Optical image operation based on holographic polarization multiplexing of fulgide film

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Fulgide, a kind of thermally irreversible photochromic compound, can be used for polarization holographic recording owing to its photoinduced anisotropy and photochromic property under the irradiation of linear polarization light. In this letter, a new technique of optical image operation based on the polarization multiplexing scheme in the fulgide film is demonstrated, which can implement the readout of two individual orthogonal polarized images separately and the subtraction or summation of the two images by simply rotating a polarizer in front of the charge-coupled device (CCD) detector.

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Fulgide is a kind of organic photochromic material, which is famous for its thermal irreversibility. It has been regarded as having applications in rewritable optical memories and photofunctional switches for a long time[1]. In our previous work, we have reported the pyrrylfulgide/polymethylmethacrylate (PMMA) film used in parallel optical data storage[2] and its holographic properties[3]. We also found that fulgide has the photoinduced anisotropy accompanying the photochromic reaction. The photoinduced anisotropy originates from the molecular alignment of the photochromic reaction under the excitation of linear polarization light, resulting in an optical axis in the film[4]. This property can be used in polarization holography image storage[5] and polarization patterns control in camouflage technology[6]. In this letter, we demonstrate an image operation based on polarization-multiplexing holography. We have already studied the image operation caused by the photoinduced anisotropy property of fulgide[7].

The holography multiplexing techniques, including angular, wavelength, phase encoding, spatial, and peristrophic multiplexing, have already been reported. These multiplexing methods can be combined with other techniques to increase storage density. Todorov *et al*. first showed that two holographic recording could be stored independently inside the same film when using different combinations for the polarization states of the reference and the object beam during recording[8]. Su *et al*. presented a technique for polarization multiplexing in $LiNbO_3$[9]. Koek *et al*. presented a technique for simultaneous readout polarization multiplexing in bacteriorhodopsin[10]. All of these studies show that the polarization holography technology is a good method to improve storage density.

In this letter, we present a new image operation technique with polarization multiplexing technique. In this method, two images have been recorded separately, after which the diffraction images are simultaneously readout. The individual image and the subtraction and summation images can be reconstructed by rotating the polarizer P before the charge-coupled device (CCD) to a proper polarization position in reconstruction processing.

The preparation of pyrrylfulgide has already been described in Ref. [11]. It was doped in PMMA matrix with cyclohexanone. The film was obtained by spreading several drops of the pyrrylfulgide/PMMA solution on an optical glass ($\phi25\times1.5$ (mm)) and dried in air. The sample concentration was about 10 wt.-%(pyrrylfulgide/PMMA); the thickness of the film was about 10 μm. The absorption peaks of the colored form and the bleached form were 573 and 365 nm, respectively, as shown in Fig. 1.

The recording and reconstruction setup of the polarization multiplexing holograms is shown in Fig. 2. Beam from He-Ne laser (35 mW, vertical polarization) was split by a beam splitter. A computer (PC) controlled the recording image on spatial light modulator (SLM). To filter the high frequency information caused by the grid structure of SLM, a diaphragm D_1 was placed at the focal of lenses L_3 and L_4. The reference beam acted as the reconstruction beam. The polarizers P_1 and P_2 were then

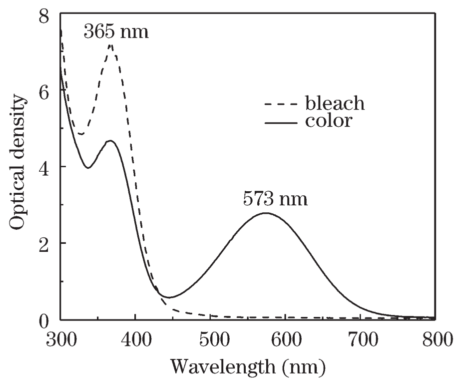

Fig. 1. Absorption spectra of the pyrrylfulgide/PMMA.

