of LCOS SLM. We experimentally construct a proof-of-concept prototype of the compact system, and the effectiveness of the system has been experimentally verified.

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1. INTRODUCTION

Phase-only liquid-crystal-on-silicon spatial light modulator (LCOS SLM) is becoming an important tool for laser processing in a range of systems [1-4]. And it has already demonstrated its potential for this application in tailoring ultrafast laser writing beams for optical data storage. A recent breakthrough has made it possible to high-capacity optical store data in fused silica [5-7]. The technology of 5D optical data storage in transparent materials paves a promising way to unlimited lifetime data storage for future cloud [8-13]. In the optical data writing process, to encode information to the nanograting structure created by laser pulses, a light field of target data pattern (multi-beam arrays) with target linear polarization state is required. Phase-only LCOS SLM can generate arbitrary data patterns by using diffractive holographic imaging, which is specifically suitable for the data writing beam generation. But the polarization control of the output image is still achieved by using an external polarization modulator. This leads to complications, bulkiness, and large delays in current methods. Therefore, it is important to develop an efficient phase and polarization modulation method only using phase-only LCOS SLMs to simultaneously control both the holographic image and its polarization state.

Currently, several works regarding polarization modulations for laser writing beam generations have been reported. Allegre *et al.* utilized two phase-only SLM in conjunction with a pair of waveplates to control the wavefront and polarization of a laser beam [14,15]. In this method, two SLMs are regarded as an "SLM convert". The first SLM is utilized to structure the beam wavefront through a phase pattern. When light passing a half-wave plate attached to the first SLMs, the horizontal polarization is tiled to +45°. The second SLM combined with a quarter-waveplate is utilized to convert incident linear polarization into a desired state of polarization. In this method, the modulation implementation is achieved by the second SLM and waveplate. However, the polarization state modulation is limited because two components of a vector beam cannot be arbitrarily accessible. Allegre *et al.* also developed another polarization beam generation method using a single SLM and a λ/4 wave-plate [16]. A phase-only liquid-crystal SLM was used to convert a linearly polarized femtosecond-pulse laser beam to radially or azimuthally polarized vortex beams. In [17], Lam *et al.* developed a generation method of continuously rotating polarization by combing cross-polarizations. The beam modulator is composed of an SLM and a quarter-wave plate. A transmissive SLM in connection with a quarter-wave plate can produce orthogonal linear polarization on two sides of the laser beam. Although these methods can generate some polarization states on the two sides of the laser beam in the femtosecond laser beam writing process, the dynamic simultaneous generation of the arbitrary linear polarization states and holographic patterns still cannot be achieved.

In [18], Hasegawa *et al.* utilized a pair of SLMs to create a holographic vector wave femtosecond laser processing system. The pulse was radiated onto the first SLM (SLM1), which displayed CGH1 for applying a pure phase delay to the p-component, that is, phase modulation. The HWP was arranged with an azimuthal angle of $\pi/8$ to rotate the linear polarization by $\pi/4$. The pulse was also radiated onto the second SLM (SLM2), which displayed CGH2 for applying a phase delay between the p- and s-components, that is polarization modulation. SLM2 was located at the image plane of SLM1. The circular or elliptical polarization reflected from SLM2 was converted to linear polarization using a QWP set to an azimuthal angle of $\pi/4$. In [19], Ono *et al.* demonstrated a vector hologram beam generation method using two radially polarized beams that works as inhomogeneous polarized light. A two-wave mixing technique using radially or linearly polarized input light from two laser sources is adopted. The polarization distribution in the cross-section of the two writing beams was controlled by an SLM.

The University of Southampton developed an improved method using a rotation-free half-wave plate matrix (HPM) to achieve polarization modulation [6, 20-23]. This method used an LCOS SLM to implement data pattern generation and a HPM to alter the writing beam's polarization state. The HPM consists of an array of half wave-plates is used to produce the designed polarization states, which was fabricated by a laser to imprint a half-wave matrix consisting of four segments with predefined fast axis directions. In [24], similar work is done where a waveplate array is fabricated with a femtosecond laser inside silica glass. In this method, the fixed HMP can provide desired polarization states for data patterns when the glass sample is moved to the correct spatial position. The mechanical movement for polarization modulation is transferred from the half-wave plate to the substrate of glass. This change brings the delay to the hundreds *ms* range; however, the mechanical delay of glass block movement still prevents the recording speed of data from reaching the current Blu-ray disc recording speed. The delay caused by glass movement is considerably large when we compare this to the refresh rate of data pattern generation and time duration of laser exposure. Another limitation of this method is the number of available polarization states for writing. This method can only provide four fixed polarization states for the information encoding due to the design of HMP. This means a significant limitation in storage density. Although the number of half-wave plates on the HMP can be increased, it will lead to more spatial movement of glass substrate due to the working principle of this method.

