Compensation method for performance degradation of optically addressed spatial light modulator induced by CW laser

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Abstract In this paper, we propose an effective method to compensate the performance degradation of optically addressed spatial light modulators (OASLM). The thermal deposition problem usually leads to the reduction of the on-off ratio of amplitude OASLM, so it is difficult to achieve better results in high-power laser systems. Through the analysis of the laser-induced temperature rise model and the liquid crystal layer voltage model, it is found that reducing the driving voltage of liquid crystal light valve and increasing the driving current of optical writing module can compensate for the decrease of on-off ratio caused by temperature rise. This is the result of effectively utilizing the photoconductive effect of Bi₁₂SiO₂₀ (BSO) crystal. The experimental results verify the feasibility of the proposed method and increase the laser withstand power of amplitude-only OASLM by about 2.5 times.

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Key words: Liquid crystal, OASLM, Beam intensity shaping, Thermal effects

I. INTRODUCTION

In the past decade, liquid crystal spatial light modulator (LCSLM) is widely used in panel display, beam control, adaptive optics, laser processing and other fields because it can precisely control the beam amplitude, wavefront, polarization and other parameters by changing the effective birefringence of liquid crystal [1-5]. In addition, LCSLM is also widely used in the field of high power laser. Large aperture liquid crystal wave plate has been successfully applied in high power laser system [6]. It is reported that some liquid crystal devices have been used for more than 15 years, but the performance is still not significantly degraded. And LCSLM has been used in American NIF [7] and China’s “Shenguang” [8-10] for beam shaping and shielding damage points. However, when the laser power reaches a high intensity, the performance of the device will degrade. Because some materials in the structure of liquid crystal devices have a certain absorption of laser [11], this actually determines the damage threshold of LCSLM.

The commonly used LCSLM can be divided into many types. According to the function of spatial light modulator, it can be divided into phase type and amplitude type [12], and according to the addressing mode, it can be divided into electrical addressing (EA) type and optical addressing (OA) type [13]. However, no matter what type of LCSLM, indium tin oxide (ITO) and polyimide (PI) are essential in most cases. It is reported that the main heat source of LCSLM under laser irradiation is ITO layer, followed by PI layer [14, 15]. Moreover, the twisted nematic (TN) liquid crystal commonly used in LCSLM is very sensitive to the operating temperature [16], which leads to the degradation of the performance of LCSLM after temperature rise. In order to solve this problem, there are many studies on phase type EASLM. Watson et al. pointed out that this is
caused by the thermal expansion and cold contraction of sealant under the action of temperature, resulting in the inability of liquid crystal to completely fill the volume between glass substrates [17]. Cao et al. reported that the increase of temperature led to the phase transition of liquid crystal and changed the light intensity in the laser irradiation area [18]. He et al. established the SLM model and believes that the temperature affects the refractive index and rotation angle of liquid crystal molecules [19, 20]. Zhu et al. believe that the performance degradation is caused by the change of liquid crystal cell thickness due to temperature rise [21].

In addition to the research on phase type EASLM, the demand of high-power laser for amplitude type OASLM is also increasing. LLNL reports that the printing speed can be greatly improved by using OASLM for surface scanning printing [22]. And its developed OASLM has been used for beam shaping of fusion level laser system [23, 24]. The system can improve the service life of optical elements by shielding damage points. The LMJ in France adopts a design similar to NIF to form a laser in the injection laser system to compensate the gain distribution of the main amplifier [25]. Cai et al. reported that surface scanning additive manufacturing can be carried out by using OASLM [26], which has a good development potential in metal printing. With the development of high repetition rate laser, it is obvious that amplitude type OASLM also faces the problem of thermal degradation, which will limit its wide application. However, there are few reports on the damage mechanism and optical properties of amplitude type OASLM irradiated by high repetition frequency or continuous laser. Therefore, it is of great significance to study the performance of amplitude type OASLM under continuous irradiation of high-power laser.

