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A polarization independent liquid crystal adaptive optics system

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Abstract
A liquid crystal device is normally limited to use with polarized light, resulting in a loss of 50% of the incident unpolarized light. In this paper, a polarization independent liquid crystal adaptive optics wavefront correction system is demonstrated. In the demonstration system, a quarter-waveplate (QWP) and mirror combination are used to rotate the plane of polarization by 90° on the return pass. The result is that both orthogonal components of the incident unpolarized light are phase modulated by the liquid crystal on silicon (LCOS) device. Theoretical analysis shows that the optical throughput of the novel system is about 19.7% higher than that of a standard, polarized LC adaptive optics system. As a demonstration, we used the LC adaptive optics system to correct the aberration of unpolarized light, and obtained a clear image of the unpolarized light source.

Keywords: wavefront sensor, adaptive optics, liquid crystals

1. Introduction

Deformable mirror (DM) devices and micro-machined electro-mechanical systems (MEMS) have been widely used as wavefront correctors in a variety of adaptive optics (AO) systems [1–7]. However, the technology is not scalable; it is very difficult to increase the number of active actuators, as would be required for its application in large telescopes. In recent years, there has been a large amount of discussion on the use of liquid crystal devices as alternatives to DMs in adaptive optics systems [8–12]. Liquid crystal (LC) devices can modulate the phase of a beam of light through tuning of the apparent refractive index with applied voltage. The LC device has many advantages for wavefront correction; a large number of pixels, low power, low cost, compactness and programmability as demonstrated by many researchers [13–19]. However, it also exhibits a number of limitations as a wavefront corrector. First, the LC phase modulation depends on the wavelength of incident light. Therefore, the working spectrum of an LC wavefront corrector is narrow. To resolve the problem, several liquid crystal on silicon (LCOS) wavefront correctors with different center wavelengths can be used to correct the broadband incident light in parallel. Second, the response time of a wavefront corrector with nematic LC is generally much longer than that of a DM. However, the response time of the nematic LCOS 256 devices manufactured by Boulder Nonlinear Systems, Inc. (BNS) is now less than 3 ms. In addition, the response times of both dual frequency LC and ferroelectric LC are less than 1 ms and are therefore comparable to that of DM. With continued improvements to LC materials, the prospect of even shorter response times is promising. Thirdly, the principle of an LC wavefront corrector is based on binary optic concepts. The diffraction efficiency depends on the number of pixels per phase wrap. Fortunately, the number of pixels in an LCOS device is at least 65 536, which is sufficient to maintain a high diffraction efficiency. Finally, LCOS devices can only phase modulate polarized light, which means, in the best case, that it can only usefully modulate 50% of incident unpolarized light. In astronomical or medical applications, the light from the object under view is often very weak. Therefore, it is very important to avoid the loss of incident light due to polarization. As a result of the above limitations, only a few papers have reported using an LC adaptive optics system to observe space objects [8, 9].

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To overcome polarization dependence, many methods have been presented or proposed [17–20]. Our group used an open loop optical layout: the modulated part of incident light is used for correction, and the non-modulated part for wavefront sensing [20]. Love proposed a novel method to modulate unpolarized light with an LC cell [17, 18], that is, a quarter wave plate (QWP) is placed between an LC cell and a mirror. In this configuration, both of the two orthogonal polarization states of incident light can be modulated after their first and second passage through the cell, respectively. Therefore, this configuration can be used to modulate unpolarized light without loss of optical throughput with a transmissive LC cell. The optical throughput is defined as the ratio of the light intensity on the charge coupled device (CCD) to one from a light source. However, commercially available LC wavefront correctors are usually based on LCOS, a reflective device. LCOS has been selected for use in many applications due to its small pixel size and relatively high reflectivity. Alternately one could use a polarizing beam splitter and pass orthogonal polarizations through two independent LCOS devices, using a polarization beam splitter to combine the light after correction. This would ease constraints on several aspects of the system, namely the QWP and multiple reflection and transmission losses. However, the whole system would be complex to control and have a relatively high cost. In our LC adaptive optics system, a LCOS is used as a wavefront corrector. Utilizing Love's principle [18], we designed and demonstrated an LC adaptive optics system to correct the aberration of unpolarized light.