In voxel writing, only linearly polarized light is used to generate the writing beam, thus, a rotatable half-wave plate (HWP) is a direct way to change the angle of a linearly polarized light. However, utilizing a rotatable HWP in voxel writing beam generation has a challenging problem: the significant decrease in writing speed due to the rotation of HWP. In this method, the dot pattern for voxel writing with linear polarization state is generated using an SLM, the light field then passes through an HWP for polarization angle modulation. Every time a new linear polarization angle is to be written, the HWP needs to be rotated to a certain angle to change the incident beam polarization state. The mechanical rotation process will cause a delay (usually in the order of seconds) [25-26]. This delay is significantly large when it comes to a recording speed of a data storage technology. Moreover, the whole writing beam generation system will become complicated because of the difficulty in the synchronization of voxel pattern generation and the external rotatable HWP.

The current existing methods usually were developed for the generation of spatially verified polarization distribution, for example, vortex polarization light field for optical tweezers. However, in the application of optical data storage in glass, each voxel writing only requires one uniform linear polarization state of light. This means that the required writing light field could usually be a discrete dot array and each dot with its own linear polarization state instead of an integral beam in previous polarization modulation applications. Therefore, a novel linearly polarized light controlling method is needed for voxel writing.

To address this issue, we proposed an efficient phase and polarization modulation method based on a single phase-only LCOS SLM to simultaneously control both the holographic image and its polarization state. In [27], we considered the zero-order noise issue caused by the pixelated structure of LCOS devices to achieve the feasibility and flexibility of a compact system for the phase and polarization modulation of light. In this paper, we demonstrated the detailed methods of a compact system for the phase and polarization modulation using based on a single LCOS SLM. The compact system is designed by a folded dynamic polarization-modulation system using LCOS-SLM. The new method uses two cascade-connected holograms presented single LCOS-SLM in conjunction with a half-wave plate to create the modulation of multiple linear polarization states and simultaneously allowing the implementation of the holographic image generation.

In this work, we aim to control arbitrary linear polarization states and simultaneously allow the implementation of the holographic image generation. This is to meet the application requirements of optical data storage in glass and it is different fundamentally from what the existing methods do, which is mainly aiming on the control of polarization distribution of a light spot (fixed shape and pattern), not the polarization control on dynamic holographic images..

2. THE PROPOSED METHOD

A. The principle

The proposed method adopts a concept of independent coding two orthogonal light components. This means that the target image and amplitude information are firstly independently encoded on horizontal and vertical light components. Then, the target image reconstruction and output polarization formation are simultaneously completed by using the focusing lens to perform the Fourier transform. However, to use a single LCOS SLM in this method, a different modulation scheme of two polarization components is needed due to the single working direction of liquid crystal molecules.

The schematic of the proposed compact system of phase and polarization modulation method using a single LCOS SLM is shown in Figure 1. In this method, a rotation scheme of the polarization plane of two light components is proposed. The active area of LCOS SLM is divided into two sections to load two CGHs. the X-direction component of the 45° polarized input beam is firstly coded by CGH1. Then, the rotation of both polarization components makes the Y component available for coding by CGH2. After two coding processes, the output target image with target polarization can be obtained. Moreover, the compact system design based on this modulation method is proposed in this work.

In this proposed method, after the X component of the light is encoded, a half-wave plate is utilized to implement the rotation of both X and Y polarization components. The half-wave plate can introduce a fixed π

phase shift between the two perpendicular polarization components (X and Y) of the input light wave, therefore altering its polarization direction. As shown in Figure 2, when the incident light has a linear polarization, the angle of the polarization direction of the input light can be shifted by the half-wave plate. And the change of polarization direction is determined by the relative angle between the input light wave and optic axis of the half-wave plate. For example, when the linear polarization direction of the input light wave is vertical and the fast axis of the half-wave plate is at 45°, the polarization direction of the output beam can change into horizontal. This behaviour of a half-wave plate can be utilized in the proposed method. To encode target image information and amplitude information on the two orthogonal polarization components of the input light wave, the polarization direction of input light is set at 45°. Due to the use of a single LCOS SLM device in the proposed method, the working direction of liquid crystal is single: either horizontal or vertical. Therefore, the rotation of two linear polarization components based on a half-wave plate is the key to the success of information coding using one LCOS SLM.

