Investigation of optical testing with a phase-only liquid crystal spatial light modulator

Zhaoliang Cao[1, 2], Li Xuan[1], Lifa Hu[1], Yongjun Liu[1], Quanquan Mu[1] and Dayu Li[1]

[1]*State Key Lab of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin, 130033, China*
[2]*Graduate School of the Chinese Academy of Sciences, Beijing, 100039, China*
caozlok@ciomp.ac.cn

Abstract: We illustrate that the phase-only liquid crystal spatial light modulator (LC SLM) can be used for optical testing. The large phase change and the phase modulation precision are discussed. The computer generated holograms (CGH) method is used to acquire the significant phase modulation. And the phase modulating characteristics of the LC SLM are measured. It shows the phase modulation depth is more than 2π and the modulation precision is down to $1/14\lambda$ (PV) and $1/100\lambda$ (rms) (λ=632.8nm). In order to verify this method, the former surface of a convex lens is tested by ZYGO interferometer. The parallel straight fringes are obtained. It is shown that PV is $1/3\lambda$ and rms is $1/20\lambda$ after compensated by the LC SLM.

OCIS codes: (220.4840) Optical testing; (230.3720) Liquid-crystal devices; (120.5060) Phase modulation; (090.1760) Computer holography; (230.6120) Spatial light modulators

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#6263 - $15.00 US Received 7 January 2005; revised 31 January 2005; accepted 31 January 2005

1. Introduction

CGHs used for optical testing have been reported in many papers [1-5]. And most of them are used to test the aspherical surface because modern optical systems need it to acquire high performances. Traditionally, the CGH has to be fabricated on one plane substrate or the spherical reference substrate and it is very difficult to do. In addition, one CGH could only measure one kind of optical surfaces. In other words, if we want to test different optical surfaces, different CGHs have to be fabricated.

The LC SLM used to produce CGH has been reported in many papers [6-8]. Many of them use it to produce the reconstruction image of the object. Others use it as space filter [9] and phase shifter. As far as we know, no one use it for optical testing.

In this paper, we illustrate that the LC SLM can be used for optical testing. Compared to other CGH employed previously by other authors, the LC SLM produced CGH could be derived dynamically and do not fabricate it on the substrate. Thus, one LC SLM can be used to test arbitrary optical surface and lots of time and money will be saved.

2 The phase modulation characteristics of liquid crystal

2.1 Jones matrix analysis

For twisted nematic liquid crystal televisions (LCTVs), sandwiched between two polarizers, if the incidence wave is $\boldsymbol{E}_{in}$, the output wave can be expressed by [10]

$$\boldsymbol{E}_{out} = \boldsymbol{P}_0 \boldsymbol{R}(\psi_2)\boldsymbol{R}(-\alpha)\boldsymbol{LCTV}(\alpha,\beta)\boldsymbol{R}(\psi_1)\boldsymbol{E}_{in} \tag{1}$$

where the rotation matrix $\boldsymbol{R}(\theta)$ is defined by

$$\boldsymbol{R}(\theta) = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{2}$$

and $\boldsymbol{P_0}$ is the Jones matrix that describes the effect of the polarizer, such that

$$\boldsymbol{P}_0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \tag{3}$$

The matrix used to describes the effect of the twisted nematic LCTV is [11]

$$\boldsymbol{LCTV}(\alpha,\beta) = \begin{bmatrix} \cos\gamma - \boldsymbol{i}\beta\sin\gamma/\gamma & \alpha\sin\gamma/\gamma \\ -\alpha\sin\gamma/\gamma & \cos\gamma + \boldsymbol{i}\beta\sin\gamma/\gamma \end{bmatrix} \tag{4}$$

here α is twist angle , β is birefringence, ψ_1 is the angle between the former polarizer and the molecular director, the angle between the back polarizer and the molecular director is given by ψ_2 , and $\gamma = \left[\alpha^2 + \beta^2\right]^{1/2}$.

If we drive the LCTV by different voltages, the liquid crystal molecule will be rotated accordingly. And $n_e(\theta)$ is given by [12]

$$n_e(\theta) = \frac{n_o n_e}{\left(n_o{}^2 \cos^2\theta + n_e{}^2 \sin^2\theta\right)^{1/2}} \tag{5}$$

where n_o is the ordinary refractive index and n_e is the off-state extraordinary refractive index. Thus, the birefringence can be written as

#6263 - $15.00 US Received 7 January 2005; revised 31 January 2005; accepted 31 January 2005

$$\beta = \frac{\pi d}{\lambda}\left[n_e\left(\theta\right) - n_o \right] \tag{6}$$

here d is the thickness of the liquid crystal layer and λ is the relevant wavelength.

