Phase-only liquid-crystal spatial light modulator for wave-front correction with high precision

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Abstract: We introduce a novel parallel-aligned liquid-crystal (LC) spatial light modulator (SLM) that has been designed to operate in a phase-only mode for wave-front correction. We measured and analyzed theoretically the electro-optic characteristics of the LC SLM and obtained a peak-to-valley value of 0.07049λ (λ = 0.6328 μm) after correction. A Strehl ratio of 0.989 indicates the approximate upper limit of an aberrated wave front that the LC SLM can correct when it is used in an adaptive optical system.

OCIS codes: (230.4110) Modulators; (060.5060) Phase modulation; (230.3720) Liquid-crystal devices; (120.5050) Phase measurement.

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1. Introduction

A liquid-crystal television (LCTV) as a spatial light modulator (SLM) has been under investigation since the 1980s [1-10]. It has the advantages of relatively low cost, high reliability, compactness, and low power consumption. Most available LC SLMs are twisted nematic (TN) models. The LC device in a TN mode produces coupled amplitude and phase modulation, which makes it difficult for the device to be used for aberrated wave-front correction. To solve the problem, one needs to select a special voltage range in which the modulator would function as a phase-mostly model according to the investigations of Konforti *et al*. [9] and Barnes *et al.* [10]. The best solution to the problem, however, is to use a parallel-aligned LCTV as a phase-only model. Our aim is to create a phase-only LC SLM and to use it for aberrated wave-front correction with high precision.

In Section 2 we introduce our parallel-aligned LC SLM with 640 × 480 pixels and its experimental setup. The theoretical analysis of the phase and amplitude modulation characteristics of a parallel-aligned LC SLM is given in Section 3. The experimental results and discussions are presented in Section 4, and the conclusions are given in Section 5.

2. Experimental description

We introduce a novel parallel-aligned LC SLM with 640 × 480 pixels that consists of a transmissive, 10.4-in. (26-cm) LCTV manufactured by Jilin Caijing Co., Ltd.. The LCTV has an active matrix thin-film transistor circuit that includes 640 × 480 pixels, and each pixel includes three red–green–blue subpixels. The size of a subpixel is 100 μm × 300 μm with a 10-μm gap between each subpixel and a 5-μm LC layer. It should be noted that the available commercial LCTV has poor quality polarizers and color filters that must be removed. Moreover the peak-to-valley value of the optical path difference introduced by the upper and lower glasses of the LCTV is at least several wavelengths across the entire area of the device. Therefore, we had to limit our investigation to a subarray of 32 × 32 pixels to determine a suitable area in which the total internal wave-front error could be managed with the device. Most importantly, we changed the LCTV from orthogonal alignment to parallel alignment, which allows for phase-only modulation of incident light. To enlarge the modulation depth of our LC SLM, we selected a LC material with 0.198 birefringence. We also measured and analyzed the response times of our LC SLM. We used a polarized He–Ne laser with 632.8-nm wavelength as the light source for all our experiments.

The experimental setup for the measurement of our LC SLM is illustrated in Fig. 1. The He–Ne laser is expanded by lenses 2 and 3 and passes through a beam splitter. Then the light is partially reflected by mirror 5 and the beam splitter to a CCD that forms a reference wave front. The transmitted light passes through the LC SLM and is partially reflected by mirror 7 back to the CCD through the LC SLM and mirror 5 as well as the beam splitter, which forms a test wave front. The interference patterns were detected with the CCD and analyzed by computer 9. Note that we used a crystal polarizer, located between mirror 5 and the LC SLM, with good optical quality for the experiment. When different gray levels were applied to the LC SLM through computer 10, one could obtain gray-level-dependent phase retardation.

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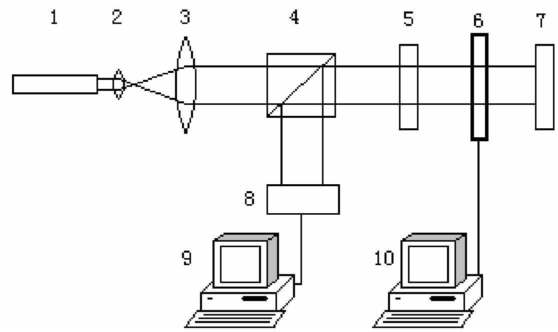

Fig. 1. Optical setup used to investigate the modulation properties of the LC SLM: 1, He–Ne laser; 2, 3, lenses; 4, beam splitter; 5, partially reflective mirror; 6, LC SLM; 7, partially reflective mirror; 8, CCD; 9, 10, personal computers.