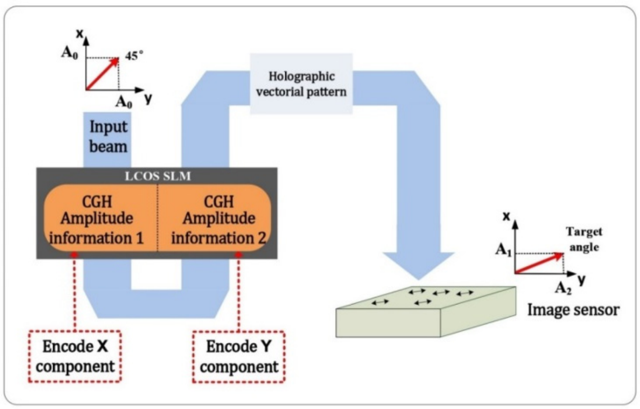

Figure 1. Schematic of the proposed compact system of phase and polarization modulation method using single LCOS SLM.

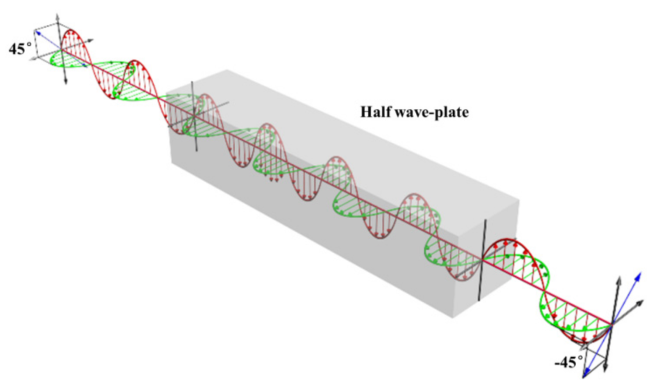

Figure 2. Principle of wave-plate used for the proposed phase and polarization modulation method based on a single LCOS SLM. The yellow light wave is the modulated polarization component, while the blue one means the unaffected one after modulation by LCOS SLM.

B. Dynamic control of light polarization

By using the polarization sensitivity [28-29] of LCOS-based phase-only modulation, the independent encoding of the holographic image and amplitude information onto the X and Y components of a single input beam can be achieved. Before the Fourier transform of the information-encoded beam, both target image information and amplitude information are not expressed. And both are stored in the form of phase distribution, and the phase distribution is directly controlled by the CGHs on LCOS SLM.

The dynamic control principle of light polarization of the proposed method is shown in Figure 3. Firstly, the linearly polarized input beam is set at 45° to the LCOS SLM with working direction at Y-axis (the horizontal direction). Then, the normalized Jones vector of the input light can be expressed as

$$\mathrm{E} = \begin{bmatrix} 1 \\ 1 \end{bmatrix} \tag{1}$$

where the amplitudes of two orthogonal vector components E_x and E_y are the same. Then, the input light beam incidents on the first half of the active area of LCOS SLM for the first modulation. In this modulation process, as shown in the schematic diagram in Figure 1, we use CGH1 with the certain phase depth information to successfully encode both target image information and amplitude information into the horizontal vector beam component (E_x). As the working direction of the LCOS SLM is horizontal, the loaded CGH1 can only modulate the horizontal component (E_x) of the input vector beam. The vertical component (E_y) is not affected.

Here, we use $\mathrm{G(x)}$ to indicate the target image information for the X-direction light component. The $\mathrm{G(x)}$ can be expressed as phase distribution on CGH1 by $\mathrm{G(x)} = \mathrm{e}^{\mathrm{i}\varphi_x}$. And the amplitude information $\mathrm{A_x}$ is encoded via the phase depth of the CGH1. Then, the Jones vector of optical vector beam after the first modulation can be expressed as

$$\mathrm{E} = \begin{bmatrix} \mathrm{A_x} \cdot \mathrm{e}^{\mathrm{i}\varphi_x} \\ 1 \end{bmatrix} \tag{2}$$

Due to the polarization sensitivity of phase-only LCOS, the Y direction component (the light wave in blue) remains unchanged and there is no phase information (target image and phase depth) has been encoded on it. After the phase-only modulation of the X-direction component (the light wave in yellow) of the input light wave, the target image will be reconstructed through the diffraction of light at an infinite distance. This is due to the use of Fourier CGH. To reconstruct the target image, a converging lens is utilized to perform a Fourier transform so that the diffraction can occur on the focal plane of a lens. This means that the X-direction component of input light will maintain the superposition state with the Y-direction component after the first modulation process when there is no lens applied. This is the key to polarization components rotation in the proposed method.

Physically, the light wave at the X direction after phase-only modulation on LCOS SLM has become the diffracted light beam, while the light wave at the Y direction has not been affected. Due to the property of far-field diffraction in the Fourier hologram, the image and amplitude information of the light field at the X-direction are stored in the form of the phase. This means that except for the phase value of the X-direction components of each pixel on the light beam area, the other property of the light waves at the X-direction will remain unchanged. Now, we can consider the X direction light component as a diffracted beam with a diffraction angle 0° to its original propagating direction and state. Therefore, the X-direction component of light maintains the superposition state with the Y-direction component; meanwhile, they are separated into two beams in the viewpoint of wave optics. In physical optics, they are still two orthogonal polarization components of one single beam but with different phase values.

