Performance of an optically addressed liquid crystal light valve and its application in optics damage protection

Dajie Huang (黄大杰)*, Wei Fan (范 薇), Xuechun Li (李学春), and Zunqi Lin (林尊琪)

National Laboratory on High Power Laser and Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

**Corresponding author: hdajie@mail.ustc.edu.cn*

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We report an optically addressed liquid crystal light valve, a home-made device that has solved the problem of low transmittance caused by opaque electrodes in present transmissive spatial light modulators. The operating characteristic of the light valve is analyzed. The optimum driving voltage of this device is 27 V at 300 Hz, as deduced from the equivalent electric model. Its transmittance reaches 80% and its contrast is approximately 40:1. Its dynamic performance, especially its ability to obscure laser light at programmed locations, is demonstrated. The results are in good agreement with the desired shape, which indicates that our light valve performs very well.

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Liquid crystal (LC) spatial light modulators are extensively used in many fields because of the need for real-time control. The electrically controlled birefringence effect of LC is mainly used to modulate the light's phase or amplitude[1−3]. The two most common types of LC modulator are transmissive thin film transistor (TFT) and reflective liquid crystal on silicon (LCOS). Both types are electrically addressed and have become mature commercial products. The advantage of the TFT-type is that the optical setup is simple because it can be inserted at the desired location. However, the biggest problem is that its transmittance is low, which is attributed to the opaque electrodes around each pixel. This low transmittance will also cause the problem of black-matrix effect[4]. The advantage of the LCOS-type is the high reflectance (currently up to 80%), which is attributed to the integration of all pixel electrodes on the reflecting surface that benefits from the complementary metal–oxide–semiconductor process. However, the reflective surface of this type of LC modulator usually has a multilayer film structure, which may cause spectral distortion when used for short-pulse modulation. Furthermore, as a reflective device, this type of LC requires normal incidence, which usually makes the optical setup complicated.

The optically addressed LC light valve recently reported by the National Ignition Facility (NIF) in the US has a better performance compared with both the TFT-type and the LCOS-type. As a transmission-type device, it has higher transmittance compared with the TFT-type[5]. Thus, this technology won the R&D100 Award in 2012[6]. The device can obscure laser light at programmed locations within the beam profile. This obscuration can prevent the harsh laser fluence from exacerbating small, isolated flaws on downstream optical components. This technology can save approximately $5 million annually for NIF[6].

The parallel processing capabilities of the optically addressed devices are much stronger than those of the electrically addressed ones. The prospect of their application in optical information processing is also promising. We have successfully developed this type of spatial light modulator recently. The aperture of the home-made device has reached 22 × 22 (mm).

This letter reports the structure and performance of the device. The optimum driving voltage is deduced from the equivalent electric model. The dynamic performance, especially its ability to obscure laser light at programmed locations, is demonstrated. Moreover, we discuss the wave front distortion of this device.

The photo of our device is shown in Fig. 1. Both the device structure and the working principle are shown in Fig. 2. The substrate close to the cell is a glass plate, and the other is a 1-mm-thick photoconductive

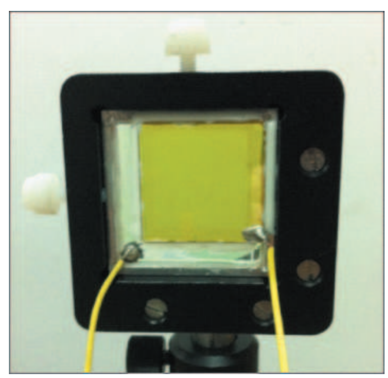

Fig. 1. Photo of the home-made device.

