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Temperature effect on the diffraction efficiency of the liquid crystal spatial light modulator

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Abstract

Temperature effect on the diffraction efficiency of the liquid crystal spatial light modulator is investigated. The birefringence of the liquid crystal as functions of the temperature is measured with and without the power supply. It is shown that the birefringence reduces while the temperature increases. And the change magnitude of the birefringence has an exponential decay relation with the applied voltage for different temperature intervals. The scalar diffractive theory is used to analyze this effect on the diffraction efficiency. It indicates that the diffraction efficiency decreases from 98.7% to 27.2% while the temperature increases from 10 to 90 °C for 16 quantified levels. At last, temperature effect on its applications in optical testing and wavefront correction is discussed. It indicates that it has almost no effect on optical testing, but has an important effect on wavefront correction. And two solutions are given to eliminate this effect.

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1. Introduction

Liquid crystal spatial light modulator (LC SLM) has been used in adaptive optics [1], optical testing [2,3], compute generated holograms (CGH) [4,5], and beam steering [6], etc. The phase and amplitude modulation can be produced by changing the birefringence of the LC. Many papers have shown temperature has an important effect on the birefringence [7–10] and the LC SLM may be used at different temperatures. Consequently, it is essential to analyze the temperature effect on the LC SLM. As we know on one has investigated this effect on the diffractive efficiency of the LC SLM.

In this paper, we mainly analyze the temperature effect on the diffraction efficiency of the LC SLM and discuss this effect on its applications in optical testing and wavefront correction. In order to analyze the temperature effect on the diffraction efficiency of the LC SLM, a single cell is selected to measure and analyze the effect of the temperature on the birefringence (Section 2). Then, temperature effect on the diffraction efficiency of the LC SLM with thousands of the pixels is investigated in Section 3. At last, this effect on its applications for optical testing and wavefront correction is considered.

2. Temperature effect on birefringence of the liquid crystal

2.1. Measurement

To measure the temperature effect on the birefringence, one 8.23 μm thick parallel aligned LC cell was fabricated. The LC material RDP-92975 (DIC) was used and its

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clearing temperature is 100 °C. The temperature effect on the birefringence was measured by the spectroscopic ellipsometer (JOBIN YVON) at the wavelength $\lambda = 632.8$ nm. Fig. 1 shows the measurement setup. The thermocouple touched the surface of the LC cell tightly. The sample was put inside the chamber. And we waited several minutes before measuring every phase data in order to obtain the accurate data. The light which comes from the incident arm of the ellipsometer traverses the LC cell and is received by the reflective arm. Thus, the phase modulation of the LC cell can be obtained. According to the equation

$$M_{\text{phase}} = 2\pi d \Delta n / \lambda, \tag{1}$$

Δn can be calculated by the measured data of the M_{phase} and d. Here M_{phase} is the phase modulation of the LC cell, λ is the wavelength, Δn and d are the birefringence and the thickness of the cell respectively.

The birefringence as a function of the temperature is measured while turning off the signal generator as shown in Fig. 2. The dots indicate the measured data and the solid line shows the fitting curve with the formula [7]

$$\Delta n(T) = (\Delta n)_0 (1 - T/T_c)^{\beta}, \tag{2}$$

here $(\Delta n)_0$ is the LC birefringence in the crystalline state (or $T = 0$ K), β is a material constant, and T_c is the clearing temperature. The fitting results show that $(\Delta n)_0$ and β are 0.29 and 0.27 respectively. We also measure the phase modulation as functions of the temperature at different voltages as shown in Fig. 3. It is shown that the same temperature interval at higher temperature causes more change of the birefringence.

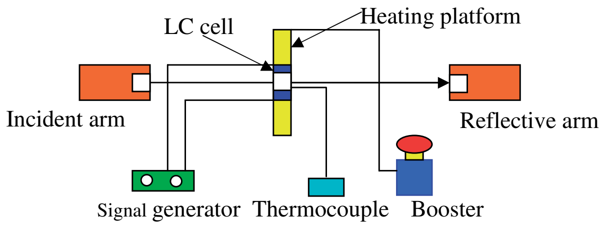

Fig. 1. The measurement setup.

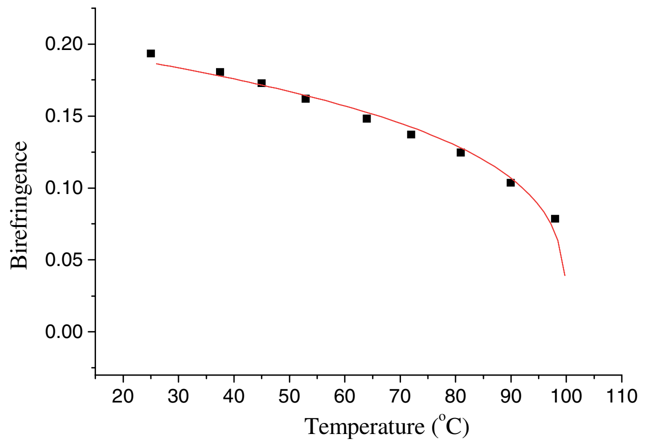

Fig. 2. The birefringence as a function of temperature; the dot donates the measured data and solid line is the fitting curve.

