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Correction for large aberration with phase-only liquid-crystal wavefront corrector

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Abstract. We introduce the novel parallel-aligned liquid crystal wavefront corrector (LC WFC) with 1920×480 pixels designed to operate at phase-only mode. The optical characteristics of the LC WFC were measured. The theory of diffractive optics is used to correct the aberrated wavefront. The measured peak-valve (PV) value of the wavefront is 9.956λ before correction and 0.837λ after that. Moreover, the measured root mean square (rms) value of the wavefront is 2.202λ before correction and 0.124λ after that. It expands LC devices' application fields.
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Subject terms: wavefront corrector; liquid crystal; adaptive optics; programmable diffractive optics; parallel-aligned; phase-only.

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1 Introduction

The liquid crystal wavefront corrector (LC WFC) has the advantages of relatively low cost, high reliability, compactness, low power consumption, etc. Normally, the LC WFC is cannibalized from the commercially available liquid crystal television (LCTV).[1–5] As used in the display industry, LCTV does not need large phase retardation, which is less than 2π. Therefore, one of their main disadvantages as an LC WFC is obviously the limited phase modulation depth, which limits their optical applications. We designed the novel parallel-aligned LC WFC in which the molecular alignment on the input and output face is parallel. In addition, it is different from the 90° alignment of the LCTV.

Correction of a large aberrated wavefront is necessary in many applications, such as astronomy. Limited by the small birefringence (about 0.25) and LC layer thickness, the phase stroke of the traditional LC device is small.[6,7] One could increase the thickness d of the LC device to obtain a large phase stroke. But because the response speed is proportional to $d-2$ of the LC device,[8] a small increase in the thickness of the LC device will severely deteriorate the response speed. The wavefront correction for a large aberration is demonstrated with a programmable 2D high-resolution LC WFC-based phase modulator system. We obtained a phase stroke of nearly 10 wavelengths using modulo 2π. It is mainly based on the theory of diffractive optics, that is, the LC WFC is used as a programmable kinoform to generate an arbitrary wavefront.

In Section 2, the experiments are described. We introduce the principle of the phase function modulo-2π in Section 3. The experimental results and discussions are presented in Section 4. An aberrated wavefront is corrected with our LC WFC, which verifies the effectiveness of the method. Finally, conclusions are given in Section 5.

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2 Experimental Description

In the paper, we introduce the novel parallel-aligned LC WFC with 1920×480 pixels made by Jilin Caijing Ltd. Co. which is a specialized LC display factory. With their help, the cannibalization of our LC WFC and specifications were completed[9] as the following: First, the available commercial LCTVs have poor-quality polarizers and color filters that must be removed. Second, we change the LCTV from an orthogonal alignment to a parallel one, which allows the phase-only modulation for incident light. Finally, to enlarge the modulation depth of our LC SLM, the LC material with a birefringence of 0.198 is selected. The polarized He-Ne laser with a wavelength of 632.8 nm was used as the light source. Dou and Giles[7] used a commercial liquid crystal spatial light modulator (LC SLM) in a double-pass configuration to increase the phase stroke. Yamauchi and Eiju[10] have shown that these advantages do not exist in the thin twisted nematic liquid crystal panels that are found in most high-resolution commercial video projectors. The result is that amplitude modulation also increases for a twisted nematic liquid crystal panel in a double-pass configuration. But a parallel aligned LC can double the phase stroke without a large amplitude modulation in the double-pass configuration.