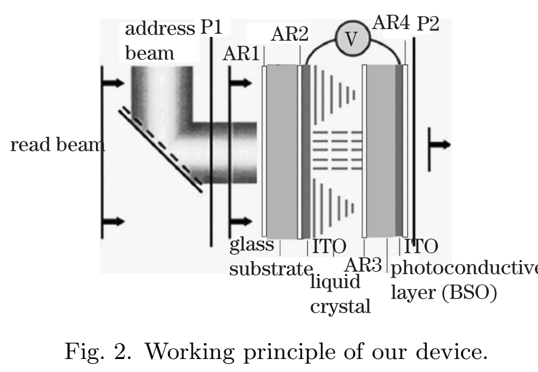

Fig. 2. Working principle of our device.

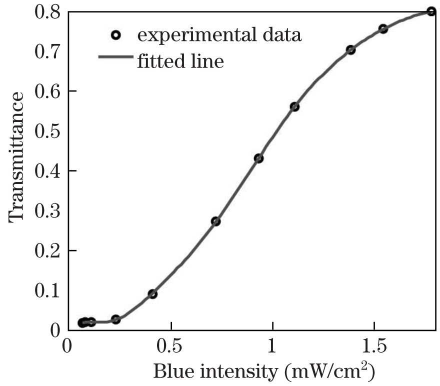

Fig. 3. Transmittance curve of the light valve when the driving voltage is 27 V at 300 Hz.

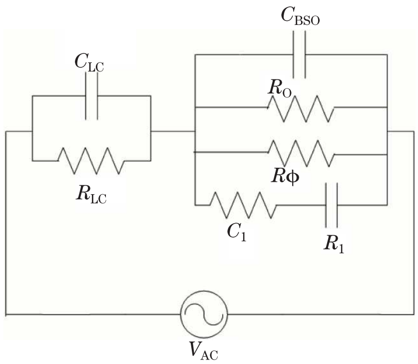

Fig. 4. Equivalent electrical model of the LC light valve.

$Bi_{12}SiO_{20}$(BSO) crystal. Transparent electrodes of indium tin oxide are deposited on the outer side of the BSO crystal and inner side of the glass plate. These two electrodes enable the serial application of a driving voltage across the photoconductor and the LC layer. The LC in the cell is in a 4.7-μm-thick twisted nematic mode. Antireflective layers are deposited on the inner and outer sides of both substrates to increase the transmittance of the device.

Considering the photoconductive characteristic of BSO crystal[7], the voltage on the LC layer changes when the intensity of the projected address beam (photosensitive light, λ <550 mm) changes, which leads to different anisotropic birefringences of the LC layer. Thus, the BSO layer enables the intensity of the address beam to locally modulate the polarization of the read beam. A downstream polarizer P2 (P2//P1) enables the polarization modulation to be manifested as an amplitude modulation. In our experiment, the read beam refers to the 1 053-nm coherent light and the address beam refers to the 470-nm incoherent light. We can control the spatial intensity distribution of the 1 053 nm coherent read beam by controlling the intensity distribution of the 470-nm incoherent address beam projected onto the BSO layer. Interestingly, the photoconductive effect of the BSO crystal at 1 053 nm is almost negligible. Thus, the 470-nm address beam and the 1 053-nm read beam do not interfere with each other.

We use the 470-nm light-emitting diode (LED) as the light source of the address beam. An amplitude LCOS spatial light modulator has been used to control the 470-nm collimated beam from the LED source. The bitmapped image is then projected onto the BSO layer through an imaging system. We can control the transmittance distribution of our light valve by setting an appropriate bitmap in the LCOS modulator.

The aperture of the light valve is 22 × 22 (mm). The intensity of blue light on the back of the photoconductor when the LCOS modulator is at its maximum reflectivity is approximately 1.8 mW/cm^2. The optimum driving voltage is 27 V at 300 Hz, which ensures a high transmittance for 1 053-nm light and a wide response range for 470-nm light. Under this condition, the transmittance of the light valve for 1 053-nm light has a monotonous, nearly linear relationship with the intensity of blue light on the BSO layer. This relationship is presented in Fig. 3. Figure 4 shows that this optically addressed LC light valve can be modelled with an electrical equivalent circuit. Similar models have been introduced for such devices using the same BSO photoconductor[8,9]. R_{LC} and C_{LC} are the resistance and capacitance of the LC