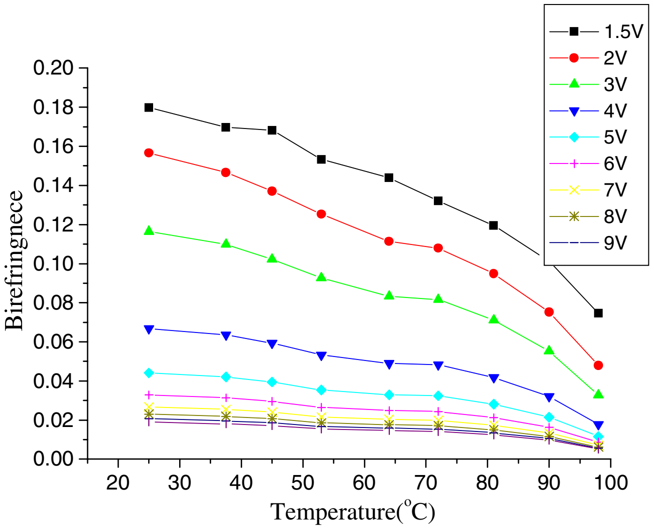

Fig. 3. The measured relations between the birefringence and the temperature at different voltages.

2.2. Data analysis

It is well known that the driving voltage of the LC SLM directly affects its phase modulation and it has been investigated in many papers [1–3,6]. But the relation between the phase modulation and the voltage or the gray level is just measured at a certain temperature. If the temperature changed, the phase–voltage function will be altered accordingly. And we will analyze this effect on the phase–voltage function. In order to investigate it, the measured data in Fig. 3 are fitted by the polynomials. Thus, we can achieve the value of the birefringence at the arbitrary temperature with the fitting curve. Assuming the temperature intervals are 10–25 °C and 25–40 °C, we can achieve the change magnitude of the birefringence as functions of the driving voltage according to the measured data and the fitting

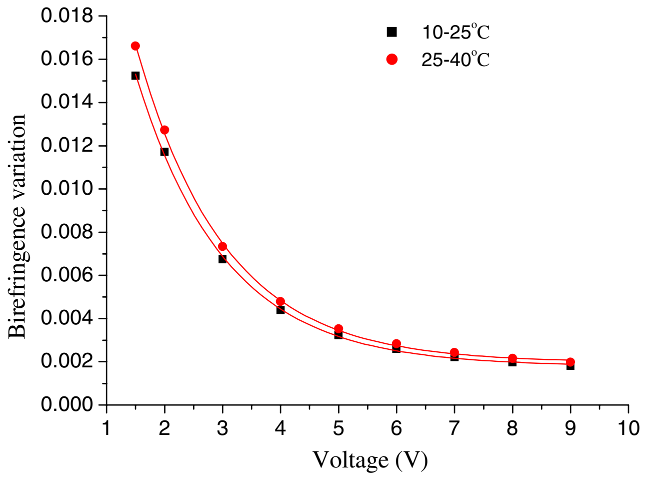

Fig. 4. The birefringence variation as functions of the voltage; the dot is the measured data and the solid line is the fitting curve.

curve. Fig. 4 shows the variation of the birefringence at discrete points from 1.5 to 9 V (the dot). And the solid lines are the fitting curves by the equation

$$B_{\mathrm{v}} = a + b\exp[-V/c], \tag{3}$$

where B_{v} and V are the variation of the birefringence and the applied voltage respectively, a, b and c are the variable used to fit the discrete data. And the fitting results show that $a = 0.00179$ and 0.00197, $b = 0.0359$ and 0.03921, and $c = 1.53538$ and 1.52895 respectively. It indicates that the change magnitude of the birefringence has an exponential decay relation with the applied voltage when the variation of the temperature is constant. And it has the similar trend for different temperature intervals.

3. Effects on the diffraction efficiency of the LC SLM

3.1. Theory

The phase retardation of the most LC SLM is 2π rad or so. And it cannot satisfy the applications such as wavefront correction, beam steering, and optical testing, etc. In order to use it in these fields, we may extend its phase modulation by the binary optics or the kinoform technique. Thus, the diffractive optics is needed to investigate the temperature effect on the LC SLM.