Because we can treat the X and Y direction of light components as two independent light waves, the half-wave plate can be introduced to independently and simultaneously rotation the direction of these two polarization components. Now, we can separately write the Jones vector of X and Y direction of polarization components as

$$E_x = \begin{bmatrix} A_x \cdot e^{i\varphi_x} \\ 0 \end{bmatrix} \qquad E_y = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{3}$$

Because of the use of a single LCOS SLM, as shown in Figure 3, only the horizontal polarization components can be modulated. Therefore, the Y direction components (the light wave in blue) need to be rotated into a horizontal polarization component before the second modulation. And CGH2 will be loaded on the second half of the active area of LCOS SLM to code the rotated Y direction polarization component. Moreover, to prevent the phase information on X direction polarization components (the light in yellow) will not be affected in the second modulation process, we must rotate it into a vertical direction in advance. Hence, the half-wave plate with the fast axis at 45° is placed in front of the second half LCOS SLM. By doing this, the target rotation of two polarization components can be simultaneously achieved before the second phase modulation. The Jones matrix of a half-wave plate with the fast axis at 45° can be expressed as

$$HWP_{45} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{4}$$

Then, the Jones vector of X and Y direction polarization components after traveling through the half-wave plate can be written as

$$E_{x'} = HWP_{45} \cdot E_x = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} A_x \cdot e^{i\varphi_x} \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ A_x \cdot e^{i\varphi_x} \end{bmatrix} \tag{5}$$

$$E_{y'} = HWP_{45} \cdot E_y = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{6}$$

Now, we can see that the previous two polarization components have exchanged their polarization direction after the half-wave plate. The $E_{x'}$ is now at the vertical direction, while the $E_{y'}$ is changed into the horizontal direction and ready for information encoding. It is important to notice that the rotation of polarization direction of two light components using a half-wave plate will not change their physical superposition relationship.

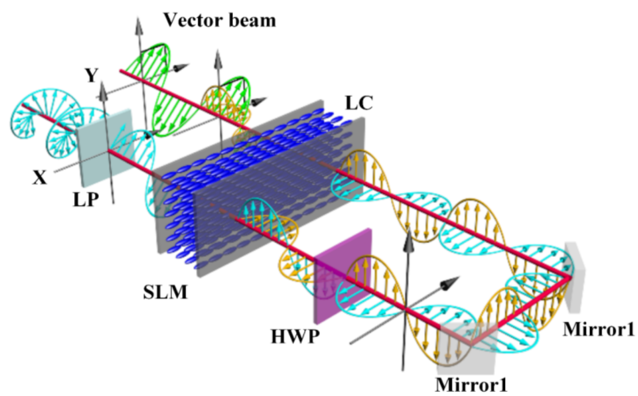

Figure 3. Principle of the proposed phase and polarization modulation method using single LCOS SLM. The yellow light wave is the modulated polarization component, while the blue one means the unaffected one after modulation by LCOS SLM.

Then, we use $G(y)$ to indicate the target image information for $E_{y'}$. $G(y) = e^{i\varphi_y}$. And the amplitude information A_y is encoded via phase depth of the CGH2. So, the $E_{y''}$ after second phase modulation can be expressed as

$$E_{y''} = \begin{bmatrix} A_y \cdot e^{i\varphi_y} \\ 0 \end{bmatrix} \tag{7}$$

Here, we can see that both two orthogonal polarization components have been encoded with the target image information and amplitude information. Like the situation in the first modulation for E_x, the modulated light component here has also become a far-field diffracted light. This means that it will remain the superposition state with $E_{x'}$. Therefore, the superposition of two polarization components is not affected by the two separate phase modulations and polarization components rotation. Therefore, the final output light field can be expressed as the direct superposition of two light components

$$E_{out} = E_{x'} + E_{y''} = \begin{bmatrix} 0 \\ A_x \cdot e^{i\varphi_x} \end{bmatrix} + \begin{bmatrix} A_y \cdot e^{i\varphi_y} \\ 0 \end{bmatrix} = \begin{bmatrix} A_y \cdot e^{i\varphi_y} \\ A_x \cdot e^{i\varphi_x} \end{bmatrix} \tag{8}$$

To simultaneously manipulating the polarization state of output light with a certain target image, we set the target information on both CGH1 and CGH2 the same as

$$G(y) = e^{i\varphi_y} = G(x) = e^{i\varphi_x} = e^{i\varphi} \tag{9}$$

Then, the Jones vector of output light will be rewritten as

$$E_{out} = \begin{bmatrix} A_y \\ A_x \end{bmatrix} \cdot e^{i\varphi} \tag{10}$$

Now, the phase (target image $e^{i\varphi}$) and polarization (amplitude ratio of A_x and A_y) modulation of light has been achieved in the proposed method.