3. Theoretical description

First, we could characterize light modulation of the parallel-aligned LC SLM theoretically. Many authors have investigated the propagation of light in a nematic LC cell. In general, the modulation characteristics of a parallel-aligned LC SLM could be analyzed with the Jones matrix [11]:

$$J = \exp(-j\phi)\begin{bmatrix} \left(\frac{\alpha}{\gamma}\right)\sin(\gamma) & \cos(\gamma) + j\left(\frac{\beta}{\gamma}\right)\sin(\gamma) \\ -\cos(\gamma) + j\left(\frac{\beta}{\gamma}\right)\sin(\gamma) & \left(\frac{\alpha}{\gamma}\right)\sin(\gamma) \end{bmatrix}, \tag{1}$$

where ∟ α is the twisted angle of the LC; $\beta = \frac{\pi d}{\lambda}(n_e - n_o)$, $\phi = \frac{\pi d}{\lambda}(n_e + n_o)$, $\gamma = \left[\alpha^2 + \beta^2\right]^{1/2}$, d is the cell gap. λ is the wavelength of incident light, and n_e and n_o are the extraordinary and ordinary refractive indices.

For parallel polarizers, the transmittance and the phase retardation could be obtained for an arbitrary TN LC cell as shown in Eqs. (2) and (3). Therefore,

$$T = \zeta\left[\cos\alpha\cos\gamma + \left(\frac{\alpha}{\gamma}\right)\sin\alpha\sin\gamma\right]^2 + \left[\frac{\beta}{\gamma}\sin\gamma\cos(\alpha + 2\psi_1)\right]^2, \tag{2}$$

$$\delta = \beta - \arg E_x, \tag{3}$$

where ζ is the arbitrary scale factor, E_x is the output vector, ψ_1 is the angle between the polarizer and the director of the LC and ψ_2 is the angle between the analyzer and the director of the LC. In our experiment, α, ψ_1, and ψ_2 are all equal to zero for our parallel LC SLM. Therefore, the normalized transmittance is equal to one and the phase retardation varies with applied voltages as follows [12]:

$$T_{parallel} = 1, \delta = \frac{2\pi d}{\lambda}\left(n_e(V) - n_0\right). \tag{4}$$

Therefore, a parallel-aligned LC SLM could theoretically be used to realize phase-only modulation for incident light, which is the basis for our investigation.

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4. Results and discussions

The results of phase-only modulation are shown in Fig. 2. Results measured with an optical powermeter show that the transmittance of our transmission-mode LC SLM is approximately 62%, even with a parallel-aligned LC. But the transmittance did not vary at different applied gray levels. These results are in good agreement with the theoretical results discussed in Section 3. Although a 1-μm modulation depth could be theoretically obtained with our LC SLM, the measured depth was approximately 0.38 μm, as shown in Fig. 2. In fact, we did not change the driving module of our LCTV after we changed the LC materials because of limited conditions. The mismatch of saturation voltage and threshold between the two LC materials could be the main factor that leads to the small modulation depth. Another reason is the brightness and contrast setting of the LCTV. For our LCTV maximum brightness leads to the largest modulation depth. A fitted curve is also shown in Fig. 2, indicating the phase retardation of each gray level from 0 to 255. Wave-front correction is based directly on the fitted data. To enlarge the modulation depth, some groups use the incident light to transmit the LC SLM several times in addition to increasing birefringence and thickness.

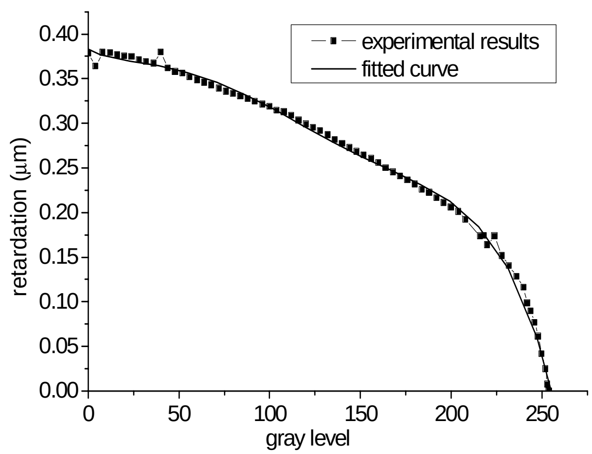

Fig. 2. Phase as a function of applied gray levels of a parallel-aligned LC SLM.