The remainder of the paper outlines our demonstration system: in section 2, we present the principle of our polarization independent adaptive optics system, and discuss its optical throughput. Experimental results and discussions are given in section 3. Finally, a summary and conclusion follow in section 4.

2. Experiment setup and optical throughput

2.1. Experiment

The electro-optic and birefringent properties of LC allow it to modulate the phase of incident light under changing applied voltage. Any incident light which strikes an LC waveplate can be divided into two different components with orthogonal polarization directions. It is possible to modulate the phase of two orthogonal components of unpolarized light with a single LCOS device through the use of a QWP, rotating their polarization directions, respectively. First, the component of incident light parallel to the LC extraordinary axis is modulated by the LCOS device in the first reflective pass. Then the polarization direction of light is rotated by 90° as it passes through the QWP twice, causing the two components of the reflected light to exchange their polarization directions. Therefore, when light is reflected by the LCOS device for the second time, both components of incident unpolarized light have been modulated. Based on this concept, we designed a novel optical layout of the LC AO system to correct unpolarized incident light.

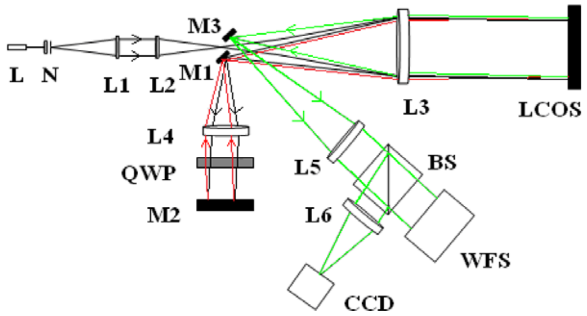


Figure 1. Optical layout for the polarization independent LC adaptive optics system, L, He–Ne laser; N, the spatial filter; L1, L2, L3, L4, L5 and L6 are lenses; M1, M2, M3 are mirrors. BS: beam splitter; QWP: quarter wave plate; WFS: wavefront sensor.

Figure 1 shows the optical layout of our LC adaptive optics system for unpolarized light. As shown in figure 1, first, the light is emitted by L, and passes through lenses L1, L2 and L3; then, it is reflected by LCOS and is reflected from M1 through the QWP; third, the light (red line) is reflected from M2 and back through the QWP and to M1 again; fourth, it (green line) is reflected from the LCOS for a second time, and back toward M3; finally, the light (green line) is reflected from M3 and towards BS. It should be noted that the incident light is not normal to the LCOS as shown in figure 1, and the tilt angle is about 5°. The system consists primarily of an unpolarized He–Ne laser (L), a model M-900 spatial filter (N) built by Newport Corp., an LCOS from BNS, a wavefront sensor ShaH 1000 from Visionica Ltd, a CCD DU 897 from Andor Ltd and a data processing computer. The LCOS SN 7543 has 512 pixels × 512 pixels and pixel size of 15 μm. The wavefront sensor ShaH 1000 has a frame rate of 500 Hz, quantum efficiency larger than 90% at 633 nm, aperture size of 3 mm, microlens focus length of 3 mm, and microlens diameter of 150 μm. The CCD DU 897 has 512 pixels × 512 pixels with the pixel size of 12 μm. The spatial filter N with an aperture of 15 μm is used to generate an ideal spherical wavefront. As shown in figure 1, light is reflected by LCOS twice before it reaches the wavefront sensor and imaging CCD.

