Beam shaping for 1 053-nm coherent light using optically addressed liquid crystal light valve

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An optically addressed liquid crystal light valve based on the photoconductive effect of the Bismuth Silicate (BSO) layer is presented. The transmittance of read beam (1 053 nm) through the light valve changes with the intensity of address beam (470 nm) projected onto the BSO layer. Beam shaping for 1 053-nm coherent light by using this device is reported. The device has the advantage of high transmittance and it can overcome the problem of black-matrix effect compared with the traditional thin film transistor (TFT) liquid crystal modulator.

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Spatial light modulators are playing more and more important roles in optics. They can control the amplitude, phase or polarization of the light and have been widely used in laser beam shaping[1,2], optical signal processing, optical neural network and so on. Real-time optical processing requires the development of 2-D spatial light modulators, among which liquid crystal spatial light modulators are the most commonly used ones. They include TFT-type (thin film transistor), LCOS-type (liquid crystal on silicon), and optically addressed liquid crystal light valve.

In many occasions, there is a strong desire to engineer a transmissive spatial light modulator as it can simplify the optical setup largely. While the reflective devices often have multilayer reflections which may lead to spectral distortions, converting imposed frequency modulation into undesirable temporal modulation. Although the TFT-type is a transmissive one, the black-matrix effect can cause a lot of problems[3], one of which is low transmittance.

The transmissive optically addressed light valve can overcome above-mentioned problems and has been studied widely[4,5]. In most cases, it has been used as a phase modulator in the following applications: wavefront correction, compensation of group delay dispersion and dynamic holography with gain[6]. While in National Ignition Facility (NIF), this kind of device has been used as an amplitude modulator in the preamplifier modules to shadow small, isolated flaws on downstream optical components[7].

Structure of the transmissive liquid crystal light valve[7] is shown in Fig. 1. The AC voltage is added to both liquid crystal layer and photoconductive layer through two transparent electrodes. Resistivity of the photoconductive layer decreases when the intensity of address beam increases. When the intensity of address beam projected onto the photoconductive layer changes, the voltage on the liquid crystal layer changes accordingly, which leads to different anisotropic birefringence of the liquid crystal layer. So the photoconductive layer enables the intensity of address beam to locally modulate the polarization of read beam. A downstream polarizer enables the polarization modulation to be manifested as an amplitude modulation. As a result, we can control spatial intensity distribution of read beam by controlling the intensity of address beam projected onto the light valve.

The detailed structure of our cell is described as follows (shown in Fig. 1). One of the substrates that closes the cell is a glass plate of 1-mm thick, while the other is a photoconductive bismuth silicate (BSO) layer of 1 mm thick. The antireflection layers are designed and the transmittance of this light valve for 1 053-nm light can reach 85%. The liquid crystal of the cell is in 90° twisted nematic mode. And the thickness of this layer is 9.12 μm. The AC voltage added to the light valve is 500 Hz, 25 V.

According to the optical absorption spectra curve and the spectral response curve of photoconductivity in BSO crystal shown in Fig. 2[8], 1 053-nm wavelength of read beam has a negligible effect on the crystal conductivity and also the crystal absorption is low. Meanwhile it implies that the wavelength of address beam must be in the optimum spectral sensitivity range of BSO crystal ($\lambda_{\mathrm{W}} \leqslant 500$ nm). We choose 470-nm light emitting diode (LED) (NSPB500AS,

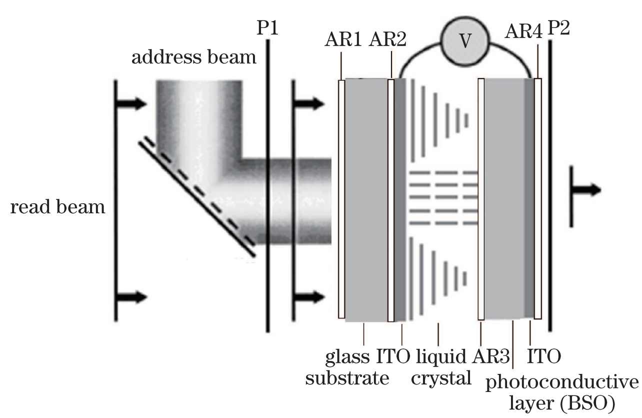

Fig. 1. (Color online) Working principle of liquid crystal light valve (P1//P2).