3. EXPERIMENTAL RESULTS

A. Proof-of-concept compact system

Figure 4 shows the experimental schematic of the proof-of-concept compact system of the proposed phase and polarization modulation method using a single LCOS SLM. The expanded and collimated laser beam passing through a linear polarizer is used as a light source. The fast axis of the linear polarizer is set at 45° to the working direction (0°) of the LCOS device. Then, the linearly polarized beam, passing through a non-polarizing beam splitter (NPBS), will illuminate the left-half of the active area of the SLM. The hologram uploaded on the SLM performs modulation to the horizontally polarized light, while the vertically polarized light is not affected and then be reflected into the HWP. When passing through the HWP, the horizontally polarized light component is now rotated into a vertically polarized light component and then be perpendicular to the working direction of the LCOS device.

Accordingly, the previously vertically polarized light component is then rotated into a horizontally polarized light component that is ready for modulation. Two mirrors here are used to redirect the light to the right-half of SLM for the second modulation. The second modulation will only affect the light component that is not modulated at the first modulation. After two independent modulations on each of the orthogonal light components, both horizontal and vertical components of the output light field now carry the same diffraction image. Then, the two beams with orthogonal polarization states (0° and 90°) will be combined into a final polarization state.

In the concept-of-proof compact system, the LCOS SLM, a linear polarizer, mirrors, a half-wave plate, beam splitters, and a polarization beam combiner are integrated into a compact structure shown in Figure 5. The LCOS SLM is fabricated by in-house developed dye-level assembly techniques. The resolution of the LCOS device used in the experiment is 1920×1080. Two beam splitters (BS004) are used, which are the non-polarizing beam splitter cube with an energy split ratio at 50:50. Two mirrors (BBSQ05-E02) with 0.5-inch ×0.5-inch is a broadband dielectric mirror with a working wavelength of 400-750 nm. A polymer zero-order half-wave plate (WPH05ME) with a diameter of 0.5 inches is used to rotate the polarization angles of two separated light components. A linear polarizer (LPVISC050) with a diameter of 12.5 mm is used to create the input light with linear polarization at 45° for the system.

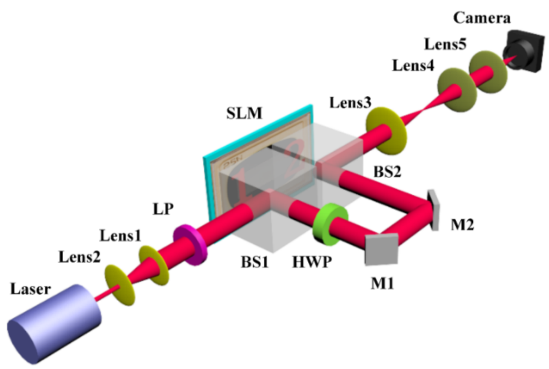

Figure 4. Schematic of the 3D optical configuration of the proposed polarization modulation system where a linear polarizer (LP), mirrors (M1 and M2), a half-wave plate (HWP), beam splitters (BS1 and BS2), and a polarization beam combiner (PBC) are used.

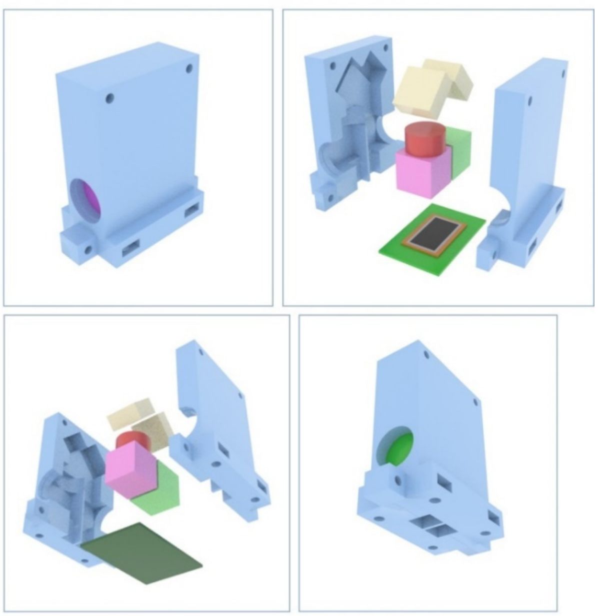

Figure 5. 3D structure of the compact system from design software 3Dmax.The optical elements and LCOS SLM are also shown in the system. The pink and green cubes represent the two non-polarizing beam splitters. The red cylinder is the half-wave plate, and the two cream cuboids are the mirrors.