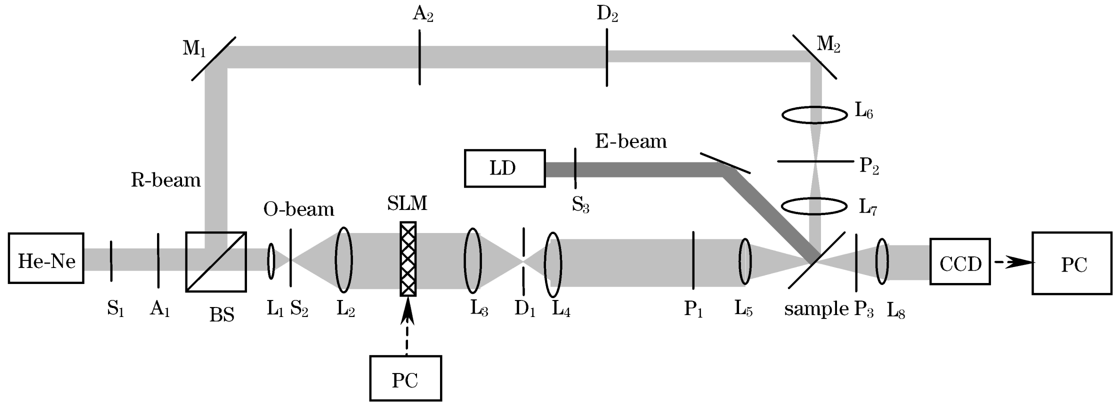

Fig. 2. Experimental setup of the polarization multiplexing holography. $S_1 \sim S_3$: shutter; A_1, A_2: attenuators; BS: polarizing beam splitters; $L_1 \sim L_8$: lenses; $P_1 \sim P_3$: polarizers; D_1, D_2: diaphragms; $M_1 \sim M_3$: mirror.

used to adjust the polarization of object beam and reference beam. The polarizer P_3before L_8 was used to select the reconstruction image. The intensity of object and reference beam was 14 mW/cm^2. The incident angle of the recording beams was 90°, which meant that the angle between the recording beam and the normal of sample was 45°. A 405-nm laser diode (LD) was employed to erase the sample from bleach state to color state.

First, the property of polarization holography recorded on fulgide was studied. The diffraction efficiency kinetic curves were measured with the numeric power meter D (United Detector Technology, 11A Photometer/Radiometer). The experimental set up has already been presented in Ref. [12]. The results are shown in Fig. 3, which shows that the diffraction efficiency of parallel linear polarization is 0.988% and that for the orthogonal linear holography is 0.4856%.

The image operation realized with the polarization holography method is presented. For the first recording, the parallel linear polarization hologram was recorded for 5 s. Both object and reference beam were in the horizontal polarization; afterwards, the polarization of the reference beam was changed to a vertical one in order to record the orthogonal linear polarization holography. The orthogonal linear polarization holography was recorded for 4 s. During the reconstruction process, the vertical linear polarization beam acted as the readout beam. When the polarizer P_3 before CCD was in horizontal polarization, the diffraction image of the parallel linear polarization holography was reconstructed on CCD. Then, while P_3 was rotated to the vertical position, the diffraction image of the orthogonal linear polarization holography was reconstructed on CCD. If the polarizer P_3 was rotated to 154° (or −26°) and 26° (or 206°), both holograms became diffracted. The subtraction and summation image was obtained on CCD.

The polarization states of all the beams in the experiment are presented in Table 1. Here we suppose the parallel polarization holography to record image a on the film, while orthogonal polarization holography recorded image b. The polarizer P_3 was set before the CCD. During the reconstruction process, when P_3 was set at different polarization positions, different images were obtained on the CCD camera.

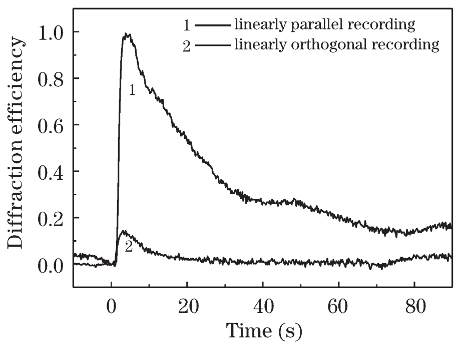

Fig. 3. Diffraction efficiency of the parallel and orthogonal linear polarization holographies.