In this paper, we build a laser-induced model based on the OASLM of BSO crystal to evaluate the thermal effect of OASLM under high power CW laser. On this basis, the effect of temperature on the transmittance of OASLM is studied. The results show that the transmittance of
OASLM increases with the increase of temperature. The threshold voltage and saturation voltage of the liquid crystal layer decrease with the increase of temperature, and the decrease degree of them is different. In order to meet the threshold voltage and saturation voltage of the liquid crystal layer at the same time, we propose to use the photoelectric characteristics of BSO, the partial voltage of liquid crystal layer is lower in low gray coding mode and higher in high gray coding mode, so as to meet two conditions at the same time to compensate the on-off ratio degradation of OASLM. Finally, only by adjusting the driving voltage of the liquid crystal light valve and output intensity of the optical writing module, the OASLM can operate normally for a long time under high power CW laser irradiation without any external heat dissipation measures.

II. THEORY

Laser induced heat transfer model

As a kind of transmission device [8], the schematic diagram of laser irradiation in practical use of OASLM is shown in Fig. 1. Different from the electrical addressed SLM, it can control intensity distribution by controlling the spatial intensity of 470 nm address beam, which will alter the resistance of BSO crystal and realize the voltage division in different regions. And there is only one layer of ITO adjacent to liquid crystal, another layer of ITO is moved to the outside of BSO, which will be different from the temperature distribution of electrical addressed SLM. Under the irradiation of CW laser, the whole device is a steady-state model, which needs to consider the internal thermal diffusion of the device.
Therefore, in order to analyze the thermal effect of OASLM under CW laser, the heat transfer model of this structure should be discussed first. It can be considered that each layer of OASLM is a heat source for absorbing laser energy. For a single wavelength, parallel incident laser, which experiences little refraction, reflection and scattering in the material, the absorption of laser energy can be analyzed by the Beer-Lambert law. The thermal distribution model of OASLM irradiated by high power CW laser at 1064 nm can be written as the following differential form:

\[
\frac{\partial I}{\partial Z} = \alpha I (1 - R)
\]  

(1)

where \( I \) is the intensity of incident laser, \( Z \) is the depth of the material, \( \alpha \) represents the absorption coefficient at 1064 nm laser, \( R \) is the surface reflectivity of OASLM to laser. After thermal deposition, the heat will change in space and time scales, it is necessary to solve the temperature distribution inside the material. As shown in Fig. 1(a), the partial differential equation of temperature distribution in the material is as follows:
\( \rho C \frac{\partial T}{\partial t} - k \frac{\partial}{\partial r} \left( \frac{\partial T}{\partial r} \right) - k \frac{\partial^2 T}{\partial z^2} = Q = \alpha I (1 - R) \)  

where \( \rho \), \( C \), \( k \) is the density, specific heat capacity and thermal conductivity of the material, and \( Q \) is the bulk heat source generated by the material absorbing laser energy. According to the geometric properties of OASLM structure layer, as shown in Fig. 1(b), there are several antireflective films in the actual structure. Because these films have little absorption of laser and are very thin, their heat transfer can be ignored. The marked parts are all key structures and are essential. A laser-induced heat transfer model is established by finite element analysis. Because the laser is incident from the front of OASLM, in order to simplify the model, the symmetry of the structure is used to reduce the size of the model, which only investigate 1/4 of OASLM, as shown in Fig. 2. The heat source region represents the part where the laser interacts with the material. The investigation part is the actual heat transfer model. The heat distribution model can be successfully established by setting the boundary conditions and the physical parameters of the material. The physical parameters of each material are listed in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Physical parameters of structural materials</th>
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<tr>
<td>Materials</td>
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</tr>
<tr>
<td>Thermal conductivity (W/mK)</td>
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<td>Absorption coefficient (1/m)</td>
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**Effect of temperature on optical properties**

The effective birefringence of liquid crystal changes with the increase of temperature. The temperature dependent birefringence can be expressed as [27]:

\[
n_e(T) = A - BT + \frac{2}{3}(\Delta n)_0 \left( 1 - \frac{T}{T_c} \right) ^ \beta
\]  

\( (3) \)
where \( n_e \) and \( n_o \) is the extraordinary index and the ordinary index, \( A \) and \( B \) are the temperature related parameters at a given wavelength, and the specific values can be solved through multiple sets of data measurement, \((\Delta n)_0\) is the effective birefringence of the liquid crystal in the crystal state (or \( T = 0 \text{ K} \)), and \( T \) is the actual temperature of the liquid crystal, \( T_C \) is the clear point temperature of the liquid crystal, \( \beta \) represents the material constant of liquid crystal. The liquid crystal studied in this paper is E7 type of which \( \beta \) is about 0.14-0.2.