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NICHIA) as light source of address beam because the divergence angle of this type is small (full-angle $< 20°$) and its output optical power can reach 25 mW.

As analysed above, in our experiment, the transmittance of 1 053-nm coherent light through this light valve has a corresponding relationship with the intensity of 470-nm light projected onto the BSO layer. So if we can control the spatial intensity distribution of 470-nm light on the BSO layer, the spatial transmittance distribution of 1 053-nm coherent light through the light valve can be controlled simultaneously.

As shown in Fig. 3, in our experiment, the intensity of address beam projected onto the BSO layer was controlled by a LCOS spatial light modulator (the light valve located in the image plane of it). As a result, we realized a programmable mask for 1 053-nm coherent light by setting an appropriate bitmap of the LCOS modulator.

CCD (2 048×2 048 (pixel)), pixel size is 7.4 μm) here was used to measure the spatial intensity distribution of 1 053-nm coherent light after the light valve's intensity modulation. In our experiment, how to set the bitmap

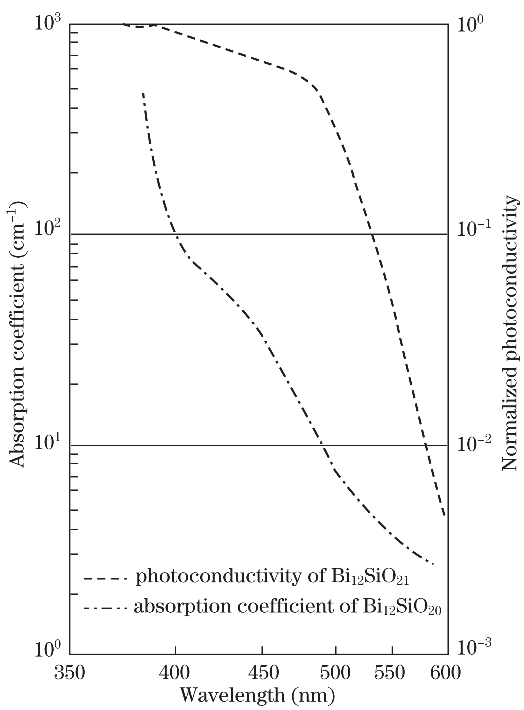

Fig. 2. Optical absorption spectra curve and spectral response curve of photoconductivity in BSO crystal[8].

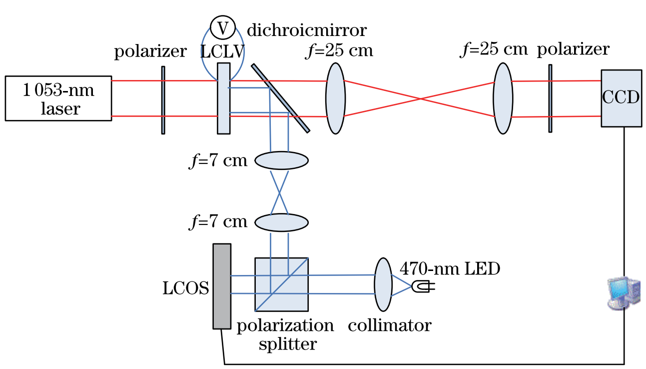

Fig. 3. Optical set up for beam shaping of 1 053-nm coherent light.

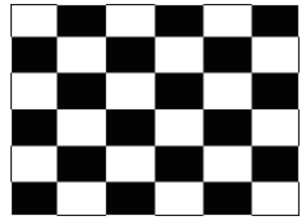

Fig. 4. Bitmap of LCOS set for testing the spatial resolution of the light valve.