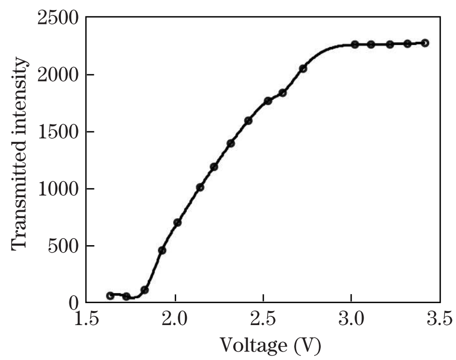

Fig. 5. The response curve of a 4.7-μm-thick LC cell composed of glass substrates.

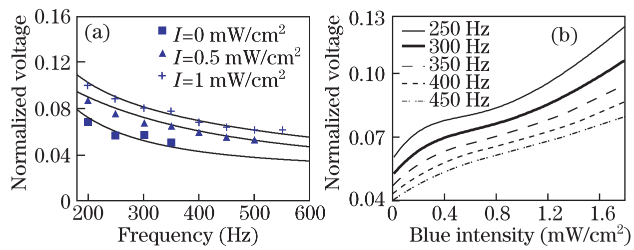

Fig. 6. (a) The normalized voltage on the LC layer as a function of the frequency of driving voltage under uniform illumination at different intensities (experimental points and theoretical curves). (b) The normalized voltage on the LC layer as a function of the blue light intensity for various operating frequencies of the driving voltage.

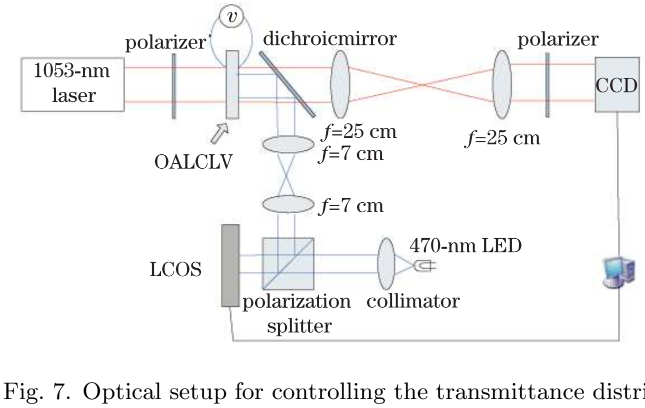

Fig. 7. Optical setup for controlling the transmittance distribution of the light valve.

layer, respectively, R_0 is the dark BSO crystal resistance, and R_Φ is its resistance under uniform illumination Φ. The value of R_1C_1 is inversely proportional to the illumination level Φ[8]. Several physical parameters have been used in the model as follows: $\rho_{\mathrm{LC}} \approx 10^{10}\ \Omega\cdot\mathrm{cm}$ and $\varepsilon_{\mathrm{LC}} \approx 10$ are the density and relative dielectric constant of the LC, respectively, and $\sigma_0 \approx 10^{-14}\ \Omega^{-1}\mathrm{cm}^{-1}$ is the dark BSO crystal conductivity.

The relationship between the transmittance of the light valve and the voltage on the LC layer is shown in Fig. 5. We measure the response curve of a 4.7-μm-thick LC cell composed of glass substrates. According to this figure, we can define $V_{\mathrm{thr}} = 1.75V$ and $V_{\mathrm{sat}} = 2.95V$.