By subtracting Eq. (4) from Eq. (3), the following relation between the birefringence index and temperature of liquid crystal can be obtained:

\[
\Delta n(T) = (\Delta n)_0 \left(1 - \frac{T}{T_C}\right)^\beta
\] (5)

The structure of amplitude type OASLM is that the alignment of liquid crystal is twisted by 90° through PI orientation layer. When a linearly polarized laser beam is incident vertically, the polarization of the output light passing through the liquid crystal cell will rotate by 90°. The angle of polarization rotation can be adjusted by adjusting the electric field intensity of liquid
crystal, combining with the polarizer behind the liquid crystal valve, the laser intensity modulation can be realized. In this case, the laser intensity through OASLM can be expressed as follows [28]:

\[
I = I_0(1 - R)\sin^2 \left( \frac{\pi}{2} \sqrt{1 + \left( \frac{2\Delta n d}{\lambda} \right)^2} \right) / \left( 1 + \left( \frac{2\Delta n d}{\lambda} \right)^2 \right)
\]  

(6)

where \(I_0\) is the incident laser intensity, \(d\) is the thickness of liquid crystal layer. Substituting Eq. (5) into Eq. (6), the relationship between intensity and temperature can be further obtained as follows:

\[
I = I_0(1 - R)\sin^2 \left( \frac{\pi}{2} \sqrt{N} \right) / N
\]  

(7)

\[
N = 1 + \left( \frac{2(\Delta n)_{0}\left(1 - T/T_C\right)^\beta}{\lambda} \right)^2
\]  

(8)

The above equation only analyzes the effect of temperature on the transmitted laser intensity, without considering the effect of electric field. When OASLM works, an electric field will be applied to the liquid crystal layer, and the birefringence of the liquid crystal can be expressed as follows [29]:

\[
\Delta n \approx \Delta n_0 - \left( \frac{U_{LC} - U_{th}}{U_{th}} \right) \Delta n_0 = \left( \frac{2\pi m\left(1 - T/T_C\right)^\beta - U_{LC}}{\pi m\left(1 - T/T_C\right)^\beta} \right) \Delta n_0
\]  

(9)

where \(U_{LC}\) is the voltage applied to the liquid crystal layer, \(U_{th}\) is the threshold voltage of the liquid crystal, \(m\) is a parameter related to the elastic coefficient, \(\Delta n_0\) is the birefringence without an applied electric field (or \(U_{LC} < U_{th}\)). The \(U_{th}\) represents the critical voltage for the deflection jump
of liquid crystal molecules, and the applied electric field does not work until it is higher than it. It is worth mentioning that only when \( U_{th} \) is slightly higher than \( U_{LC} \) Eq. (9) can it be established. As the difference between \( U_{LC} \) and \( U_{th} \) becomes too larger, the small angle approximation will no longer be satisfied. The \( U_{th} \) of the liquid crystal also changes with the temperature, which can be expressed as follows [29]:

\[
U_{th} = \pi m \left(1 - \frac{T}{T_C}\right)^{\beta/2}
\]

The liquid crystal light valve in OASLM is a series structure composed of ITO, BSO crystal and liquid crystal layer. The voltage of liquid crystal layer is not directly loaded, but determined by the external driving voltage of liquid crystal light valve and the partial voltage of BSO crystal [9]. The actual voltage of the liquid crystal layer can be expressed as:

\[
U_{LC} = U_{AC} \frac{1}{\frac{1}{R_0} + \frac{1}{R_\phi} + j\omega C_{BSO} + \frac{j\omega C_1}{1 + j\omega R_1 C_1}}
\]

where \( U_{LC} \) is the liquid crystal layer voltage and \( U_{AC} \) is the external driving voltage. \( R_0 \) is the dark resistance of BSO, and \( R_\phi \) is the resistance of BSO exposed to the writing light, which changes with the intensity of the writing light. \( R_1 \) and \( C_1 \) are the trapping effect resistance and capacitance of BSO crystal, respectively. The parameters can be calculated from the electrical properties of liquid crystal and the electrical impulse response of BSO.