The adjusted phase modulation depth of our LC WFC is

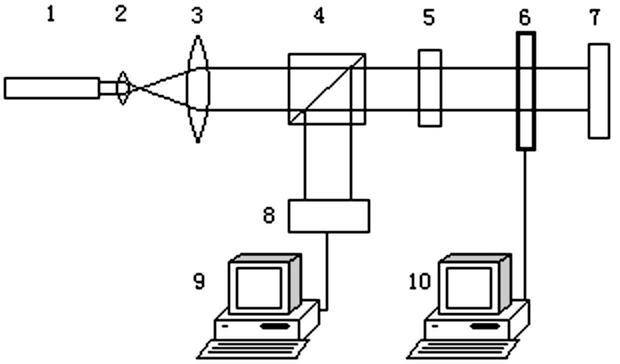


Fig. 1 Optical setup used to investigate the modulation properties of the LC WFC: 1, He–Ne laser; 2, 3, lenses; 4, beamsplitter; 5, partially reflective mirror; 6, LC WFC; 7, partially reflective mirror; 8, CCD; 9, 10, personal computers.

0.92λ ($\lambda=632.8$ nm) after we set the maximum brightness and minimum contrast of the LC WFC. When our LC WFC is used to make a kinoform, the reconstructed wavefront with the small phase modulation depth that is less than 2π will have a strong noise and low diffractive efficiency. To enlarge the phase modulation stroke of LC WFC, it is necessary and reasonable to encode a kinoform on the LC WFC. First, the incident light is passed twice through our LC WFC as shown in Fig. 1. Therefore, its phase modulation depth is up to 1.84λ. Note that an interferometer scale factor of 1 for the Zygo interferometer is chosen to double the phase modulation depth of our LC WFC. Second, a phase modulation depth greater than 2π makes it possible for a kinoform method to enlarge the phase correction. An array of 32×32 pixels, corresponding to an area of about 1 cm^2, was selected to conduct the experiment.

The results of pure-phase modulation are shown in Fig. 2. Transmittance of LC WFC measured with an optical power meter indicates that it does not vary at different applied gray levels. And the phase stroke of the LC WFC is

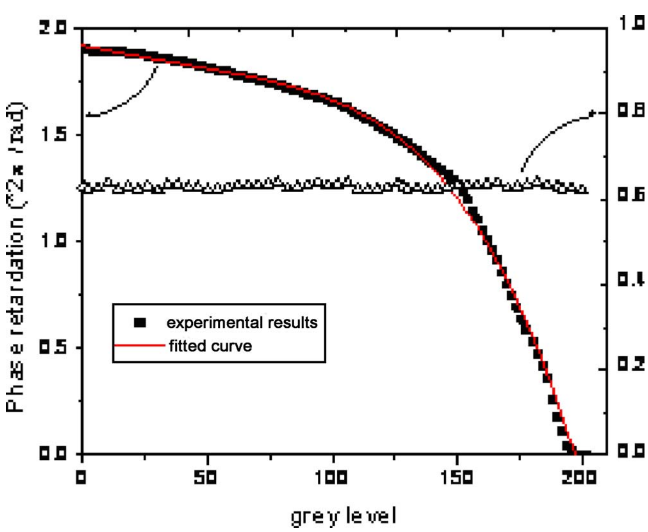


Fig. 2 Phase as a function of applied gray levels of a parallel-aligned LC WFC, square: phase, triangle: transmittance, line: fitted results.

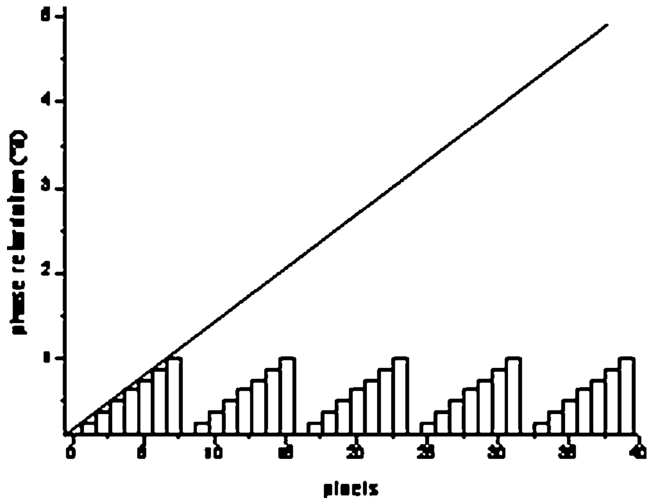


Fig. 3 Schematics of the phase modulo 2π. Line: the original phase; bar: quantified phase.