According to Fig. 4, the voltage drop V_{LC} across the LC layer can be calculated as

$$V_{\mathrm{LC}} = V_{\mathrm{AC}}\cdot \frac{\frac{1}{R_0}+\frac{1}{R_\Phi}+\mathrm{j}\omega C_{\mathrm{BSO}}+\frac{\mathrm{j}\omega C_1}{1+\mathrm{j}\omega R_1C_1}}{\frac{1}{R_0}+\frac{1}{R_\Phi}+\mathrm{j}\omega C_{\mathrm{BSO}}+\frac{\mathrm{j}\omega C_1}{1+\mathrm{j}\omega R_1C_1}+\frac{1}{R_{\mathrm{LC}}}+\mathrm{j}\omega C_{\mathrm{LC}}}. \quad (1)$$

Figure 6 shows the results from the model and the physical parameters of the system mentioned earlier. Figure 6(a) shows the normalized voltage on the LC layer as a function of the frequency of driving voltage under uniform illumination at different intensities. We can obtain the experimental points according to the light valve's transmittance and the results in Fig. 5. The close agreement between the theoretical and the experimental points confirms the validity of this equivalent electric model. Figure 6(b) shows the normalized voltage on the LC layer as a function of the blue light intensity for various operating frequencies of the driving voltage.

Figure 6 shows that the relationship between the transmittance of the light valve and the blue light intensity on the BSO layer changes when the amplitude or frequency of the driving voltage is changed. Given the limited power of the LED source, we need to select an appropriate driving voltage of this light valve to ensure a

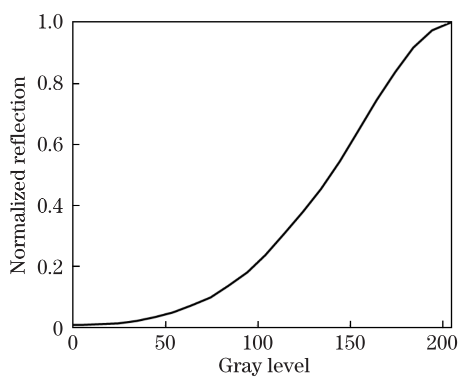

Fig. 8. Response curve of the LCOS modulator.

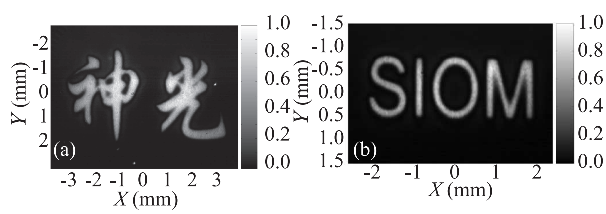

Fig. 9. Beam profile of the 1 053-nm coherent light in the shape of "神光" and "SIOM".

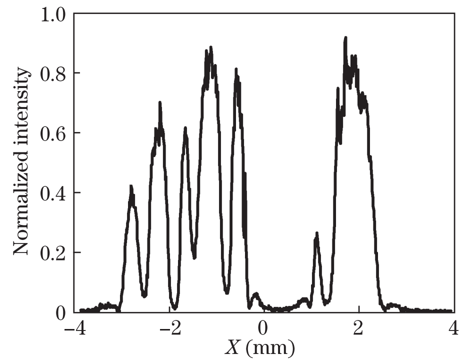

Fig. 10. One-dimensional distribution of the middle row in Fig. 9 (a).

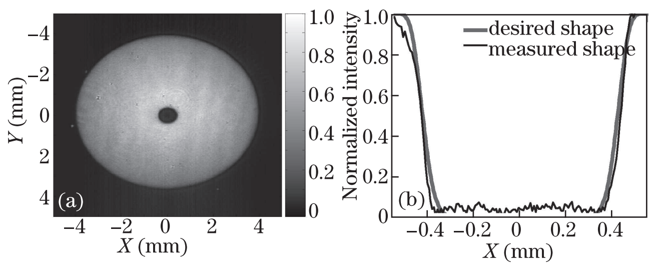

Fig. 11. (a) Beam profile with a "blocker" in the center and (b) through-center lineout of a blocker obscuration.