The working principle of the compact system is shown in Figure 6. The input beam enters the system from the pink beam splitter, and the output beam exists from the green beam splitter. Due to the LCOS SLM is in reflective mode, the incident beam is designed to be normal to the LCOS surface and be bounced back to the coming direction. The LCOS SLM is split into two independent halves by loading two independently calculated CGHs. To avoid the input beam transmissive propagation through the beam splitter, an extra beam blocking film will be placed between two beam splitters.

The structure of the compact system is designed using software 3Dmax and be fabricated by high precision 3D print (Ultimaker S5). Figure 7 shows the final compact system integrated with LCOS SLM and optical components using the self-fabrication structure. The fabrication error is around 0.1mm after each making. To ensure the high precision assembly of every optical element, the final version of the compact system has been selected from five experimental versions. The optical path alignment has been tested before and after the assembly of the LCOS SLM so that the two incidences on the LCOS surface have been calibrated to be perpendicular. The angle input linear polarizer has been also calibrated to ensure that the input polarization has 45° to the working direction of LCOS SLM. Also, the angle of the half-wave plate is calibrated to ensure that two polarization components have been rotated 90° after passing through the wave plate.

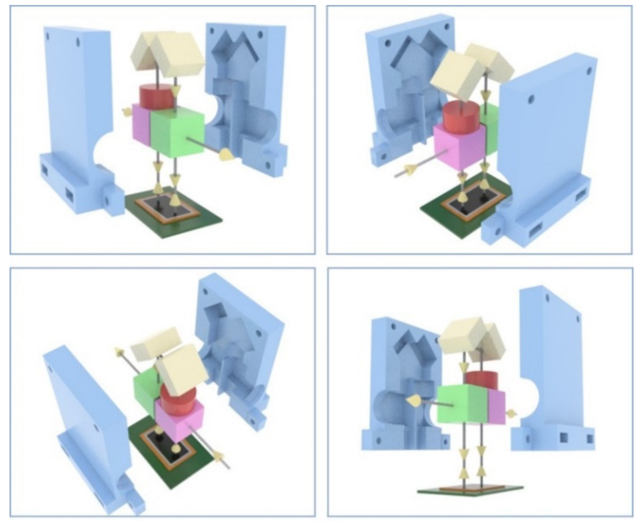

Figure 6. Schematic of the optical path of the compact system.

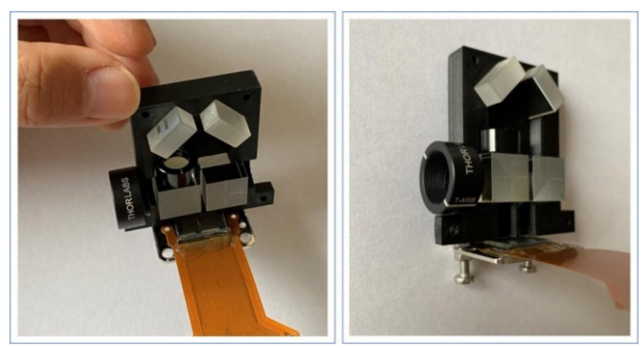

Figure 7. Prototype of the proposed compact system. All optical elements and LCOS SLM has been assembled, and the half of structure is removed to show the inside of the optical system.

B. Results and Discussion

In this part, the experiment results of phase and polarization modulation using the compact system have been shown. Due to the use of a single LCOS, two CGHs with the same target image information and different amplitude information (according to the target polarization) have been independently calculated and put spliced to form one joint CGH. Each of the sub-CGHs takes half of the active area of LCOS SLM. Here, two experiment results are shown in Figure 8 and Figure 9. The desired polarization images can be obtained by controlling holograms. These results indicated that the compact system can achieve the same performance in simultaneous phase and polarization modulation as the method of single beam coding. To provide high-quality experimental results, the adjustment in optical elements position in the compact system is required. To acquire high accuracy polarization modulation, the calibration of half-wave plate angle to the LCOS SLM working direction is also needed.

We also performed the comparison with the phase and polarization control system using two LOCS SLMs. The phase and polarization modulation method proposed in the two-LOCS-SLMs-based system is based on the principle of the single beam coding method introduced in this work. Thus, these two methods have similarities in many aspects. The major difference between the two methods comes from the new design of polarization components rotation in the compact system. Table 1 demonstrated the comparison of the two methods. The principle of phase and polarization modulation in both the compact system and the single beam coding system is the same. In both methods, the object of phase-only modulation on LCOS SLMs is the two orthogonal polarization components of one single input beam. The holographic target image information and the polarization components amplitude information are simultaneously encoded by computer-generated holograms. The target image information is calculated by the GS algorithm, and the polarization components amplitude information is controlled by using different phase depths of holograms to manipulate the first-order diffraction efficiency. Therefore, like the single beam coding method, the proposed compact system can also provide a glass-motion-free data writing function in optical data storage in a glass substrate. Moreover, the output target image and target polarization can be reconfigurable and dynamically altered at the speed of the refresh rate of LCOS SLMs.