doubled compared with the results of our previous work, mainly because of a chosen interferometer scale factor of 1. A fitted curve is also shown in Fig. 2, indicating the phase retardation of each gray level from 0 to 205. The wavefront correction is based directly on the fitted data. For our LC WFC, the zero gray level corresponds to a high voltage and the 256th gray level corresponds to a low voltage. The voltage corresponding to the 205th gray level is lower than the threshold voltage of the LC. Therefore, no phase modulations were observed above the 205th gray level.

3 Theoretical Description

For quasi-monochromatic sources it should be possible to extend its range of operation by using diffractive optics theory.[11,12] The idea here is to subtract integer multiples of the wavelength of light and program the WFC to produce just the fractional part of the desired retardation. This is the underlying principle of Fresnel lenses, and one of our experimental aims of this study was to determine empirically how far we might usefully extend the phase-modulated range of the LC WFC by this technique. In fact, diffractive wavefront is modulo 2π. Figure 3 shows schematics of the phase modulo 2π. The solid curve in Fig. 3 reflects the original wave aberrations of 10π. The bar is the quantified phase. One wavelength corresponds to eight pixels.

4 Results and Discussions

The apparatus used in our wavefront correction is shown in Fig. 1. A traditional phase conjugate algorithm is used to correct the aberrated wavefront. The 3D wavefront diagrams before and after corrections are shown in Fig. 4. Figure 4(a) shows the wavefront before correction and 4(b) shows the wavefront after correction. The measured PV (peak valley) of the wavefront was 0.21308λ before correction and 0.07049λ after correction. The measured rms value of the wavefront was 0.036λ before correction and 0.01λ after correction. The results indicate that our LC WFC could obtain high-precision wavefront correction results.

According to the diffractive optics, the aberrated wavefront correction was conducted with our LC WFC. In Fig.

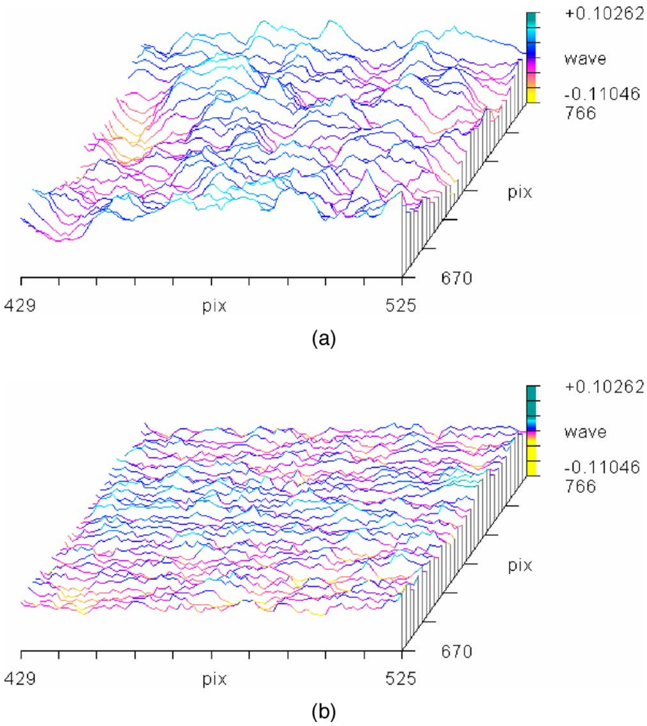


Fig. 4 The 3D plot of wavefront (a) before correction and (b) after correction.