To analyze the concept theoretically, Jones matrices of optical components used in the setup are established [17, 18]. The relationship between input and output Jones vectors of light is

$$\begin{bmatrix} x_{\text{out}} \\ y_{\text{out}} \end{bmatrix} = L'Q'MQL \begin{bmatrix} x_{\text{in}} \\ y_{\text{in}} \end{bmatrix} \quad (1)$$

where L and L' are the forth and back Jones matrices of LCOS, respectively, and they are identical. Considering that the physical structure of LCOS is different from that of a transmission LC device, its Jones matrix could be obtained by the Jones matrix multiplication of two LC layers and a mirror. The Jones matrix of LCOS is therefore

$$L = \mathrm{e}^{-\mathrm{i}\alpha} \begin{bmatrix} \mathrm{e}^{-\mathrm{i}\alpha} & 0 \\ 0 & \mathrm{e}^{\mathrm{i}\alpha} \end{bmatrix} \quad (2)$$

where $\alpha = 2\pi \Delta n d/\lambda$, i is the basic imaginary unit, d is the thickness of the LC layer of LCOS, Δn is the birefringence of

LC, and λ is the wavelength of 633 nm. Q is the Jones matrix of QWP and Q' is its Jones matrix on the return pass given by

$$Q = 0.707 \begin{bmatrix} 1 & \mathrm{i} \\ \mathrm{i} & 1 \end{bmatrix} \tag{3}$$

$$Q' = Q. \tag{4}$$

M is the Jones matrix of the mirror given by

$$M = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}. \tag{5}$$

Therefore, assuming an unpolarized input light source, the output light is obtained according to equations (1)–(5):

$$\begin{bmatrix} x_{\mathrm{out}} \\ y_{\mathrm{out}} \end{bmatrix} = L'Q'MQL \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \mathrm{i}\mathrm{e}^{-\mathrm{i}2\alpha} \begin{bmatrix} 1 \\ 1 \end{bmatrix}. \tag{6}$$

The result in equation (6) indicates that the two components of unpolarized input light are retarded by the LCOS device with the same phase value. Therefore, the optical layout of our LC adaptive optics system, as shown in figure 1, could theoretically be used to correct unpolarized light.

2.2. Optical throughput

Theoretically, the optical throughput will be twice that of a conventional LC AO system as both polarization components of the incident light are used and corrected. However, as several optical components are introduced, the reflective and transmission losses are increased. The quantitative value of these light losses depends on the optical coating on the surface of the optical devices. We assume reasonably that the reflectivity R_{mirror} of all mirrors is 99.5%, transmittance T_{lens} and T_{QWP} of all lenses and the QWP is 95%, and the light intensity from N in figure 1 is equal to one. Therefore, the normalized light intensity I_{ccd} incident on the CCD in figure 1 could be calculated as the following:

$$I_{\mathrm{ccd}} = 0.5 T_{\mathrm{lens}}^{10} T_{\mathrm{QWP}}^{2} R_{\mathrm{mirror}}^{4} R_{\mathrm{LCOS}}^{2} \tag{7}$$

where the coefficient of 0.5 accounts for the beam splitter. R_{LCOS} is the reflectivity of the LCOS. In a conventional LC AO system, a polarizer is used. Furthermore, optical devices of M1, M2, QWP, and L4 are not present. Therefore, the normalized light intensity $I_{\mathrm{ccd,old}}$ could be calculated as the following:

$$I_{\mathrm{ccd,old}} = 0.25 T_{\mathrm{lens}}^{6} R_{\mathrm{mirror}} R_{\mathrm{LCOS}} \tag{8}$$