In the paper, the LCTV we used is parallel aligned and just one polarizer is used. Thus, we can achieve $\alpha=0$, $\psi_1=0$ and $\gamma=\beta$. And the Eq. (1) can be rewritten as

$$\boldsymbol{E_{out}} = \boldsymbol{P}_0 \boldsymbol{R}(0)\boldsymbol{LCTV}(0,\beta)\boldsymbol{R}(0)\boldsymbol{E_{in}} \tag{7}$$

Multiplying the matrices in Eq. (7), the output wave is given by

$$E_{out} = \begin{bmatrix} i\sin\beta - \cos\beta \\ 0 \end{bmatrix} \tag{8}$$

The transmitted intensity is given by

$$T = \left|E_x\right|^2 = 1 \tag{9}$$

and the relative phase shift is given by

$$\delta = \beta - \arg\left(E_x\right) = 2\beta = \frac{2\pi d}{\lambda}\left(n_e\left(\theta\right) - n_o\right) \tag{10}$$

According to Eq. (9), the transmittance is a constant for the parallel aligned LC SLM. And we can achieve the result that the relative phase shift is a function of the driving voltage, as the different voltage corresponds to a certain tilt angle of the liquid crystal molecules.

2.2 The measurement of the phase retardation

In order to realize the phase-only modulation, one LCTV (VGA) is reconstructed by us. Two polarizers are removed, the color film is cleared, the rubbing orientation is parallel aligned and the liquid crystal is changed with large Δn. Now, the LCTV is changed to a phase-only LC SLM which is active addressed, consisting of 640×480×3 pixels. The thickness of the liquid crystal is 5μm and the pixel size is 100μm×300μm.

For the phase-only LC SLM, each gray level corresponds to a certain voltage. The phase retardation as a function of grey level is measured with the spectroscopic ellipsometry fabricated by JOBIN YVON (Fig. 1). The phase modulation depth is more than 1λ (λ=633nm). And the largest phase difference between two pixels is 0.05λ when the phase retardation is limited in one wavelength. As the LC SLM is active addressed, the phase control quality is at least down to 0.05λ. The relation between transmitted intensity and grey level is also measured by using optical detector (shown in Fig. 1). We can see that the transmitted intensity is almost not changed corresponds to different grey level.

#6263 - $15.00 US Received 7 January 2005; revised 31 January 2005; accepted 31 January 2005

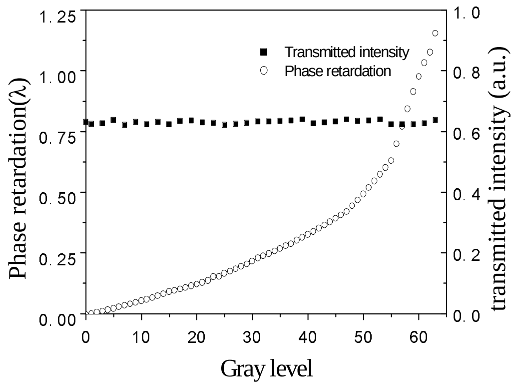

Fig. 1. Measured transmitted intensity and phase retardation at different grey levels. Squares and circles are the experiment data for transmitted intensity and phase retardation.

2.3 Phase modulation precision

The application for optical testing requires the phase-only LC SLM to create significant phase changes with very high accuracy. First, its phase modulation precision is investigated by using the ZYGO interferometer (Fig. 2). One distorted glass is introduced in the optical layout for measuring the phase modulation precision. The wavefront before and after corrected is measured by ZYGO interferometer (Fig. 3). The peak to valley (PV) variation of the wavefront is 0.22λ (λ=632.8nm) and the rms variation is 0.036λ without correction. After the wavefront is corrected, the residual wavefront is measured again and the results show that PV is down to 1/14λ and rms is 1/100λ. As the phase-only LC SLM has such high phase modulation precision, it can be used for optical testing.