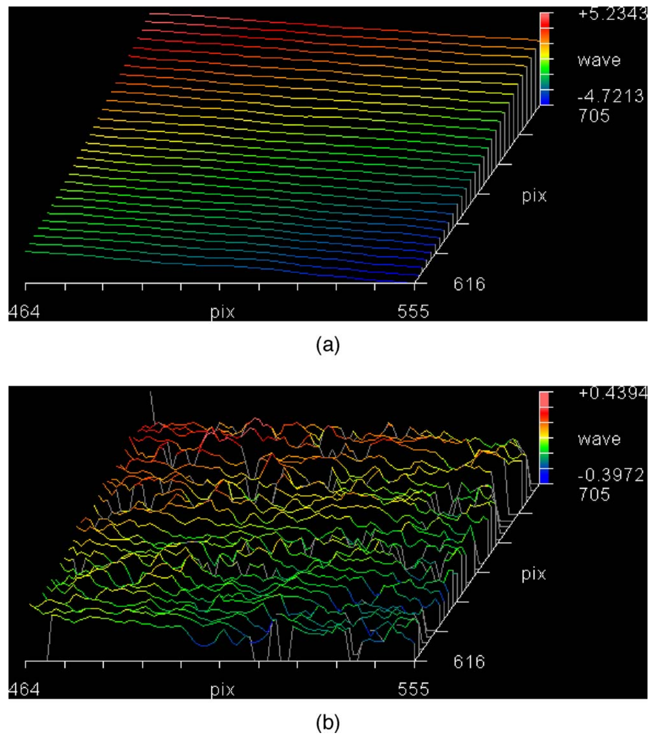


Fig. 5 The 3D plot of wavefront (a) before correction and (b) after correction.

1, a glass was inserted between partially reflective mirror 5 and LC WFC 6 in order to introduce a large aberration. Note that the tilt terms were included in the Zygo measurement. The 3D wavefront diagrams before and after corrections are shown in Fig. 5. Figure 5(a) is the uncorrected aberrated wavefront. It should be noted that the aberrated wavefront with tilt and tip aberrations could be measured with a Zygo interferometer. These items were corrected in our experiment. Figure 5(b) shows the wavefront after the correction. Obvious improvements of PV values were observed in Fig. 5. The measured PV value of the wavefront is 9.956λ before correction and 0.837λ after that. In addition, the measured rms value of the wavefront is 2.202λ before correction and 0.124λ after that. A very large aberration was obtained with our pure-phase LC WFC. Note that the traditional methods of increasing the thickness and birefraction of the LC are difficult when trying to obtain such a phase stroke.

