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High Closed Loop Correction Accuracy with a Liquid Crystal Wavefront Corrector *

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We investigate the accurate control of a liquid crystal wavefront corrector. First, the Gamma correction technique is adopted to amend the nonlinear phase modulation. Then, the control method and wavefront reconstruction are considered. Lastly, a closed loop correction experiment is carried out and a high correction accuracy is obtained with peak to valley (PV) of 0.08λ *(*$\lambda = 632.8$ *nm), the wavefront phase rms* 0.015λ*, as well as the Strehl ratio of 0.99. The diffraction-limited resolution is achieved.*

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Liquid crystal spatial light modulators (LC SLMs) are very promising devices for adaptive wavefront correction,[1−4] beam shaping,[5] and tunable lens,[6] etc. Compared to deformable mirrors, they have the advantage of low cost, large number of active elements, low consumption, and compact size. Some researchers have used them in adaptive optics systems and acquired significant results in laboratory.[7,8] Dayton *et al.*[9] installed an adaptive optics system with a dual-frequency liquid crystal wavefront corrector (LC WFC) in a 3.67 m telescope to correct the distortions of turbulence and obtained the resolvable image of the International Space Station. For the correction accuracy of an adaptive optics system, the number of active elements is a decisive factor. Because an LC WFC has millions of pixels, its system is qualified to realize the high correction accuracy with PV of $\lambda/10$. In this Letter, we investigate the way to control an LC WFC accurately and to realize the high correction accuracy.

Liquid crystal material is a uniaxial birefringence material with a fast axis and a slow axis. The phase of the light with the polarization along the slow axis will be delayed with respect to that along the fast axis. The phase delay can be calculated with the formula

$$\Delta\varphi = \frac{2\pi}{\lambda}\int_0^d [n_e(\theta_z) - n_0]dz, \tag{1}$$

where d is the thickness of the liquid crystal, λ is the relevant wavelength. As liquid crystal material is a uniaxial crystal, $n_e(\theta_z)$ can be obtained with the index ellipsoid equation[10]

$$n_e(\theta_z) = \frac{n_o n_e}{(n_o^2\cos^2\theta_z + n_e^2\sin^2\theta_z)^{1/2}}, \tag{2}$$

where n_o is the ordinary refractive index and n_e is the off-state extraordinary refractive index. The tilt angle of the liquid crystal molecule θ_z can be calculated by[10]

$$\begin{aligned}\Big(\frac{dz}{d\theta_z}\Big)^2 &= K_{11}(1 + K\sin^2\theta_z)\\ &\quad\cdot\Big[G - \frac{D_z^2}{\varepsilon_0\varepsilon_\perp(1+\beta\sin^2\theta_z)}\Big]^{-1},\\ K &= \frac{K_{33}-K_{11}}{K_{11}},\quad \beta = \frac{\varepsilon-\varepsilon_\perp}{\varepsilon_\perp},\\ G &= \frac{D_z^2}{\varepsilon_0\varepsilon_\perp(1+r\sin^2\theta_z)},\end{aligned} \tag{3}$$

where ε_0 is the vacuum dielectric constant, $\varepsilon_\perp$ and $\varepsilon_\parallel$ are the dielectric constants along the perpendicular and parallel directions, respectively, D_z is the electric displacement vector in z direction. When the electric field is on, the electric displacement vector D_z is changed and the tilt angle of the liquid crystal molecule will be changed according to Eq. (3). Consequently, the extraordinary index $n_e(\theta_z)$ is changed and the phase delay will be altered, too. Therefore, the strength of the electric field can be used to modulate the phase of the light.