The fundamental difference between the compact system and the single beam coding method is the use of two polarization components. Table 2 shows the SLM utilization comparison of different methods. In the method of single beam coding, two orthogonal polarization components are independently and sequentially modulated by two orthogonally placed LCOS SLMs. The working direction of two LCOS SLMs is aligned to their corresponding polarization component, respectively. This is because the directions of two polarization components of the input beam are left unchanged in this method. However, in the compact system, only one LCOS SLM is used so that there is only one working direction (either horizontal or vertical) for information encoding. Therefore, in the compact system, the independent rotation of two polarization components' direction is introduced to adapt the single liquid crystal molecule direction. This optical rotation can effectively exchange the direction of two polarization components for sequential information encoding, and the rotation does not affect the coded holographic target image information and amplitude information on polarization components.

Due to the use of a single LCOS SLM in the compact system, the cost of the writing beam generation system is largely reduced. This is because the LCOS SLMs device (liquid crystal cell and driving system) takes up the most hardware cost apart from the femtosecond laser system in data writing. More importantly, the compact system method can also be largely simplified polarization direction calibration. Because the input light needs to be 45° to the working direction of LCOS SLM, a precise polarization direction calibration is required. When only one LCOS SLM and one input beam are used, the direction calibration only needs to be conducted between one input beam and one LCOS SLM. However, in the previous method of the single beam coding, when two LCOS SLMs and one input beam are used, the input beam needs to be at 45° for both LCOS devices at the same time. Therefore, the calibration process becomes more complicated in this situation. In the compact system, the maximum input beam size can be half of the active area of LCOS SLM due to the use of a single LCOS device, thus, the total light intensity for phase and polarization modulation is reduced comparing with the single beam coding method

The proposed method has a potential application in the laser processing to optical data storage in the future. Here, we demonstrated how to use our vector beam laser processing for optical data storage. In optical data storage, when we consider the number of data bits that one voxel can carry, we can start from the number of available coding states (the combination of polarization states and retardance levels) for a voxel. Figure 10 shows an example of each voxel carrying 3 bits of data. The retardence level is normally controlled by the pulse length and times of the laser, and the polarization state of voxel is directed determined by the polarization state of the writing light field. To simultaneously control the data image pattern and its polarization state is the aim of our work.

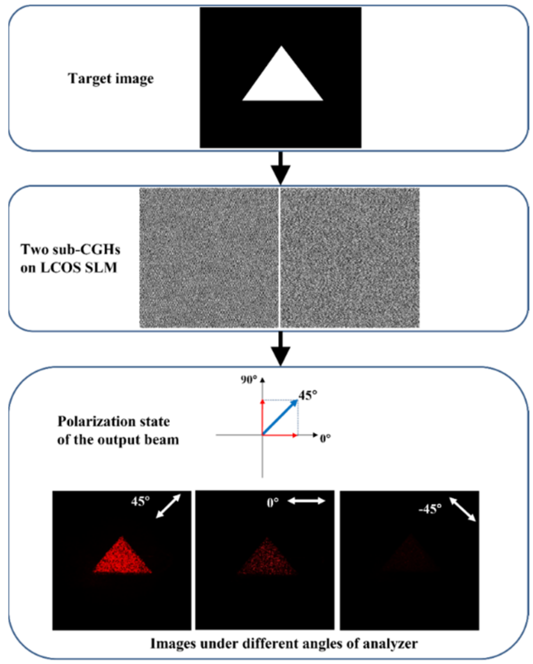

Figure 8. Images of output light field with target image (solid triangle) and target polarization state (45°).

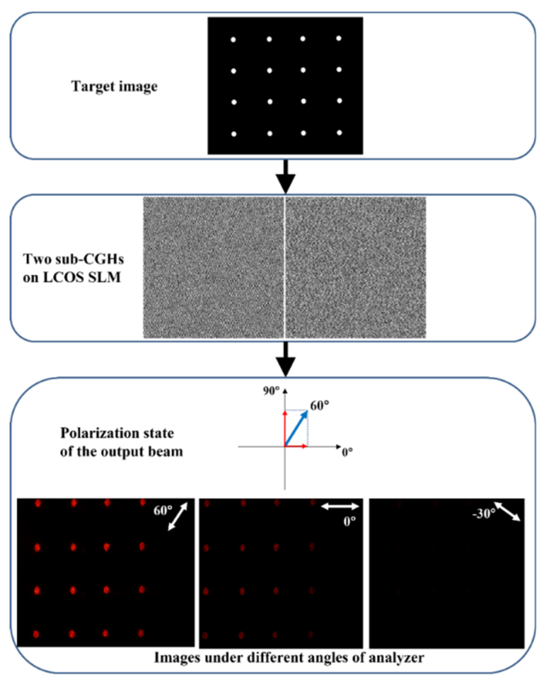

Figure 9. Images of output light field with target image (4x4 dot array) and target polarization state (60°).