By further processing the relationship between voltage and birefringence and the relationship between transmittance and refractive index, the relationship between transmittance and temperature under applied voltage can be obtained, by substituting Eq. (9) into Eq. (8) can get the following relationship:
\[ N_{ULC} = 1 + \left( \frac{2d\Delta n_0}{\pi m_0} \right)^2 \left( 2\pi m \left( 1 - \frac{T}{T_0} \right)^\beta - U_{LC} \left( 1 - \frac{T}{T_0} \right)^\beta / 2 \right) \] (12)

The transmittance of OASLM under temperature and voltage can be obtained by solving Eq. (12) as follows:

\[ T_{SLM} = \frac{I}{I_0} = (1 - R)\sin^2 \left( \frac{\pi}{2N_{ULC}} \right) / N_{ULC} \] (13)

where \( T_{SLM} \) is the transmittance of OASLM, when calculating the effect of temperature on transmittance, \( U_{LC} \) is a given fixed value, \( \Delta n_0 \) is the birefringence at room temperature without external electric field. According to Eq. (12) and Eq. (13), when the voltage of the liquid crystal layer is constant, the transmittance of OASLM increases with the increase of temperature.

III. NUMERICAL SIMULATION AND THEORETICAL ANALYSIS

The external boundary of OASLM in the laser-induced model is affected by air convection. For the surface exposed to air, the heat transfer coefficient is set as \( h = 5 \) W/ (m\(^2\)·K), the profile generated by the simplified model is set as a symmetrical boundary, and the ambient temperature is set as 298.15 K. According to the model parameters in Table 2, the laser beam is Gaussian distribution, and the laser power density is set to 16 W/cm\(^2\). The steady-state temperature distribution on the \( y=0 \) plane of the liquid crystal light valve is shown in Fig. 3(a), \( L \) represents the distance from the laser irradiation center (or \( L = x \)). The high temperature region of OASLM is concentrated in the BSO Crystal region. This is because the BSO Crystal has a certain absorption to the laser, and the ITO is in direct contact with the air, so the thermal conductivity is low, and the heat cannot be dissipated in time. The temperature distribution of ITO layer, LC layer and K9 substrate as shown in Fig. 3(b), where ITO1 is the conductive film layer on the BSO crystal side,
and the temperature of LC layer is close to that of ITO in the liquid crystal light valve. The
temperature in this region has a direct impact on the performance of OASLM, and the maximum
temperature difference between K9 substrate and liquid crystal layer is about 4 K. Because of the
Gaussian distribution of the beam, the temperature gradient is most obvious in the central region
of laser irradiation, and gradually decreases along the horizontal direction. Fig. 3(c) shows the
temperature distribution in the depth direction of OASLM at the laser irradiation center, and the
temperature increases uniformly from K9 side along BSO side. It can be seen that under the
irradiation of high power CW laser, the temperature of liquid crystal light valve will far exceed
the normal working temperature, which will affect the performance of OASLM.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
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<tr>
<td>Beam diameter</td>
<td>8</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of K9</td>
<td>3</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of BSO</td>
<td>1</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of ITO</td>
<td>50</td>
<td>nm</td>
</tr>
<tr>
<td>Thickness of ITO</td>
<td>100</td>
<td>nm</td>
</tr>
<tr>
<td>Thickness of ITO</td>
<td>4.8</td>
<td>um</td>
</tr>
</tbody>
</table>
Fig. 3. (a) Temperature distribution on the y=0 plane of laser-induced liquid crystal light valve. (b) Temperature distribution along transverse direction of ITO layer, K9 layer and LC layer. (c) Temperature distribution along the depth direction at the center of liquid crystal light valve, the small icon shows the material structure distribution along the Z direction.

The temperature induced degradation is mainly due to the change of birefringence which affects the transmittance of OASLM. When the liquid crystal light valve is in the “OFF” mode, this means the linearly polarized light passes through the TN liquid crystal cell and rotates 90°, and there is no light output after passing through the polarizer, the initial transmittance \( T_{\text{SLM}} = 0 \).

As the temperature changes, the transmittance is affected by temperature by calculating Eq. (12) and Eq. (13), as shown in Fig. 4(a). In the analysis and calculation, the reflectivity \( R \) is not affected by temperature and voltage and is a constant. For the convenience of calculation, we make \( R = 0 \).