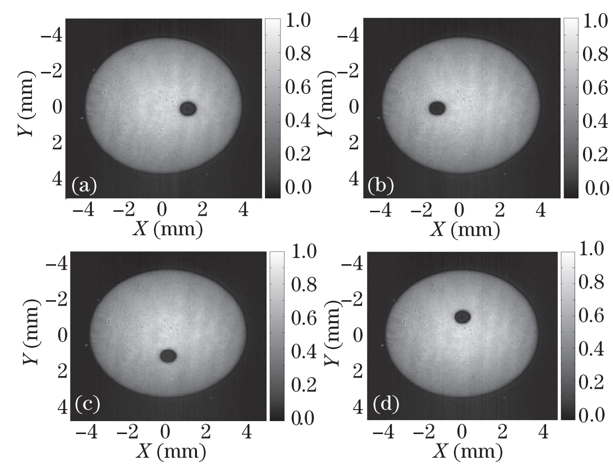

Fig. 12. The "blocker" moves. (a) ΔX=1.2 mm, (b) ΔX=–1.2 mm, (c) ΔY=1.14 mm, and (d) ΔY=–1.14 mm.

high transmittance for 1 053-nm light and a wide response range for 470-nm light. The voltage on the LC layer will increase when the operating frequency is decreased. We found that the spatial resolution of the light valve is poor when the operating frequency is lower than 200 Hz. This result is attributed to the increased sensitivity of the voltage on the LC layer to the blue light intensity on the BSO layer in a low operating frequency. The transmittance of the light valve would still be zero when the amplitude of the driving voltage is increased to 27 V at an operating frequency of 200 Hz. Thus, the proposed device can have a good off-state when the operating frequency $f_{\mathrm{AC}} > 200$ Hz in the absence of blue light irradiation.

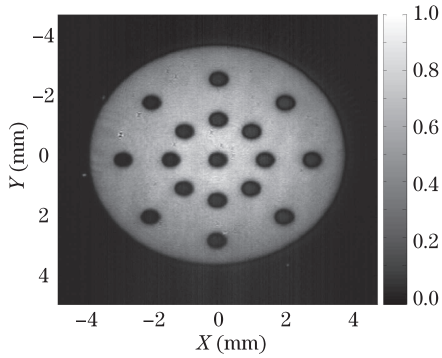

Fig. 13. Demonstration of the introduction of more "blockers" with our light valve.

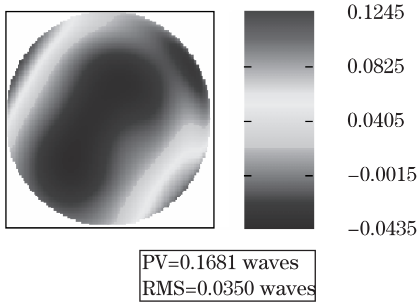

Fig. 14. Static wave front distortion of our light valve.

Figure 5 shows that the amplitude of the driving voltage must satisfy the following relationships:

$$V_{\mathrm{AC}} \cdot \mathrm{ratio}_{\mathrm{off}} \leqslant V_{\mathrm{thr}}, \quad (2)$$

$$V_{\mathrm{AC}} \cdot \mathrm{ratio}_{\mathrm{on}} \geqslant V_{\mathrm{sat}}, \quad (3)$$

where $\mathrm{ratio}_{\mathrm{off}}$ is the normalized voltage on the LC layer in the absence of illumination on the BSO layer and $\mathrm{ratio}_{\mathrm{on}}$is the normalized voltage on the LC layer in the presence of illumination on the BSO layer up to 1.8 mW/cm^2. Equation (2) ensures a good off-state of this light valve in the absence of illumination on the BSO layer. Equation (3) ensures a high transmittance for 1 053-nm light in the case of limited LED power. Equations (2) and (3) are equivalent to

$$\mathrm{ratio}_{\mathrm{off}} \leqslant 0.065, \mathrm{ratio}_{\mathrm{on}} \geqslant 0.109. \quad (4)$$

Interestingly, the transmittance of the light valve reaches a high value and the response range of blue light intensity increases when Eq. (3) is adjusted to $V_{\mathrm{AC}} \cdot \mathrm{ratio}_{\mathrm{on}} \approx V_{\mathrm{sat}}$. Thus, we can adjust Eq. (4) as

$$\mathrm{ratio}_{\mathrm{off}} \leqslant 0.065, \mathrm{ratio}_{\mathrm{on}} \approx 0.109. \quad (5)$$

Figure 6(b) shows that the operating frequency should be ideally adjusted to $f_{\mathrm{AC}} \approx 300$ Hz. Figure 3 shows the transmittance curve of our light valve when the driving voltage is 27 V at 300 Hz.