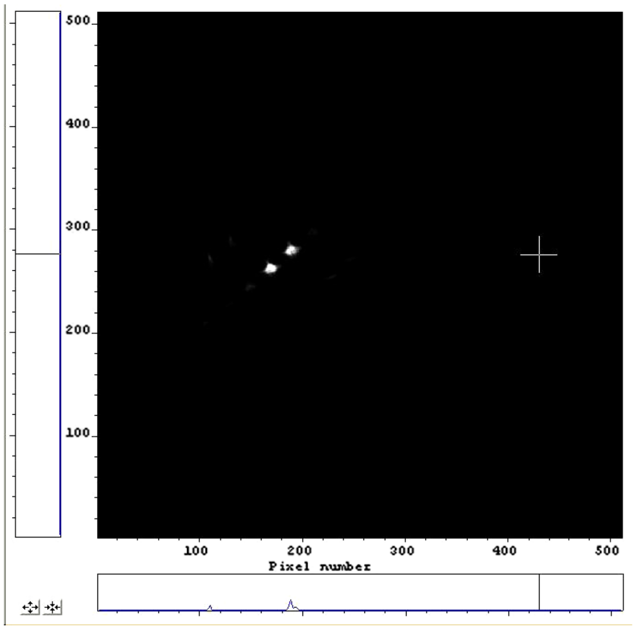
where the coefficient of 0.25 is due to the introduced polarizer and a beam splitter. It should be noted that the reflectivity R_{LCOS} of available LCOS devices from BNS has been increased up to 0.95 by introducing a dielectric mirror and increasing the fill factor of the LCOS backplane. Therefore, according to equations (7) and (8), the normalized intensity ratio between I_{ccd} and $I_{\mathrm{ccd,old}}$ is about 1.197 times. Therefore, the optical throughput for our polarization independent LC adaptive optics system is 19.7% more than that of a standard system. One way to improve the optical throughput of our system even further is to replace all of the lenses with aspheric mirrors. An aspheric LC AO system with high reflectivity aspheric mirrors will minimize throughput losses due to lenses. In addition, unlike standard LCOS with reflectivity of 61.5%, it is up to 90%–95% for the available improved LCOS with high efficiency mirrors. Therefore, the value of 19.7% could be increased to at least 28.8% in future.

In our experiment, the reflectivity R_{LCOS} is about 61.5%. Therefore, the normalized light intensity I_{ccd} will be about 0.128 according to equation (7). Clearly there are still very large optical throughput losses. This is mainly due to two factors: first, the LCOS device itself has a low reflectivity R_{LCOS}, second, there are a number of lenses with low transmittance. In addition, it is not technically difficult to replace all lenses in figure 1 with high reflectivity aspheric mirrors. Therefore, it is possible for an LC AO system to have a high optical throughput close to that of a DM AO system, but in a narrow spectrum. For the entire visible light spectrum, several LCOS devices with different center wavelengths are needed to expand the working spectrum of an LC AO system. Although our LC adaptive optics system could correct the aberration of unpolarized light, additional optical elements such as a lens, QWP, and a mirror were introduced in the system. Because of the limitations of their reflectivity, there will be some light loss. Therefore, in practical systems, antireflective coating can be used to reduce the loss of the lens and QWP.

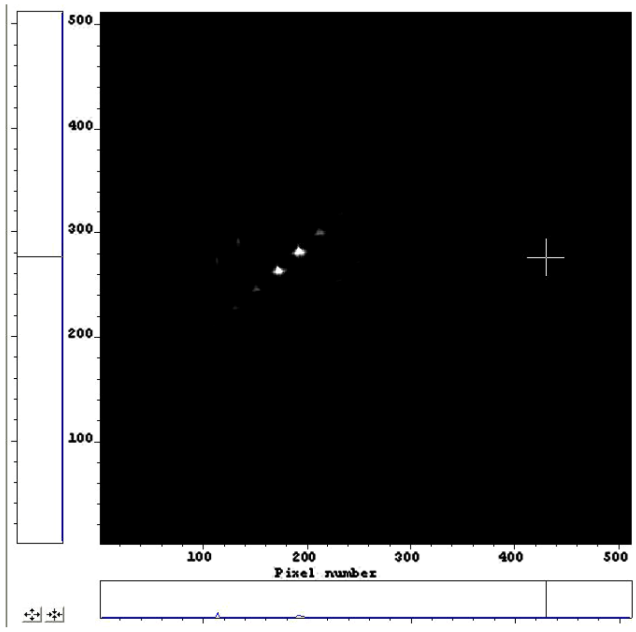
3. Results and discussion

To demonstrate the concept experimentally, a blazed grating phase map was applied to the LCOS device. A polarizer was placed in front of the CCD. By rotating the polarizer, we obtained an image of the input light on the CCD in horizontal and vertical polarization directions. The results are shown in figures 2(a) and (b) with horizontal and vertical polarization directions, respectively. Note that there are two bright spots in both figures 2(a) and (b). The lower spot is the zeroth order, and the upper is the first diffractive order. It is clear that in both polarization directions, the image shows energy in the first diffractive order. Therefore, the experimental results in figure 2 confirm that our LC AO system can be used to correct unpolarized light.