With the increase of temperature, the transmission rate of OASLM increases gradually, and the transmittance increases sharply when it approaches the clear point (332 K), which makes OASLM unable to modulate amplitude. In the process of temperature rise, the liquid crystal is mainly affected by the electric field and temperature, and the temperature affects the threshold voltage of
the liquid crystal light valve. In order to ensure the normal voltage response of OASLM, the $U_{LC}$ of the liquid crystal layer usually requires slightly higher than the threshold voltage $U_{th}$. With the increase of temperature, the $U_{th}$ of liquid crystal changes. Obviously, the voltage $U_{LC}$ of liquid crystal layer also needs to be adjusted, which needs to be realized by adjusting the external driving voltage $U_{AC}$. According to Eq. (10) and Eq. (11), the relationship between the driving voltage of OASLM and the temperature is obtained, as shown in Fig. 4(b). With the increase of temperature, the driving voltage begins to decrease until the liquid crystal reaches the clear point, and the effect of electric field is no longer considered. It is worth mentioning that the damage performance of OASLM irradiated by CW laser is different from that irradiated by pulsed laser. Under high power pulsed laser irradiation, OASLM will produce unrecoverable physical damage points, which is limited by the damage threshold of ITO. Under high power CW laser or quasi CW laser, the thermal deposition of OASLM leads to the degradation of equipment performance, which is a recoverable damage, which is limited to the clear point of liquid crystal. Before that, the performance degradation caused by temperature can be compensated by electric field, which can use OASLM more effectively.

![Fig.4.](image) (a) Relationship between transmittance and temperature of OASLM. (b) The required adjustment of driving voltage with temperature.
In order to reduce the effect of temperature, the transmission change can be compensated by adjusting the electric field of the liquid crystal layer. When the liquid crystal light valve is in the “OFF” mode, and can make it respond to voltage, the $U_{LC}$ of the liquid crystal layer needs slightly higher than the threshold voltage $U_{th}$. When the liquid crystal light valve is in the “ON” mode, the voltage of the liquid crystal layer also needs to meet the saturation voltage, which is the voltage value that enables the liquid crystal molecules to deflect completely. It is necessary to reduce the voltage $U_{LC}$ of the liquid crystal layer and meet the requirement of saturation voltage at the same time. In Eq. (11), the factors that affect the liquid crystal layer voltage include the resistance $R_\phi$ and driving voltage of BSO crystal. The $R_\phi$ can be realized by adjusting the signal intensity of the writing beam, which is controlled by the driving current. The driving voltage and current of OASLM in normal working state are 24 V and 600 mA respectively. The voltage distribution of liquid crystal layer under different driving voltage and driving current in each gray mode is calculated by Eq. (11), as shown in Fig. 5. Only reducing the driving voltage can reduce the $U_{LC}$ of the liquid crystal layer obviously, but at the same time, the $U_{LC}$ of the liquid crystal layer at each gray level is reduced. In particular, the saturation voltage decreases significantly, which makes the electric field of the liquid crystal light valve insufficient, resulting in the decrease of the transmittance of OASLM. With the decrease of driving voltage and the increase of driving current of writing light, the BSO crystal has higher resistance in low gray mode, and the $U_{LC}$ of liquid crystal layer is reduced as scheduled. The $R_\phi$ of BSO crystal in high gray mode is smaller, so the liquid crystal layer can get more voltage, the liquid crystal light valve can meet the saturation voltage, and the transmittance of OASLM is guaranteed, the compensation process is shown in Fig. 6. In addition, increasing the driving current of writing light only adjusts the intensity of the addressed blue LED and will not be directly loaded on the liquid crystal cell. The increased blue
light intensity is not enough to damage the liquid crystal. However, increasing the driving current may reduce the service life of blue LED.

Fig.5. The voltage of LC layer changes with the loaded gray level under different driving conditions.

Fig.6. The flow chart of the proposed compensation method.

IV. EXPERIMENTAL SYSTEM AND RESULTS

Fig. 7 shows the experimental measurement device. CW fiber laser is used to irradiate OASLM to study the variation of optical properties of OASLM with temperature rise. The amplitude type OASLM (720 × 720) device used in the experiment is home-made [8-10], the optical aperture is 22 mm × 22 mm, the transmittance is greater than 85% at 1064 nm, and the switch ratio is greater than 100:1, the default driving voltage is 24 V, and the driving current is 600 mA. The central wavelength of the laser is 1064 nm, and the diameter of the spot irradiated on OASLM is 8mm.
The driver is used to adjust the driving voltage and current of address beam. The polarizer1 (POL1), polarizer2 (POL2) and half wave plate (HWP) are used to fine-tune the power of read-out laser beam. The laser power density irradiated on OASLM can be calculated by power meter. The thermal imager is used to detect the surface temperature liquid crystal light valve. The neutral density filter (NDF) is used to protect the CCD from damage. Polarizer3 (PLO3) and analyzer (ANA) are aligned in parallel to make OASLM output initially in the “OFF” mode, and the CCD is used to detect the light field intensity distribution of the system.