The response time of a LC SLM is important for its use in adaptive optics. In general, the LC molecules response when the applied voltage is increased, and LC molecules relax when the applied voltage is zero. Therefore, a LC device takes more time to respond when the applied voltage decreases. To quantify a LC device, the rise and decay times are usually defined as an intensity change between 10% and 90%. Rise time τ_{on} and decay time τ_{off} could be calculated theoretically as follows [13]:

$$\tau_{on} = \eta d^2 \big/ \left[\pi^2 K_{11}\left(V^2/V_c^2 - 1\right)\right], \tag{5}$$

$$\tau_{off} = \eta d^2 /(\pi^2 K_{11}), \tag{6}$$

Where η is the viscosity coefficient, K_{11} is the splay elastic constant of the LC, V is the applied voltage, and d is the gap in the LC cell. We prepared two kinds of parallel-aligned LC cells with different thicknesses. The LC material is the same as that of our LC SLM. The measured and expected results are listed in Table 1, including a comparison of the experimental and theoretical response times that are as much as four and five times longer than expected. First, it

#5535 - $15.00 US Received 1 November 2004; revised 30 November 2004; accepted 1 December 2004

should be pointed out that the strong surface anchoring and zero pretilt angle at the surface boundaries are assumed in Eqs. (5) and (6), which will lead to a theoretical response times shorter than practical response times [14]. Second, it is partly due to the nonuniform thickness of LC cells. Finally, we believe that the changes in parameters between the original mixture and the one that we used for the experiments justify the difference in response times. All the same, we could infer that the rise time of our LC SLM with a 5-μm-thick LC layer is less than 10 ms, and the fall time is less than 50 ms. According to Wu [15], a faster response time of the parallel-aligned LC could be obtained by tuning the phase retardation of the LC cell to be equal to or in the vicinity of $N\pi$ (N is an integer.).

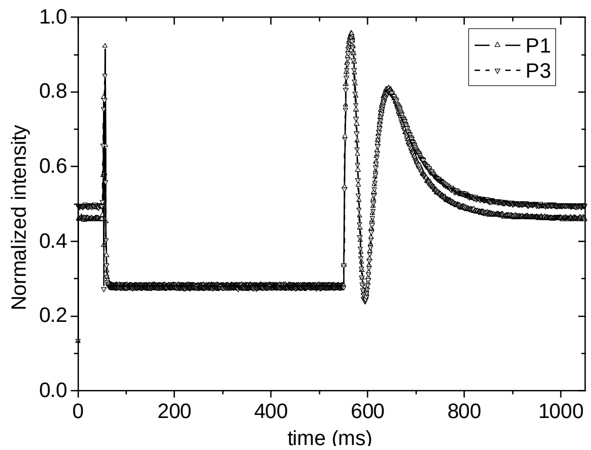

Fig. 3. Transmittance as a function of response times for a parallel-aligned LC cell.

Table 1. Experimental and Theoretical Response Time of a Parallel-Aaligned LC Ccell

Sample	**d**	**Theoretical result (ms)**		**Measured result (ms)**	
	(μm)	τ_{on}	τ_{off}	τ_{on}	τ_{off}
P1	5.8	1.8	9.2	8.5	50
P3	6.88	2.6	12.8	9	51.5

A traditional phase conjugate algorithm was used to correct the aberrated wave front [16,17]. The apparatus that we used for our wave-front correction is shown in Fig. 1. Like most LC SLMs of other groups, our parallel-aligned LC SLM also has poor optical quality glass. The plane wave was distorted after it transmitted through the glass of the LC SLM. Therefore, the most important factor for application of a LC SLM is to know the extent of its precision. In fact, we used the LC SLM to correct the self-aberration of its glass panel. The two-dimensional wave-front diagrams before and after correction are shown in Fig. 4. Figure 4(a) shows the aberrated wave front that was produced by the poor quality glass of the LC SLM. An aberrated wave front without tilt and tip aberrations can be measured with a Zygo interferometer, as shown in Fig. 4. These items were not corrected in our experiment because of the limited small modulation depth of our LC SLM. Several obvious valleys and peaks could be seen in the uncorrected wave front, as shown in Fig. 4(a). After correction, original valleys and peaks disappeared and tens of new smaller valleys and peaks appeared in the measured corrected wave front, as shown in Fig. 4(b). The measured peak-to-valley value of the wave front was 0.21308λ before correction and 0.07049λ after correction. The measured rms value of the wave front was 0.036λ before correction and 0.01λ after correction. We obtained high

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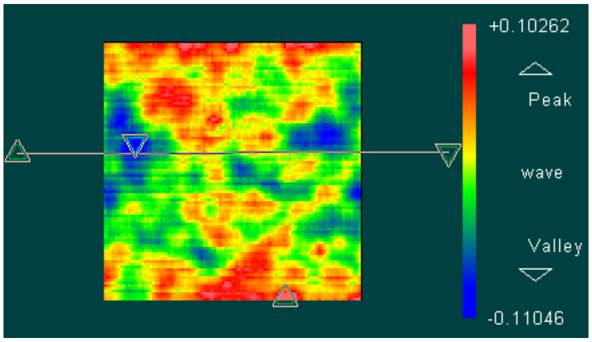
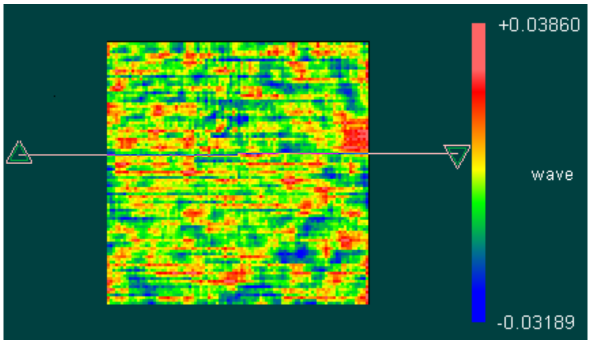
precision with our phase-only LC SLM. As far as we know, the less than 0.1λ precision has not been obtained with a TN LC SLM until now. In fact, it is difficult to obtain precision with the SLM of a TN LC because of its complex modulation.