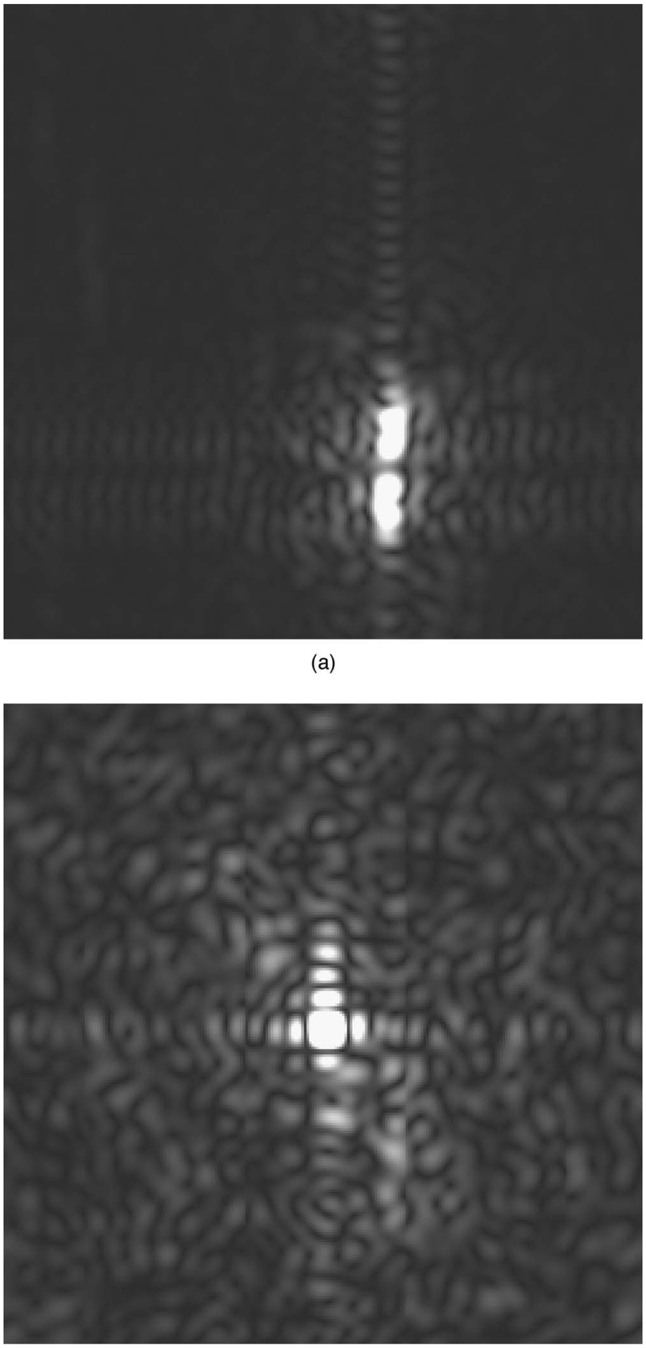
When a plane wavefront is focused, the resulting intensity pattern—the point spread function (PSF)—is the well-known Airy disk. When the plane wavefront becomes aberrated, say, by passing through the aberrated media, the PSF is no longer a perfect airy disk. Destructive interference reduces the PSF peak intensity and spreads the light out, thereby blurring the image.

Figure 6 shows the PSF both before and after correction. The Strehl ratio (SR) after correction is up to 0.827 from 0.219 before correction. The position of the central speckle is not located in the center of the picture due to the large tilt and tip terms in Fig. 6(a). In addition, two speckles with the same intensity were observed in it. After correction, the obvious improvement is observed in Fig. 6(b). First, the position of the central speckle shifted to the center of the picture. Second, only one speckle with the maximum intensity was observed. Experimental results indicate that a large aberration was easily removed. In fact, it is possible to be used in the tip-tilt adaptive optics systems to compensate for the overall tilt and tip terms of adaptive systems.[13]

Figure 7 shows the interferogram before and after correction. Ten interferometric strips could be obviously observed in Fig. 7(a). But there is not one in Fig. 7(b) after correction. We have reported the response speed of our LC WFC in our previous work. To improve it more, new LC devices are investigated based on ferroelectric LC (FLC)[14] and dual-frequency LC.[15] The bistable characteristics of FLC lead to a small PSF of 0.405.[14] But almost all nematic liquid crystal material exhibits some dual-frequency behavior, that is, a change in the sign of the dielectric anisotropy with a change in the frequency of the applied voltage. Therefore, we could obtain continuous phase-gray characteristics and high PSF and high respondse speed with double-frequency LC. Also, it is considered good to improve the response speed of an LC device.