A commercial LC SLM (LCR-2500, Holoeye) was used as the LC WFC and it has a frame rate of 77 Hz, pixels of 1024×768, and pixel pitch of 19 μm. The phase modulation of the LC WFC was measured with a ZYGO interferometer as shown in Fig. 1. It is indicated that the LC WFC can realize phase modulation of 1.015λ ($\lambda = 632.8$ nm). Consequently, the larger phase modulation can be obtained with the kinoform technique.[11] However, the curve of the phase modulation shown in Fig. 1 is nonlinear because the driving

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software is specially for the display, but not for the wavefront correction. As the nonlinearity of the phase modulation curve, the larger phase step will be produced between the adjacent two grey levels and the correction accuracy will be decreased. Furthermore, the nonlinearity will increase the complexity of the programme. This nonlinearity can be corrected with Gamma correction technique which is originally used to correct of the nonlinearity between the brightness and the driving voltages in LC displays. With the new Gamma curve, the linear curve of phase modulation can be achieved as shown in Fig. 2. The maximum phase step between two adjacent grey levels is 0.006λ. It is small enough to make the high accuracy wavefront correction with PV of $\lambda/10$.

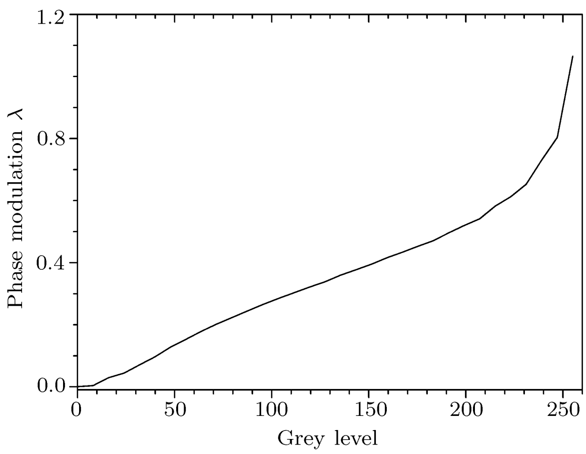

Fig. 1. Phase modulation as a function of the grey level measured with ZYGO interferometer.

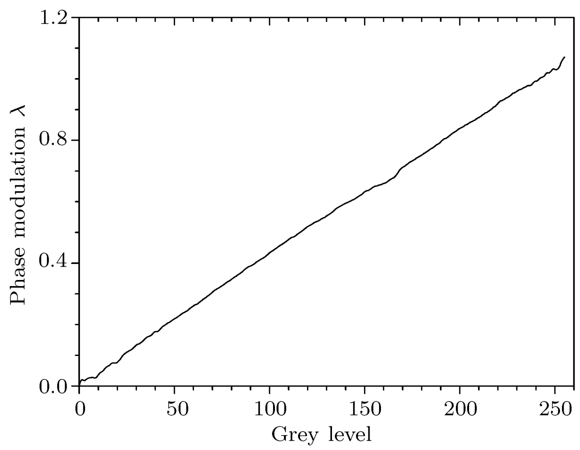

Fig. 2. Linear relation between the phase modulation and the grey level measured with a ZYGO interferometer.

The optical layout of the adaptive optics system is shown in Fig. 3. A He–Ne laser ($\lambda = 632.8\,\mathrm{nm}$) is used as the linear polarized light source, and a half wave plate is used to rotate its polarized orientation. The light beam goes through the spatial filter and a collimation lens, then enters into the LC WFC. The reflected light from the LC WFC is split into two beams. One goes to the CCD camera and the other to the wavefront sensor.

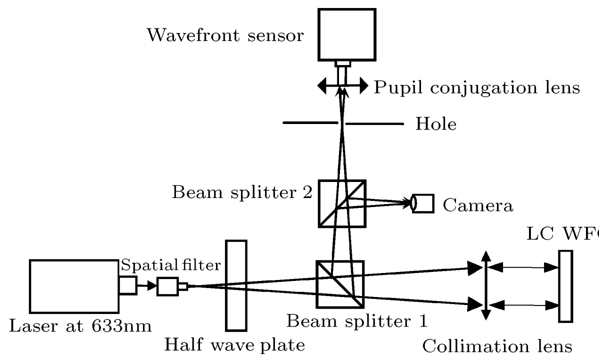

Fig. 3. Optical layout of the closed loop correction.

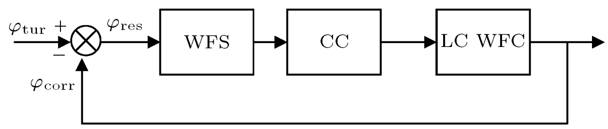

Fig. 4. Block-diagram of the adaptive optics system.