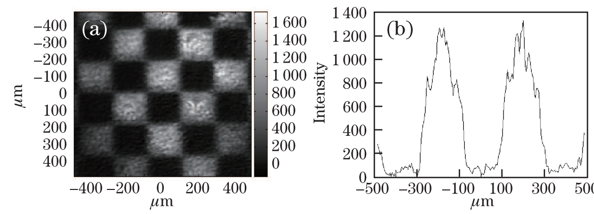

Fig. 5. (a) Beam profile of 1 053-nm coherent light through the light valve when the unit size is 200 μm for testing the spatial resolution; (b) cross section of (a).

of the LCOS modulator (we call it LCOS below) became the key. Although the transmittance of 1 053-nm coherent light through the light valve had a corresponding relationship with the intensity of 470-nm light on the BSO layer, it was difficult to calculate the desired blue intensity directly (because it involved the electro-optic response model of liquid crystal layer and the photoconductive response of BSO layer, also it was difficult to measure the intensity distribution of blue light on the BSO layer synchronously). Our general idea could be described as follows. By setting a series of bitmaps in the LCOS and measuring the intensity distribution of 1 053-nm coherent light behind the light valve simultaneously, we could get a corresponding relationship between the grey level of LCOS and transmitted 1 053-nm light intensity in different positions. As a result, we could set the bitmap of LCOS according to the desired intensity distribution of 1 053-nm coherent light. Obviously this method is easy to operate because we do not need additional optical setups other than in Fig. 3.

Firstly, we tested the spatial resolution of this light valve. The bitmap of LCOS was set in the form of Fig. 4 ('white' means the grey level is 255, and 'black' means the grey level is 0). We reduced the size of grid unit gradually and measured the intensity distribution of 1 053-nm light through the light valve simultaneously. As shown in Figs. 5(a) and (b), when the size of grid unit is 200 μm, the pixel structure was clear. When the unit size was reduced to 60 μm (shown in Figs. 6(a) and (b)), we could still see the pixel structure but the edge between light and dark area became blur. At the same time, we measured the intensity distribution of blue light on the BSO layer (The light valve was removed and CCD was put in that position). We could see its pixel structure was clear (shown in Figs. 7(a) and (b)). So we could deduce that when the unit size was 60 μm, the interaction between liquid crystal molecules was strong. And it was difficult to realize mutational intensity distribution in just a few microns. Meanwhile it means that this device has the advantage of generating non pixellated spatial transmittance.

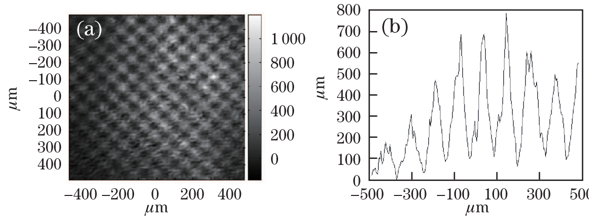

Fig. 6. (a) Beam profile of 1 053-nm coherent light through the light valve when the unit size is 60 μm for testing the spatial resolution; (b) cross section of (a).

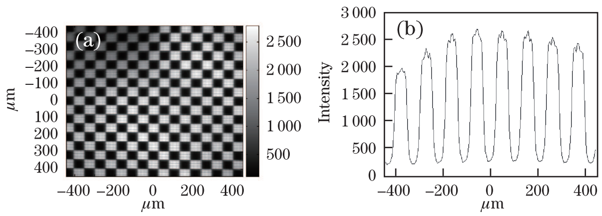

Fig. 7. (a) Beam profile of blue light projected onto the BSO layer when the unit size is 60 μm for testing the spatial resolution; (b) cross section of (a).

Spatial laser beam shaping of 1 053-nm coherent light was performed then. Bitmap of LCOS was firstly designed as follows. We set the grey level of all pixels to 255, 245, 235, $\cdots$, 5, respectively, and record the corresponding intensity distribution of 1 053-nm coherent light with CCD in each case. According to the above 26 datas, we could get the transmitted intensity I (x, y, G) of 1 053-nm light when the grey level was G in position (x, y) of LCOS:

$$I(x,y,G) = \begin{cases} I(x,y,G_N) & \text{if } G = G_N = 10N-5 \\ (G-G_N)/10\cdot[I(x,y,G_{N+1}) \\ \quad -I(x,y,G_N)] + I(x,y,G_N) & \text{if } G \neq G_N = 10N-5 \end{cases}$$
$$G = 0, 1, 2, \cdots, 255;\ N = 1, 2, 3, \cdots, 26. \quad (1)$$

If the desired intensity $I\_design(x, y)$ was the closest to $I(x, y, G)$, we then set the grey level to G in position (x, y) of LCOS. So the bitmap of LCOS could be set using this method and laser beam shaping was performed.