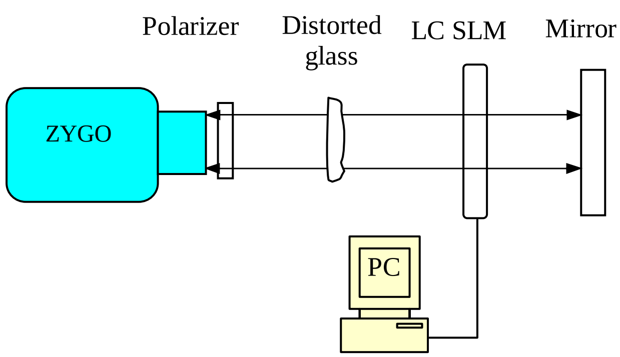

Fig. 2. Optical layout for measuring the phase modulation precision

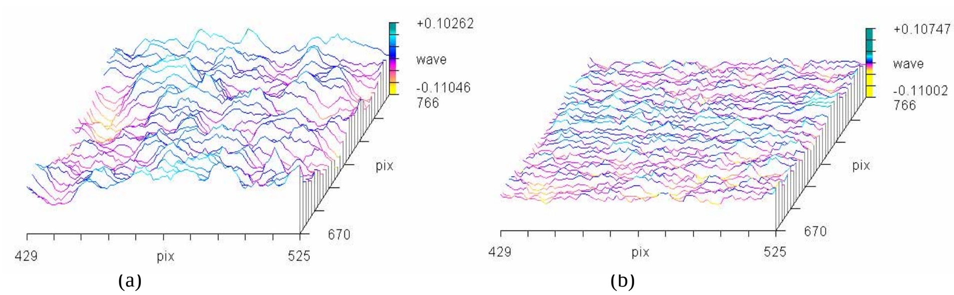

Fig. 3. The wavefront phase map: (a) before corrected; (b) after corrected

3 Experiments for optical testing

3.1 Kinoform

The LC SLM also needs to produce significant phase changes in optical testing. And it can be realized by using the kinoform method. For the CGH, its phase function can be written as [13]:

$$\varphi_{CGH} = \varphi_{out} - \varphi_{in} \tag{11}$$

Where φ_{CGH} is the phase function of CGH, φ_{out} and φ_{in} are the wavefront coming out from the CGH and the wavefront going into it respectively. If we use the reference wave to test an optical surface, the phase distribution of the CGH can be written as:

$$\varphi_{CGH} = \varphi_{sur} - \varphi_{ref} \tag{12}$$

Where φ_{ref} and φ_{sur} are the phase functions of reference wave and optical surface respectively. As the modulation depth of the LC SLM is 1λ (λ=633nm), the kinoform method can be used to produce the phase of the CGH. After φ_{CGH} is modulated by 2π, we can obtain the remainder. Then, the remainder is quantified to N levels and produced by the LC SLM. And this method is investigated to produce the large phase shift concretely in other paper [14].

3.2 Optical testing

In order to verify the phase-only can be used for optical testing, one convex lens is chosen as the tested optical element. As its radius of curvature is very large, the optical layout used to test flat surface is used here (Fig. 4). From Fig. 4 we can see that while one plane wave passes through the kinoform, it will be modulated to the coming out wave which can irradiate on the tested optical surface along the normal orientation of every point of the surface. The light reflected by the tested optical surface will pass through the LC SLM again and be changed to plane wave. The obtained interference pattern should have no fringe.

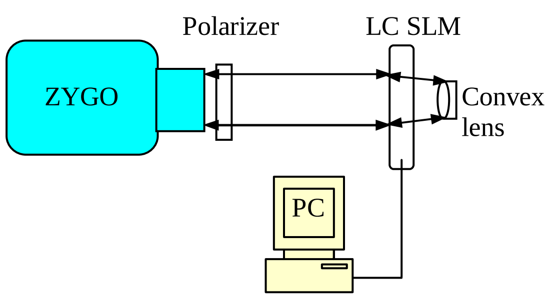

Fig. 4. Optical layout for testing the convex lens

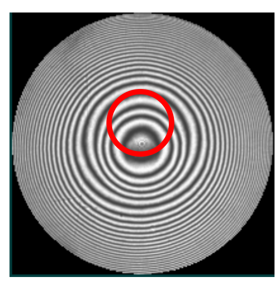

Fig. 5. The interferogram of the former surface of the convex lens; the red circule is the mask

In the paper, the aperture diameter of the convex lens is 50mm, and the aperture diameter and the incident angle of the crystal polarizer is 30mm and 56.5° respectively. First, the former surface of the lens is tested without the LC SLM (Fig. 5). One circle mask (Fig. 5) is selected at the center of the interferogram as the effective testing area which is limited by the size of the crystal polarizer. The modulation area of the LC SLM corresponds to the circle mask is 1cm×1cm (32×96 pixels). Then, the surface of the lens is measured again with the circle mask. And the measured phase map can be looked on as the ideal surface that we want to achieve. The measured data of the phase can be acquired from the computer linked to the ZYGO interferometer and inputted to another computer which controls the LC SLM. The controlling software programmed by us reads the data and produces the kinoform onto the LC