A block diagram of the closed loop control is shown in Fig. 4. The distorted wavefront $\varphi_{\rm tur}$ is measured by the wavefront sensor (WFS). The control computer (CC) reads the measured data from the WFS and calculates the conjugated wavefront with the response matrix. The conjugated wavefront is sent to the LC WFC to correct the distorted wavefront. The outputted corrected wavefront compensates for the distorted wavefront, and the residual $\varphi_{\rm res}$ will be detected by the WFS at the next time. Then, $\varepsilon_{\rm res}$ is accumulated on the compensated wavefront. Thus, when the WFS detects the wavefront continuously, the outputted corrected wavefront will approach the distorted wavefront $\varphi_{\rm tur}$ gradually, and the residual $\varphi_{\rm res}$ will reduce to zero.

The Modal method is used to reconstruct the wavefront. In this method, the phase of the wavefront is represented by the coefficients of expansion in a set of basis Zernike modes. The reconstruction calculates $A = \{a_k\}$ first. Then, the distorted wavefront can be expended with the formula

$$\varphi_j = \varphi(x_j, y_j) = \sum_{k=0}^{M} a_k z_k(x_j, y_j), \tag{4}$$

where a_k is the coefficients of Zernike polynomials, z_k is the modes of Zernike polynomial, M is the number of modes. Consequently, the coefficient matrix A should be reconstructed first. Differentiating Eq. (4) and solving it with least-square method, the solution can be obtained with the matrix form[12]

$$A = (D^T D)^{-1} D^T G, \tag{5}$$

where A represents the coefficient vector of the Zernike polynomial, G is the slope matrix measured by the WFS, D is the response matrix. Since G is known, if D is acquired, A will be calculated with Eq. (5).

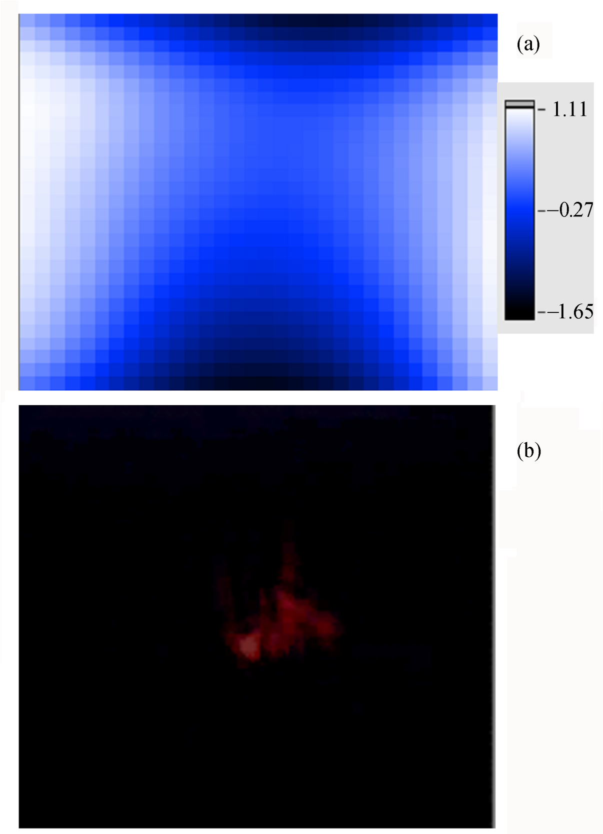

Fig. 5. Open loop state: (a) distorted wavefront in units of λ, (b) blurry point image.