When the grey level of all pixels was set to 255 in circular area Φ_{diamater} = 1.5 mm, the intensity distribution of transmitted 1 053-nm coherent light was measured (shown in Fig. 8(a) and (b)).

We made the target intensity distribution centrosymmetric and flat-top in the center, super-gauss in the edge. Its one-dimensional normalized expression was

$$I(\rho) = \begin{cases} 1 & \rho \leqslant \rho_0 \\ \mathrm{e}^{-(\frac{\rho-\rho_0}{\omega})^5} & \rho > \rho_0 \end{cases}, \quad (2)$$

where we define ρ_0=0.3 mm and w=0.11 mm so that $I(\rho) = 1\%$ when ρ=0.45 mm.

This intensity distribution was shown in Figs. 9(a) and (b). According to Eqs. (1) and (2), the bitmap of LCOS was designed using the method mentioned above. And then, the actual output intensity distribution of 1 053-nm coherent light after shaping was shown in Figs. 10(a) and (b).

FM (Field modulation) and FF (Filling factor) are usually used to measure the beam quality of laser, which are defined as

$$\text{FM} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}, \quad (3)$$

$$\text{FF} = \frac{\int_s I(x,y)\mathrm{d}s}{I_{\max}\cdot S}, \quad (4)$$

where $I_{\max}$ and $I_{\min}$ mean maximum and minimum intensities in the flat-top of laser beam in Eq. (3). In Eq. (4), s means effective region, $I_{\max}$ means maximum intensity in the region s, and S means the area of this region.

To get high energy efficiency, FM must be as small as possible while FF must be as large as possible. In this experiment, FM decreased from 40% to 15% and FF increased from 39% to 67% after shaping which means the beam quality was improved largely.

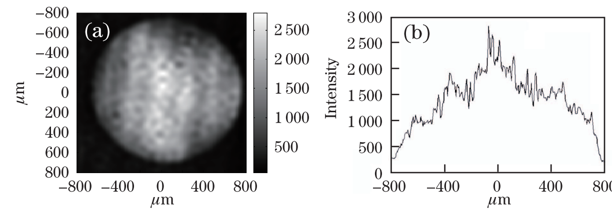

Fig. 8. (a) Beam profile of 1 053-nm coherent light through the light valve before shaping; (b) cross section of (a).

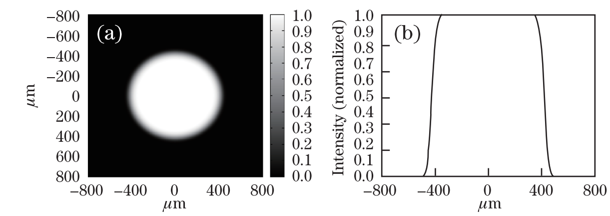

Fig. 9. (a) Target beam profile when it is designed flat-top in the center; (b) cross section of (a).

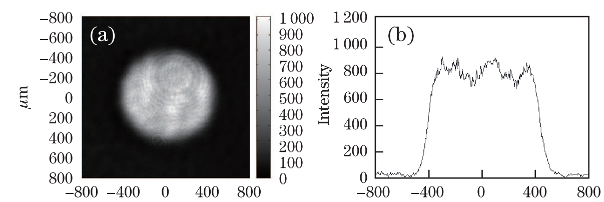

Fig. 10. (a) Beam profile of 1 053-nm coherent light through the light valve after shaping when the target intensity distribution is flat-top in the center; (b) cross section of (a).

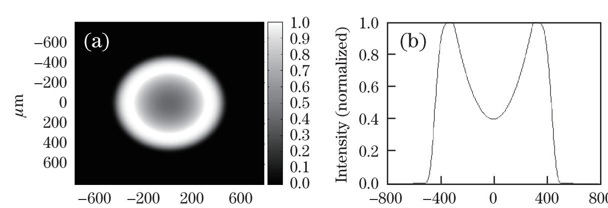

Fig. 11. (a) Target beam profile when it is designed parabolic in the center; (b) cross section of (a).