![Fig. 7. Schematic diagram of OASLM temperature rise performance test experimental system, POL: Polarizer, HWP: Half wave plate, BS: Beam splitter, NDF: Neutral density filter, L: Lens, and ANA: Analyzer.](image)

When OASLM is in the “OFF” mode, the CCD cannot detect the light intensity at normal operating temperature (298 K), the transmittance of the device is 0. Detect the temperature change of liquid crystal light valve under different laser power density, as shown in Fig. 8(a), each result is obtained under long-term irradiation. The results show that the temperature increases with the increase of laser power density. Because there are no thermal management measures, when the power density reaches 23 W/cm$^2$, the liquid crystal temperature reaches the clear point (332 K). In order to prevent OASLM from not working and can be compensated, it is more appropriate to set the laser power of subsequent experiments to 21 W/cm$^2$. In the process of reaching the clear point from the ambient temperature, the light field intensity detected by CCD changes with the increase of the temperature of the liquid crystal light valve, which converts the light field intensity change...
into the transmittance change of OASLM, as shown in Fig. 8(b). The results show that the transmittance of OASLM increases continuously with the increase of temperature until the liquid crystal light valve loses its effect.

Fig. 8. (a) Temperature of OASLM as a function of laser power density. (b) Transmittance of OASLM as a function of temperature, the red data points are the experimental data and the blue curve is the fitting curve.

Through the previous theoretical calculation, the influence of temperature on the transmission of OASLM can be compensated by reducing the driving voltage. When the laser intensity is set to 21 W/cm², the transmittance increases due to the temperature rise (326 K) of the OASLM. At this time, the OASLM cannot reach the "OFF" mode, and the light field intensity distribution is shown in Fig. 9(a). Then, by reducing the driving voltage for compensation, the change of the light field is shown in Fig. 9(b) to Fig. 9(d), the corresponding voltages are 22 V, 20 V and 19 V respectively. The results show that the increase of transmittance caused by temperature is compensated. The compensation voltage at different temperatures is recorded, and the relationship diagram shown in Fig. 9(e) is obtained, which is basically consistent with the theoretical calculation results. In addition, in order to verify the influence of driving voltage and driving current on the transmittance of OASLM under different operating temperatures, the relationship curve (gamma curve) between the transmittance and gray level of OASLM under
different gray level is detected by CCD, as shown in Fig. 9(f). Curve 1 is the gamma curve of OASLM in normal operation (at 298 K-310 K). At this time, the power density of the laser is below 7.5 W/cm², the driving voltage is 24 V and the driving current is 600 mA, Curve 2 shows the gamma curve when the temperature is raised to 326 K by laser irradiation, the power density of the laser reaches 21 W/cm². In this case, OASLM cannot work in black mode. By adjusting the driving voltage to 19 V, the gamma curve is shown in curve 3, which essentially reduces the threshold voltage of the liquid crystal light valve and enables OASLM to be in “OFF” mode. However, the voltage of each gray level is reduced, resulting in a significant reduction in the overall transmittance of OASLM, which seriously affects the utilization of laser. Through the analysis of the results in Fig. 5, when the driving current is increased to 1000 mA, the gamma curve shown in curve 4 is basically the same as that at 298 K. The influence of temperature on the performance of OASLM is compensated, and the device can work stably for a long time. It is worth noting that this scheme can compensate that the maximum temperature is lower than the clear point temperature. After the temperature reaches the clear point, the liquid crystal no longer has anisotropy and no longer has modulation effect on the beam.
Fig. 9. (a) Distribution of light field after increasing transmittance after temperature rise at 24 V. (b) (c) and (d) Light field distribution at 22 V, 20 V and 19 V. (e) OASLM driving voltage as a function of temperature, red data points represent experimental data. (f) Gamma curves under different driving and different temperatures. Curve 1: 298 K, 24 V, 600 mA, Curve 2: 326 K, 24 V, 600 mA, Curve 3: 326 K, 19 V, 600 mA, Curve 4: 326 K, 19 V, 1000 mA.