Table 1. Polarization States in Recording and Reconstruction of Linear Polarization Multiplexing Holography

		Orthogonal Linear	Parallel Linear
Object Beam		↔	↔
Reference Beam		↕	↔
Reconstruction Beam		↕	↕
Diffraction Beam		↔	↕
Diffraction Beam after P	P (↔)	↔ (b)	none
	P (↕)	none	↕ (a)
	P (↕)	↗(a-b)	↗ (a-b)
	P (↕)	↖ (a+b)	↖ (a+b)

Here is the theoretical analysis of the polarization direction of the diffraction light. Suppose the Jones matrix of the diffraction image of the parallel linear holography (vertical polarization) is

$$\vec{P} = p \begin{bmatrix} 0 \\ 1 \end{bmatrix} \mathrm{e}^{\mathrm{i}\varphi_{\mathrm{P}}}, \tag{1}$$

where P is the diffraction efficiency of the parallel polarization holography. The Jones matrix of the diffraction

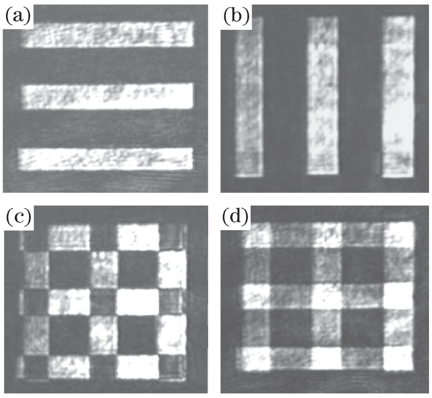

Fig. 4. Reconstruction image on CCD when polarizer P_3 was set at different positions. The positions of polarizer P_3 are 90° (270°), 0° (180°), 26° (206°), and 154° (−26°) to reconstruct the (a) parallel, (b) orthogonal linear holographies, (c) subtraction, and (d) summation image .

image of the orthogonal linear holography (horizontal polarization) is

$$\vec{O} = o \begin{bmatrix} 1 \\ 0 \end{bmatrix} e^{i\varphi_o}, \tag{2}$$

where o denotes the diffraction efficiency of the orthogonal polarization holography. The phase between these two diffraction beams is $\Delta\varphi = \varphi_p - \varphi_o = 0$.

Therefore, the summation field of these two diffraction beams is

$$\vec{E}_+ = \vec{P} + \vec{O} = \begin{bmatrix} o \\ pe^{-i\Delta\varphi} \end{bmatrix} = oe^{i\varphi_0} \begin{bmatrix} 1 \\ p/o \end{bmatrix}. \tag{3}$$

This is because the diffraction efficiency of these two types of polarization holography is different, the amplitudes of these two diffraction beams are not the same. Therefore, the summation field is an ellipse polarization beam. The angle of the summation field and X-axis is

$$\psi = \frac{1}{2} \cdot \tan^{-1} \Big[\Big(\frac{2op}{o^2 - p^2} \Big) \Big]. \tag{4}$$

From Fig. 3, the diffraction efficiency of parallel linear polarization is 0.988% and that for orthogonal linear holography is 0.4856%. Therefore, the angle of the summation field and x-axis is 154° or −26°.

In the same way, the subtraction field of these two diffraction beams is

$$\vec{E}_- = \vec{P} - \vec{O} = \begin{bmatrix} -o \\ pe^{-i\Delta\varphi} \end{bmatrix} = oe^{i\varphi_0} \begin{bmatrix} -1 \\ p/o \end{bmatrix} \tag{5}$$

and the angle of the subtraction field and X-axis is

$$\psi' = \frac{1}{2} \cdot \tan^{-1} \Big[\Big(-\frac{2op}{o^2 - p^2} \Big) \Big]. \tag{6}$$

Thus, the angle is 26° or 206°. When the polarizer P_3 was set at 0° (or 180°) and 90° (or 270°), the two individual images were respectively obtained (Fig. 4). When the polarizer P_3 was set at 154° (or −26°), the summation image was obtained. Finally, when the polarizer P_3 was set at 26° (or 206°), the subtraction image was also obtained.

In conclusion, the image operation based on polarization multiplexing holography is realized on fulgide film. The two diffraction images of polarization multiplexing holography and their respective summation and subtraction images can be simply reconstructed by rotating the polarization direction of the polarizer in front of the CCD. The same result can be obtained with the circularly polarized light multiplexing holography. This kind of information operation can be applied in all holographic recording films that have the photoinduced anisotropy property.

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