#6263 - $15.00 US Received 7 January 2005; revised 31 January 2005; accepted 31 January 2005

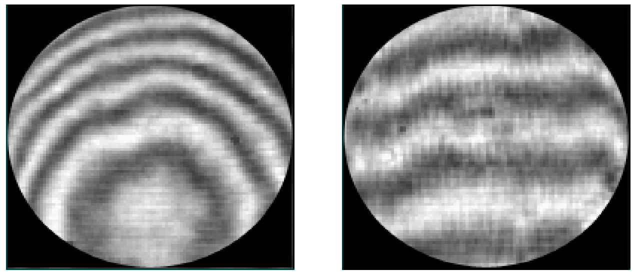

Fig. 6. The interferograms: (a) without the kinoform; (b) with the kinoform.

SLM. When the phase modulation is turned on, the surface of the circle mask is tested again. The measured results are shown in Fig. 6 and Fig. 7.

Figure 6 shows the interferograms obtained by the ZYGO interferometer with and without the kinoform. We can see that the curved fringes almost change to the parallel straight fringes. It illustrates that the kinoform produced by the LC SLM acts as the compensator used in testing aspherical surface. The phase maps before and after phase modulating is shown in Fig. 7. Before the modulation, the PV and the rms of the wavefront are 1.332λ and 0.298λ respectively. After the modulation, the PV and the rms change to 0.32λ and 0.054λ.

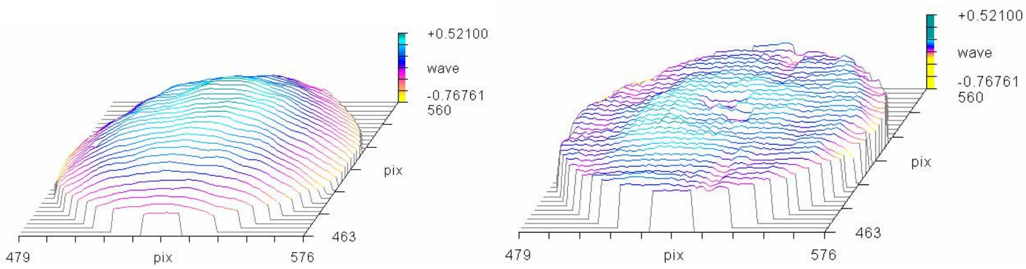

Fig. 7. The phase maps: (a) without the kinoform; (b) with the kinoform.

4. Discussions

We can conclude that the phase-only LC SLM appears feasible for optical testing from the experimental results. But there are some problems: (1) after the phase modulation, there are still 4 fringes in the interferogram (Fig. 6(b)) because there has tilt aberration in the test system and it can be removed by adjusting the tested convex lens. But the tilt aberration isn't included in the phase map (Fig. 7) as it is removed by the software of ZYGO. (2) The modulation precision isn't up to 1/14λ (PV) and 1/100λ (rms) in the optical testing experiments. We think that it is mainly caused by the large pixel size. As the phase distribution of the former surface is circular symmetric but the pixel is square, the circle is formed by a lot of little squares while the LC SLM is used as the kinoform. Apparently, the larger pixel size, it is the larger fitting errors which affect the phase modulation precision. The LC SLM can be used for optical testing only if the pixel size is small enough. Fortunately, there are many liquid crystal displays whose pixel size (9μm×9μm) much smaller than what we used in the paper.

5. Conclusions

The LCTV used for optical testing is investigated in the paper. Two main problems, which occurred while the LC SLM is used to test optical surface, are discussed experimentally. The

Received 7 January 2005; revised 31 January 2005; accepted 31 January 2005

large phase shift can be realized by using the kinoform method. And the phase modulation precision is up to 1/14λ (PV) and 1/100λ (rms). But just the precision PV is 0.32λ and rms is 0.054λ is achieved while we use the phase-only LC SLM to test the surface of the convex lens. Through the analysis, the pixel size is the main problem which causes the decrease of the precision. And we will purchase one LCTV which has little pixel size to realize the high precision in the optical testing. In spite of using it to test the convex surface, the phase-only LC SLM is feasible for testing other optical surface, for example, the aspherical surface.

Acknowledgments

This work is supported by National Natural Science Foundation (50473040) and Changchun Institute of Optics, Fine Mechanics and Physics's Innovation Foundation (C03M11Z).