The Fresnel phase lens is selected to analyze the temperature effects on the LC SLM because the wavefront produced by the LC SLM for wavefront correction and optical testing is similar to the sphere wavefront produced by the Fresnel phase lens. For the analysis, we exploit the scalar diffractive theory and use the cylindrical coordinates. According to the rotational symmetry and the periodicity along the r^2 direction, the complex amplitude of the light traversing the Fresnel phase lens that is illuminated with a plane wave of unit amplitude can be expressed as [11]

$$f(r^2) = f(r^2 + jr_{\mathrm{p}}^2), \tag{4}$$

where j is an integer and the period is r_{p}^2. And it can be expressed by the Fourier series

$$f(r^2) = \sum_{n=-\infty}^{+\infty} A_n \exp[\mathrm{i}2\pi n r^2/r_{\mathrm{p}}^2]. \tag{5}$$

The distribution of the complex amplitude at the diffraction order n can be obtained [12]

$$A_n = 1/r_{\mathrm{p}}^2 \int_0^{r_{\mathrm{p}}^2} f(r^2)\exp[\mathrm{i}2\pi n r^2/r_{\mathrm{p}}^2]\mathrm{d}r^2. \tag{6}$$

For the Fresnel phase lens, the light is mainly concentrated on the first order ($n = 1$). The diffraction efficiency of a perfect Fresnel lens with L steps is defined by the intensity of the first order at its primary focus

$$\eta = I(n = 1) = |A_1|^2 = \sin c^2(1/L). \tag{7}$$

If we can achieve the phase distribution function $f(r^2)$, the diffraction efficiency will be obtained by Eqs. (6) and (7).

3.2. Effects of the temperature on the diffraction efficiency

We may assume each pixel of the LC SLM has the same characteristic as the same LC material is used. Thus, the measured and analyzed results in Section 2 can be utilized to investigate the temperature effect on the diffraction efficiency of the LC SLM.

As the driving circuits of the LC SLM are fabricated with the VLSI techniques, ordinarily, the maximum driving voltage is 5 V. And the threshold voltage of the nematic LC material is 1 V or so. Accordingly, the range of the driving voltage 1–5 V is selected and the thickness of the cell is 3.16 μm. One period of the Fresnel lens with four levels is selected as an example to illustrate the temperature effect on the phase distribution function and T is the period as shown in Fig. 5. If the phase–voltage curve is obtained, the phase distribution can be realized by applying different voltages or grey levels on the pixels [1,2].

We suppose the phase modulation increases from 0 to 2π rad while the driving voltage changes from 1 to 5 V. The phase error $\Delta\phi$ caused by the temperature changing can be calculated with the measured data in Fig. 2. Consequently, the phase distribution function is acquired and the diffraction efficiency can be calculated by Eqs. (6) and (7). Assuming the starting temperature is 10 °C, the diffraction efficiency as functions of the temperature can be calculated

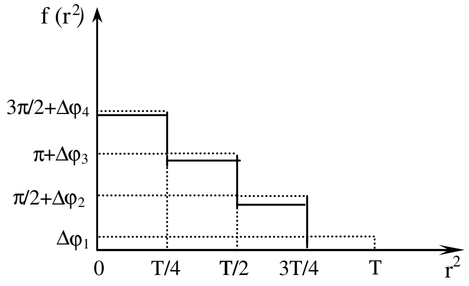

Fig. 5. The phase distribution of the Fresnel lens with four levels.

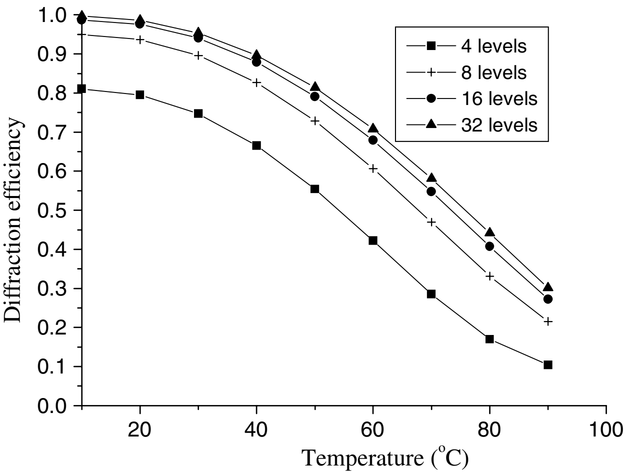

Fig. 6. The diffraction efficiency as functions of the temperature.

at 4, 8, 16, and 32 levels as shown in Fig. 6. The diffraction efficiency decreases drastically while the temperature increases from 10 to 90 °C. And the variation of the diffraction efficiency decreases with the number of the quantified level increases. In other words, the temperature has the larger effect on the smaller quantified level.