The response matrix D can be measured before we perform the closed loop correction. The procedure is as follows: the first 36 modes were applied on the LC WFC one by one; while the first mode is sent to the LC WFC, the WFS measures the response and outputs the slopes of the wavefront to the CC; the CC records these slope values in the first two rows of the response matrix. Similarly, the response of second mode will be recorded at next two rows. Assuming that the number of the microlens is N and that M modes are used to measure the response matrix, the response matrix can be expressed as

$$D = \begin{pmatrix} S_{x_1 z_1} & S_{x_2 z_1} & \cdots & S_{x_N z_1} \\ S_{y_1 z_1} & S_{y_2 z_1} & \cdots & S_{y_N z_1} \\ \vdots & \vdots & \ddots & \vdots \\ S_{x_1 z_M} & S_{x_2 z_M} & \cdots & S_{x_N z_M} \\ S_{y_1 z_M} & S_{y_2 z_M} & \cdots & S_{y_N z_M} \end{pmatrix}.$$

where S_{x_k} and S_{y_k} are the slopes of the kth microlens along the x and y directions, respectively, and $k = 0, \cdots, N$. This response matrix is stored in the CC before the closed loop correction. Thus, while the slope matrix G is measured in the closed loop control, the coefficient matrix A can be calculated with Eq. (5). Then the wavefront can be reconstructed with Eq. (4) and the conjugated signal is sent to the LC WFC to correct the distortions.

A closed loop correction experiment was performed with the above-mentioned control method. As the diameter of the incident light beam is larger than the window of the LC WFC, the stop of the optical system was rectangular. The turbulence was produced by an electronic iron of 20 W. Before correction, the WFS detected the average distorted wavefront with PV of 2.7λ and phase rms of 0.6λ (Fig. 5(a)). The distorted point image was captured by the camera as shown in Fig. 5(b). The first 36 Zernike modes and the gain of 0.8 were used in the system, and the closed loop bandwidth was 4 Hz. After closed loop, PV and the rms phase of the wavefront are down to 0.08λ and 0.015λ, respectively (Fig. 6(a)). The Strehl ratio is improved to be 0.99. The corrected point image, i.e. the diffraction image of the rectangle, is shown in Fig. 6(b). It suggests that the system approximately reaches the diffraction-limited resolution we have ever obtained in the previous work.[13]

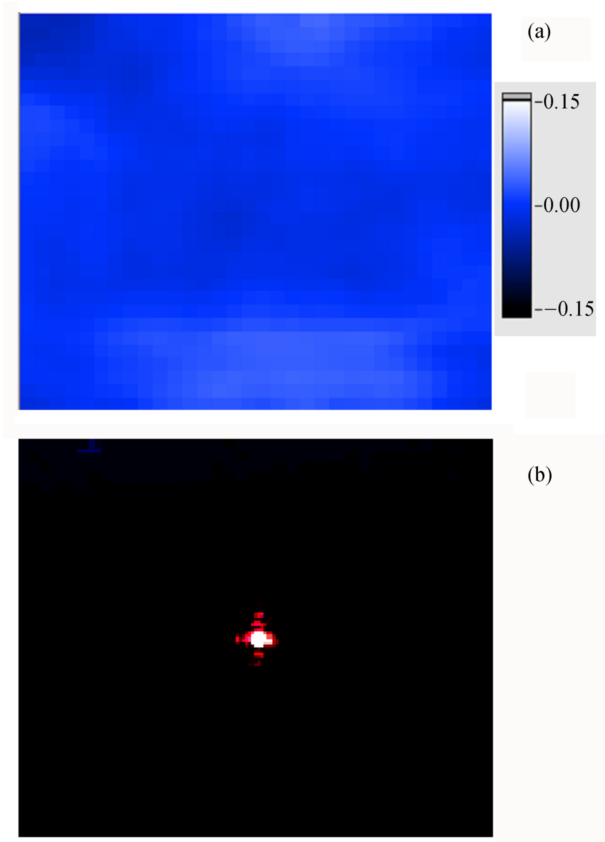

Fig. 6. Closed loop correction results: (a) the corrected wavefront in units of λ, (b) the corrected point image.

In summary, high correction accuracy is realized with a liquid crystal wavefront corrector. The nonlinearity of the phase modulation is corrected with Gamma correction technique. The closed loop control method and wavefront reconstruction are investigated. With the closed loop correction, high correction accuracy with PV of 0.08λ and the wavefront phase rms of 0.015λ is fulfilled and the Strehl ratio is up to 0.99. The quasi-diffraction-limited resolution is also acquired.

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