(a)



(b)

Fig. 4. Two-dimensional plot of the wave front (a) before correction and (b) after correction.

Correspondingly, Fig. 5 shows the interferometer patterns with tilt and tip aberrations before and after correction. An obvious improvement can be seen in Fig. 5. The point-spread functions (PSFs) of the wave front before and after correction are shown in Fig. 6. The Strehl ratio in Figs. 6(a) and 6(b) are 0.849 and 0.989, respectively. As is well known, the PSF could be used as a fair appraisal of a LC SLM in an optical system, and the Strehl ratio gives an approximate upper limit of the ability of a LC SLM to correct aberrated wave fronts when it is used in an adaptive optical system. In our experiment, the Strehl ratio was improved from 0.849 before correction to 0.989 after correction. The bright speckles in fig.6 are due to the electrode structure of the LC SLM. When the PSF is close to one, they form a regular pattern, which is close to the diffraction limit. It should be noted that the intensity of the PSF at the central bright speckle is much larger than that at other ones in Fig. 6. The LC SLM will have more and more pixels with the improvement of processing technologies. What's more, the size of a pixel will be much smaller than ever, which leads to both a higher precision of wavefront correction and denser pixel structure. But the effect of its pixel structure on the wavefront correction also needs to be investigated besides many issues for the use of LC SLM in adaptive optics [18].

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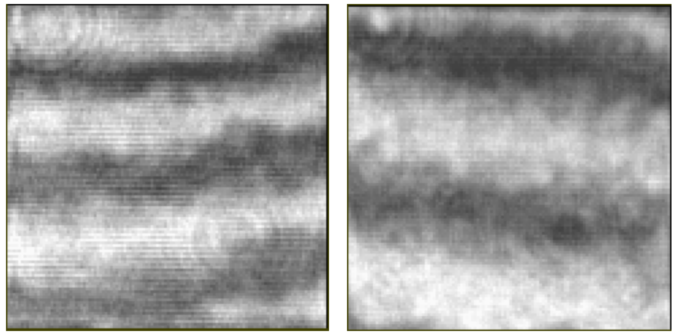
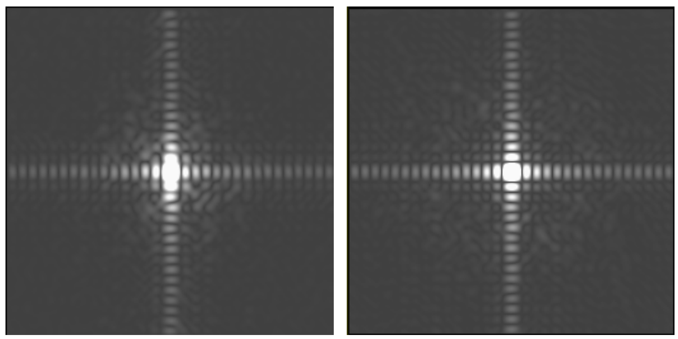


(a) (b)

Fig. 5. Comparison of the interferometer wave-front patterns: (a) uncorrected and (b) corrected for an area of 1 cm^2.



(a) (b)

Fig. 6. Comparison of the wave-front PSFs (a) uncorrected and (b) corrected in the area of 1 cm^2.

5. Conclusions

In summary, we introduced a parallel-aligned LCTV with 640×480 pixels as a LC SLM. We have shown that the rise and fall times of a LC SLM are less than 10 and 50 ms, respectively. The peak-to-valley value of the wave front was 0.07049λ after correction, which we obtained with our phase-only LC SLM. As far as we know, the precision of less than 0.1λ has not been obtained with a twisted nematic LC SLM until now. The Strehl ratio of 0.989 obtained with our experiment indicates the approximate upper limit of the ability of a LC SLM to correct aberrated wave fronts when it is used in an adaptive optical system. The experimental results indicate that our parallel-aligned modulator can be used for adaptive optical wave-front correction. A parallel-aligned LC SLM is attractive for many applications of optics, such as medical, imaging, metrology, optical communication, lithography, and laser systems, and effort should be expended to improve the properties of LC SLMs so their use can be extended to these disciplines.

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