Table 1. Comparison of single beam coding method and compact system

Methods	Phase modulation	Polarization modulation	Multi-polarization states writing	Delay	Output polarization states and image
Single beam coding system	CGH	Sequential coding of two components	Glass motion free	SLM refresh rate (60~100Hz)	Customizable
Compact system	CGH	Sequential coding of two components	Glass motion free	SLM refresh rate (60~100Hz)	Customizable

Table 2. SLM utilization comparison of single beam coding method and compact system

Methods	Input beam size	SLM utilization for polarization modulation	Polarization components calibration
Single beam coding system	SLM size	Two SLMs	Direction of two SLMs
Compact system	Half SLM size	Single SLM	Direction of single SLM

The polarization angle of voxel is one of parameter used for encoding data bits. Thus, a data page in the glass block consists of voxels with different polarization angles, and the voxels with a same polarization angle can have an arbitrary location distribution according to the encoded data. Therefore, the writing beam of voxels needs to able to produce a random multi-beam pattern, at the same time, the multi-beams light field needs to have the target linear polarization state. As shown in Figure 11, when one data page has four different polarization states of voxels (0°,45°,90°,135°), four exposures of four different writing beams (different target image and target polarization state) is needed to finish a data page.

The existing writing methods are mostly sequential writing. Some recent methods use phase-only LCOS SLM to generate data pattern, however, they still need external polarization modulator to convert the polarization state of holographic light field into the target. For sequential writing, many times of glass sample movement for the writing of one data page are needed. Due to the use of motor-driven platform, the mechanical delays caused by acceleration and deceleration processes take up a major part in the time duration of the current writing process. For methods using external polarization modulators, some still require sample stage movement, and the polarization modulator also will introduce delays. The proposed method requires no glass sample movement during the writing of each data page and no external polarization modulator. Therefore, apart from the femtosecond laser and glass sample moving in depth, the writing speed can be increased by using the proposed method.

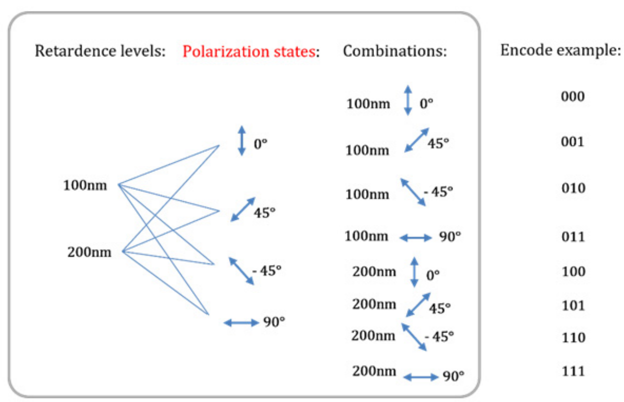

Figure 10. An example of data bits encoding and decoding as binary code onto the single voxel.

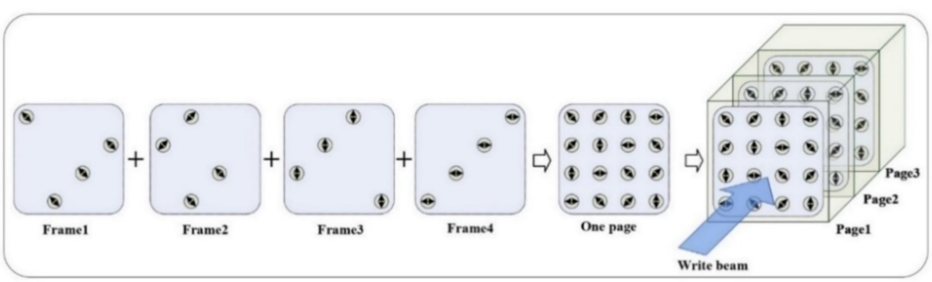

Figure 11. Schematic of the writing process of a data page in optical data storage in a glass.

4. CONCLUSIONS

In this paper, an efficient method for simultaneous phase and polarization modulation has been proposed. To verify the effectiveness of the method, the proof-of-concept compact system has been physically designed and fabricated by using high-precision 3D printing. The compact system of phase and polarization modulation can independently control the diffraction pattern of horizontal and vertical polarization light components. When we utilize this system to generate the desired polarization information for data writing in optical data storage using glass, the polarization state of the output light field can be dynamically controlled by only changing the CGH on LCOS SLM without any external device. The proposed optical design and modulation method are different from the existing ones, for being able to control arbitrary linear polarization states and allow the implementation of holographic image generation at the same time. This is suitable for the application requirement of optical data storage in glass.

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Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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