Load the pattern on the OASLM to test the performance. Fig. 10(a) shows the gray pattern loaded on the OASLM, and the gray size is sinusoidal along the Y direction. Fig. 10(b) shows the light field distribution when the laser power density is 7.5 W/cm², and the OASLM performance is normal. When the laser power density increases to 21 W/cm², the temperature rise reaches 326 K, the light field distribution of OASLM is shown in Fig. 10(c). The result shows that the temperature has a greater impact on the performance of OASLM at low gray level and less at high gray level. The light field distribution obtained after compensation according to the proposed method is shown in Fig. 10(d). At this time, the light field distribution is basically consistent with that at 7.5 W/cm². Fig. 10(e) is a comparison diagram of transmittance at the same section line position in three light field distributions. The results show that the OASLM can maintain normal
performance under high power density. In some working cases, OASLM only needs to load binary patterns, by loading strip patterns with gray levels of 0 and 255, as shown in Fig. 11(a), the light field distribution of laser power density at 7.5 W/cm$^2$ and 21 W/cm$^2$ is detected by CCD, as shown in Fig. 11(b) and Fig. 11(c). The increase of temperature makes the 0 gray level area in OASLM unable to reach the “OFF” mode, which has a negative impact on the working performance. By adjusting the light field distribution after voltage and current, the transmittance of 0 gray level area decreases significantly, as shown in Fig. 11(d). Take a section line in the light field distribution under the three working states for comparison, as shown in Fig. 11(e). The results show that the corrected transmittance distribution is basically consistent with the OASLM index under normal operation, this means that the transmittance is still higher than 85% and the switching ratio remains greater than 100:1. In addition, although the proposed method can make the OASLM work normally at higher power density, there will be a certain temperature gradient in the irradiation area for the scene where the laser spot is Gaussian distribution, as shown in Fig. 3. When the temperature gradient is large, the threshold voltage in different regions will vary greatly. In this scenario, the compensation method needs to be further studied.

**Fig. 10.** (a) Gray level sinusoidal distribution pattern, the red circle indicates the laser irradiation area. (b) Optical field distribution at 7.5 W/cm$^2$. (c) Optical field distribution at 21 W/cm$^2$. (d)
Optical field distribution at 21 W/cm² after compensated. (e) Comparison of transmittance at section line positions in (b), (c) and (d).

Fig. 11. (a) Binary gray bar pattern, the red circle indicates the laser irradiation area. (b) Optical field distribution at 7.5 W/cm². (c) Optical field distribution at 21 W/cm². (d) Optical field distribution at 21 W/cm² after compensated. (e) Comparison of transmittance at section line positions in (b), (c) and (d).

V. CONCLUSION

In summary, we have analyzed the thermal distribution and optical properties of amplitude OASLM after temperature rise based on the laser-induced model and numerical simulation of OASLM. The laser model results show that the heat source of OASLM is mainly concentrated in the ITO layer on the BSO side, and the temperature of the liquid crystal layer is mainly affected by the temperature of the ITO layer inside the liquid crystal cell. The numerical calculation of temperature and transmittance shows that the transmittance of OASLM increases nonlinearly with the increase of temperature, and the threshold voltage of liquid crystal layer decreases with the increase of temperature. By adjusting the driving voltage and current of OASLM, the compensation effect of performance degradation caused by temperature rise is realized. Using the photoelectric characteristics of BSO crystal, OASLM working at high temperature can still be in low transmittance state in low gray mode and high transmittance in high gray mode. The
experimental results show that the laser withstand power of OASLM can be increased from 7.5 W/cm² to about 21 W/cm², the damage power threshold is increased by 2.5 times, and the working performance of OASLM is still good after compensation. The switching ratio is higher than 100:1 and the transmittance of the device is higher than 85%. Therefore, this compensation method can expand the application range of OASLM. In addition, we speculate that the transmittance change caused by temperature can also be compensated by adjusting the voltage on TN liquid crystal light valve in other applications. The results in this paper are carried out without thermal management. For the equipment with thermal management, this method can also be used to improve the irradiation laser power density. The content of thermal management will be introduced in another article.

Acknowledgement

This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences, Grant No. XDA25020303. We thank the financial support of Self Deployed Projects of Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences.

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