This case shows that the transmittance has a monotonous, nearly linear relationship with the blue light intensity on the BSO layer. The transmittance reaches the maximum value up to 80% when Φ=1.8 mW/cm^2, indicating that the response range of the blue light intensity has indeed reached the maximum value. This result also further proves the validity of the above electric model.

We use an amplitude LCOS spatial light modulator (Holoeye, Germany, 1 280 × 768, pixel size is 20 μm) to control the 470-nm collimated beam from a LED source and to demonstrate the dynamic performance of our light valve. The bitmapped image is then projected onto the BSO layer through an imaging system. The transmittance distribution of the light valve for the 1 053-nm light will change synchronously when a different bitmap is set in the LCOS modulator. The optical setup is shown in Fig. 7. A charge-coupled device (2 048 × 2 048, pixel size of 7.4 μm) is placed at the image plane of the light valve and is used to measure the intensity distribution of the 1053-nm transmitted light.

The response curve of the LCOS modulator at 470 nm is shown in Fig. 8. Figures 3 and 8 show that the transmittance distribution of our light valve can be controlled by setting an appropriate bitmap in the LCOS modulator.

Figure 9 shows the beam profile of the 1 053-nm coherent light in shape of "神光" and "SIOM". Figure 10 shows the one-dimensional distribution of the middle row in Fig. 9(a). The contrast is approximately 40:1, which meets the requirements of the SGII-Up laser system in China.

The presence of small, isolated flaws on downstream optical components can initiate damage to high-power laser systems and induce the potential to grow in size on subsequent high-fluence laser shots. "Blocker" obscurations at programmed locations upstream of the amplifier chain should be introduced to shadow these flaws. The optically addressed LC light valve has been used for this purpose[6]. Our device currently have this capability and will be used in the SGII-Up laser system.

Figure 11(a) shows a "blocker" in the center of the beam. Figure 11(b) shows that the experimental result is in good agreement with the desired shape. Figures 12(a-d) show the results when the "blocker" moves ΔX=1.2 mm, ΔX=–1.2 mm, ΔY=1.14 mm, and ΔY=–1.14 mm. The position error is less than 1%. Figure 13 demonstrates its ability to introduce more "blockers".

Wave front distortion of this light valve has also been considered. We have measured the static wave front distortion of this light valve with a Hartmann sensor. The static wave front distortion refers to the wave front distortion of transmitted light with respect to incident light. This distortion relates to the flatness of two substrates and the LC layer. The beam size of the 1 053-nm light in the experiment has a 7-mm diameter and PV$<0.2\lambda$.

The result is relatively good compared with the result in NIF[5]. Dynamic wave front distortion is negligible when the light valve is used to introduce "blockers". Thus, only the static wave front distortion needs to be considered. Figure 14 shows that this distortion is small and can be eliminated by the follow-up phase compensator (such as a deformable mirror).

In conclusion, we discribe the structure of a new LC light valve. The operating characteristic of the device is analyzed. The optimum driving voltage is 27 V at 300 Hz, which ensures a high transmittance for 1053-nm light and a wide response range for 470-nm light.

The high transmittance (80%), high contrast (40:1), and small wave front distortion (0.17λ) ensure that our device performs well. The dynamic performance, especially its ability to obscure laser light at programmed locations, is also demonstrated. This home-made device will be used in the SGII-Up laser system in China.

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