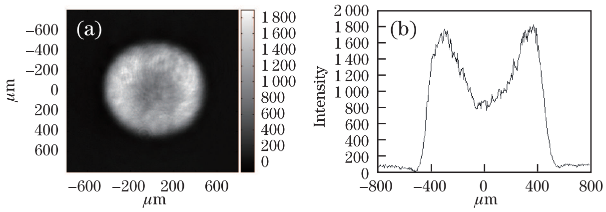

Fig. 12. (a) Beam profile of 1 053-nm coherent light through the light valve after shaping when the target intensity distribution was parabolic in the center; (b) cross section of (a).

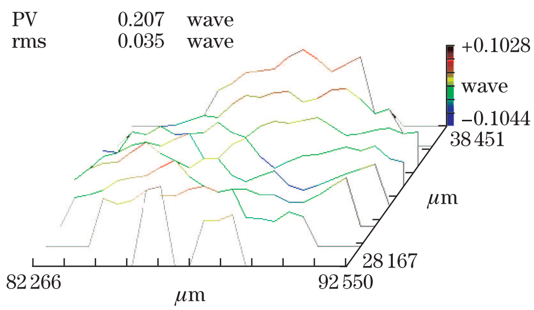

Fig. 13. Wavefront distortion of this light valve.

In this case, the target intensity distribution was designed parabolic as it could pre-compensate the spatially dependent gain of amplifiers in high power laser systems. The desired intensity distribution was also centrosymmetric and its one-dimensional normalized distribution was

$$I(\rho)=\begin{cases}\dfrac{(1-Y_0)\cdot\rho^2}{\rho_0^2+Y_0} & \rho\leqslant\rho_0\\ \mathrm{e}^{-(\frac{\rho-\rho_0}{\omega})^5} & \rho>\rho_0\end{cases}, \qquad (5)$$

where we define ρ_0=0.3 mm and w=0.147 mm so that $I(\rho)=1\%$ when ρ=0.5 mm.

In the central part, the ratio $\frac{I(\rho=0)}{I(\rho=\rho_0)}=Y_0$ describes the shape of parabola. In our experiment, we defined $Y_0=0.4$ and this ideal intensity distribution was shown in Figs. 11(a) and (b).

According to Eqs. (1) and (5), the bitmap of LCOS was designed and the intensity distribution of 1 053-nm light after shaping was shown in Figs. 12(a) and (b). The ratio $\frac{I(\rho=0)}{I(\rho=\rho_0)}$ was about 700/1 700=0.41. This value just had a difference of 3% with the desired one.

From the above results, our light valve indeed has the capacity of arbitrary shaping the 1 053-nm coherent light. The key in the experiment is how to set the bitmap of LCOS and our method has been proved feasible. This method is easy to operate because we do not need additional optical setups other than in Fig. 3.

From above, the spatial resolution of this light valve is about 60 μm and it is hard to realize mutational intensity distribution in just a few microns. As the liquid crystal thickness directly affects the spatial resolution[9,10], we can estimate that the spatial bandpass of our light valve at 50% maximum MTF is about 16 lp/mm. This value is obviously close to our experimental result. As there is an interaction between the liquid crystal molecules, when the spatial transmittance of the light valve changes locally, the transmittance in the adjacent region will change at the same time. Meanwhile it means that this device has the advantage of generating non pixellated spatial transmittance.

At the same time, the phase distortion should be considered when the light valve is used for intensity modulation. The wave front distortion after passing through this light valve have been measured using a fully automatic interferometer (Zygo, USA) at a wavelength of λ=633 nm. The maximum wave front deviation over a beam diameter of 10 mm is $\lambda/5$ (λ=633 nm, shown in Fig. 13). For λ=1 053 nm, we can estimate that this value is reduced to 0.13λ. As the twist angle of the liquid crystal layer is 90°, the phase shift δ varies very small when the intensity transmittance changes[11]. So our light valve can obtain quasi-intensity-only modulation with negligible phase variation.

In conclusion, we demonstrate spatial laser beam shaping of 1 053-nm coherent light with optically addressed liquid crystal light valve. By controlling the intensity of 470-nm incoherent light projected onto the BSO layer with a LCOS modulator, the spatial intensity distribution of 1 053-nm coherent light through the light valve could be controlled correspondingly. The key in the experiment is how to set the bitmap of LCOS and our method has been proved feasible. The experimental results also show that our light valve indeed has the capacity of arbitrary shaping the 1 053-nm coherent light and it has the advantage of high transmittance and generating non pixellated spatial transmittance.

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