5 Conclusions

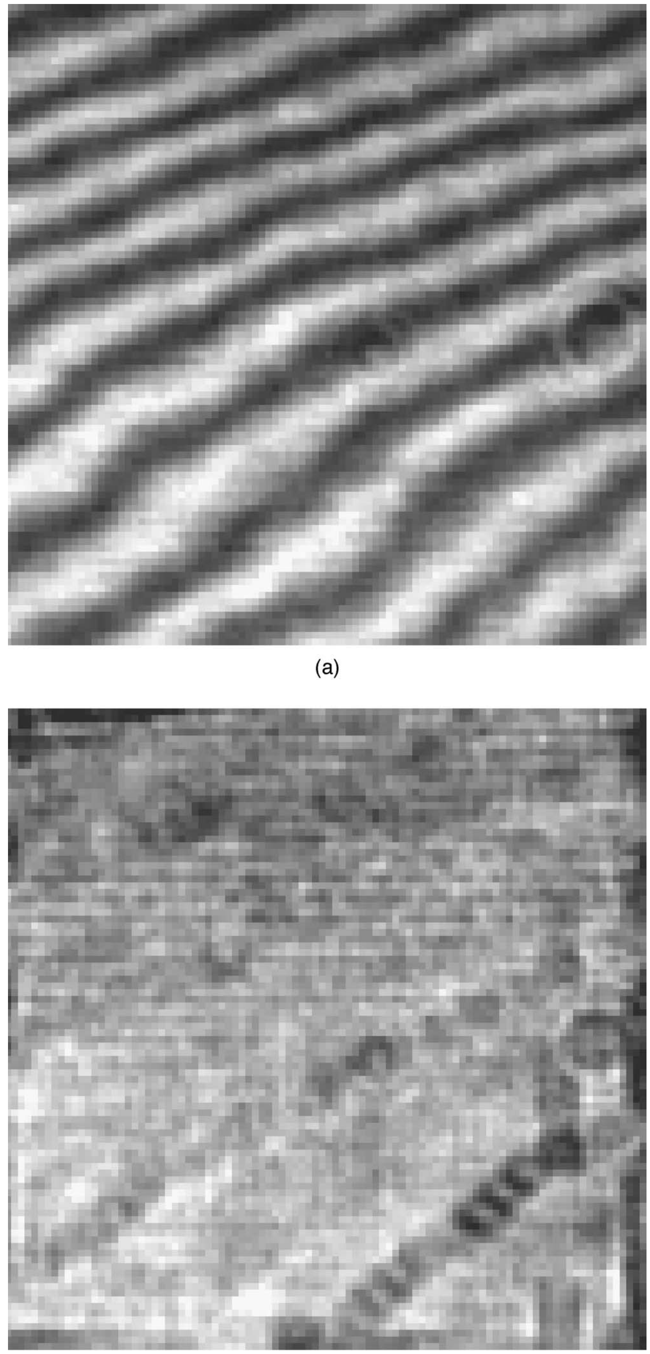
In conclusion, we introduce the parallel-aligned LCTV with 1920×480 pixels as the LC WFC. The measured PV value of the wavefront is 9.956λ before correction and 0.837λ after that. In addition, the measured rms value of the wavefront is 2.202λ before correction and 0.124λ after that. A phase stroke of more than nine wavelengths was obtained with our pure-phase LC WFC. The experimental results indicate that our parallel-aligned modulator can be used in adaptive optical wavefront correction. Besides wavefront correction, a parallel-aligned LC WFC could also be used



(a)

(b)

Fig. 6 The comparisons of PSF between a corrected wavefront and a noncorrected one on the area of 1 cm^2 of (a) the PSF before correction and (b) the PSF after correction.



(a)

(b)

Fig. 7 The comparisons of the interferometer patterns between a corrected wavefront and a noncorrected one on the area of 1 cm^2 (a) before correction and (b) after correction.

in phase-only filters (POF). In fact, parallel-aligned LC WFC is very attractive for many applications of optics, such as, medical imaging, metrology, optical communications, and laser beam steering.

Acknowledgments

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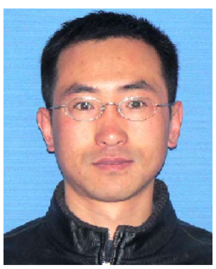

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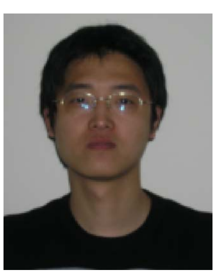

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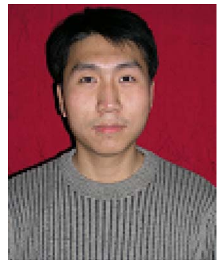

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