4. Discussions

It indicates that the temperature has the large effect on the diffraction efficiency while the LC SLM is used with the kinoform technique. And we will discuss this effect on its applications for optical testing and wavefront correction.

4.1. Optical testing

If using the LC SLM as a compensator for optical testing [2], the laser can be used as the light source. So, the diffraction efficiency is not a problem because we can adjust the intensity of the laser to produce the fringe with the high contrast. And the optical testing always is done at the room temperature. For the temperature of 20 ± 10 °C, the maximum reduction magnitude of the diffraction efficiency is 0.0172 and 0.0155 respectively while the number of the quantified level changes from 4 to 32 as shown in Fig. 7. Therefore, temperature effect can be ignored for optical testing at room temperature.

4.2. Wavefront correction

Compared to the optical testing, the LC SLM used for wavefront correction in the adaptive optical system is completely different. It demands the LC SLM has the high diffraction efficiency because it is generally used in the imaging optical system and the brightness of the object is often very weak. And the adaptive optical system is usually used at different circumstances and the temperature may changes very drastically. As the diffraction efficiency increases very small when the quantified level is larger than 16 (it can be seen Fig. 6), we may select 16 as the number of the quantified level. The diffraction efficiency for 16 levels decreases from 98.7% to 27.2% while the temperature increases from 10 to 90 °C. Thus, we must consider this effect. And it may be solved by the following two methods:

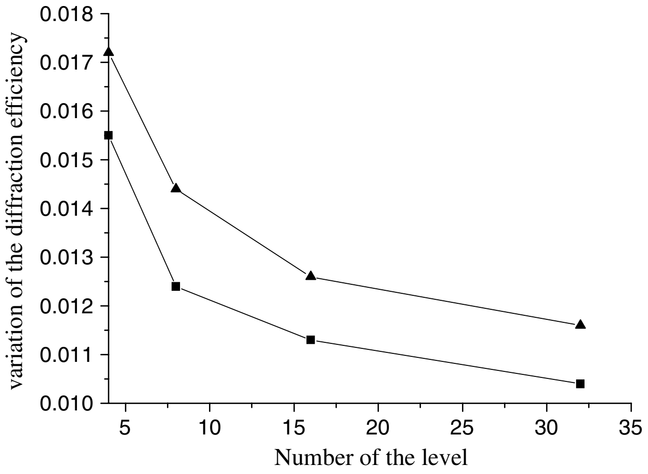

Fig. 7. The variation of the diffraction efficiency as functions of the number of the level; the square and the triangle donate the temperature decreases and increases 10 °C respectively.

1. *Constant temperature*. In order to realize it, we may install the LC SLM in a thermostatic container. But it may cause some other problems, for example, complication of the optical system, enhancing the weight which is fatal for using it in aviation and spaceflight, etc.
2. *Adjust the phase–voltage function according to the variation of the temperature*. If the working temperature is known and its fluctuation is small enough, we can fabricate the LC SLM to modulate 2π and measure the phase–voltage function at this temperature beforehand. Then, the LC SLM may work normally and correct the wavefront accurately while it is used in the working temperature. If the working temperature fluctuates very large, the LC SLM must have 2π phase modulation at the upper limit of the fluctuation as the birefringence of the LC decreases while the temperature increases. Then, the different phase–voltage functions are measured at different temperatures with little fluctuation for the purpose of eliminating the temperature effect. And a temperature detector may be used to detect the working temperature timely. Thus, the control software can select the corresponding phase–voltage function to correct the wavefront according to the detected temperature.

5. Conclusions

Temperature effect on the diffraction efficiency of the LC SLM is investigated in the paper. In order to analyze the temperature effect on the LC SLM, one single cell is selected to measure the temperature effect on the birefringence of the LC. It is shown that the birefringence reduces while the temperature increases. And the change magnitude of the birefringence has an exponential decay relation with the applied voltage for different temperature intervals.

According to the measured and the analyzed data of the single cell, the phase error caused by the temperature can be calculated for each pixel. Thus, the phase distribution function can be acquired and the temperature effect on the diffraction efficiency may be analyzed. It indicates that the diffraction efficiency decreases drastically while the temperature increases from 10 to 90 °C. And the decrease of the diffraction efficiency is 70% for 16 levels. At last, temperature effect on its applications in optical testing and wavefront correction is discussed. It is shown that it has almost no effect on optical testing, but has an important effect on wavefront correction. Constant temperature and adjusting the phase–voltage function method is introduced to eliminate this effect.

Although we just use the nematic LC RDP-92975 to measure and analyze the temperature effect on the LC SLM, it should have the similar results and conclusions for other nematic LC materials as they have the approximate characteristic. And the analysis and the conclusions also can be extended to other applied fields except optical testing and wavefront correction.

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