However, as shown in both figures 2(a) and (b), the energy of the zeroth order is significant, i.e. the unmodulated light is not negligible. This is primarily due to two factors: one is the oblique angle of incidence of light on the LCOS; the other is due to the QWP. In order to realize a linear 0–2π LC phase response to voltage, a look up table (LUT) curve is measured for normally incident light on the LCOS. However, oblique incident operation leads to a slightly different LUT curve. Therefore, if the original LUT curve is used in an oblique incident condition, diffractive efficiency will decrease a little, which means the energy of the zeroth order will be increased. That is to say, the blazed grating generated by the LCOS is not ideal partly because the phase error would be larger for non-normal incident light. In addition, the fill factor in the



(a)



(b)

Figure 2. Images of a light source on the CCD in two orthogonal polarization directions: (a) horizontal polarization direction; (b) vertical polarization direction.

experiment is 83.4%. From our previous experiments with normal incident light, the light intensity ratio of zero diffraction order and the first diffraction one is about 1:5, which depends on the amplitude of the applied grating map. Theoretically, the diffraction efficiency of the first order could be more than 90% when the number of steps in the blaze profile is more than 16. Therefore, in the practical system, the light throughput would be a little lower than the theoretical value. Another factor is the QWP. From our experience, the rotating abilities of our QWP for two perpendicular polarization states of incident light are different, that is, a portion of the 90° polarization state cannot be rotated to 0°. Generally, the incident light should be normal to the QWP plane. However, in our experiment, there is a small tilt angle between the incident light and the normal direction of the QWP. Therefore, the polarization direction of rotated polarized light is not ideal.

The unmodulated light must be removed to successfully achieve high precision wavefront correction. Therefore, a grating gray map was also applied as a background to the LCOS device to separate the zeroth order from the first order. By adjusting the edge position of M3 to reflect only the first order, light from the zeroth order was filtered out. In addition, the polarizer in front of the CCD was removed. Therefore, we could obtain only modulated unpolarized light in our LC adaptive optics system. The wavefront correction results without a polarizer in the optical layout are given in figure 3. Figures 3(a) and (b) shows the wavefront before and after correction, respectively. Their rms values are 0.837λ and 0.099λ, respectively. Figures 3(c) and (d) shows the image of the light source before and after correction, respectively. It could be said that after correction, the light energy becomes much more concentrated, as shown in figure 3(c) compared to (d).

In fact, there are three parameters that dominate all forms of losses as mentioned above: the reflectivity of mirrors, transmittance of lenses and QWPs, and the diffraction efficiency of LCOS. Usually, when the incident light is normal to the LCOS, the intensity of the first order will be about three times higher than that of the zeroth order. However, for tilt incident light, the LUT of LCOS should be different because the phase modulation characteristics of LCOS will be a little different. However, further investigation should be conducted to decrease the losses.

4. Summary

In conclusion, we have demonstrated a novel LC adaptive optics system for unpolarized light. There are two main advantages to our system: first, it could successfully correct aberrations in unpolarized incident light. Second, its optical throughput is about 19.7% higher than that of a conventional LC adaptive optics system in the presently available best conditions. Furthermore, the approach is simple and low cost. In addition, one need not change the structure of LC devices for unpolarized light correction. It should be noted that the LCOS in our experiment is a phase-only device. For a twisted nematic (TN) LCOS, the optical layout in figure 1 and this approach are equally valuable. However, there is an angle difference of 90° between the LC molecular directors in the upper and lower LC layers of a TN LCOS. Loss of incident light will be observed due to the partial amplitude modulation inherent in these devices. Although we have demonstrated this technique for wavefront control, the basic concept could equally serve a variety of LC-based applications.

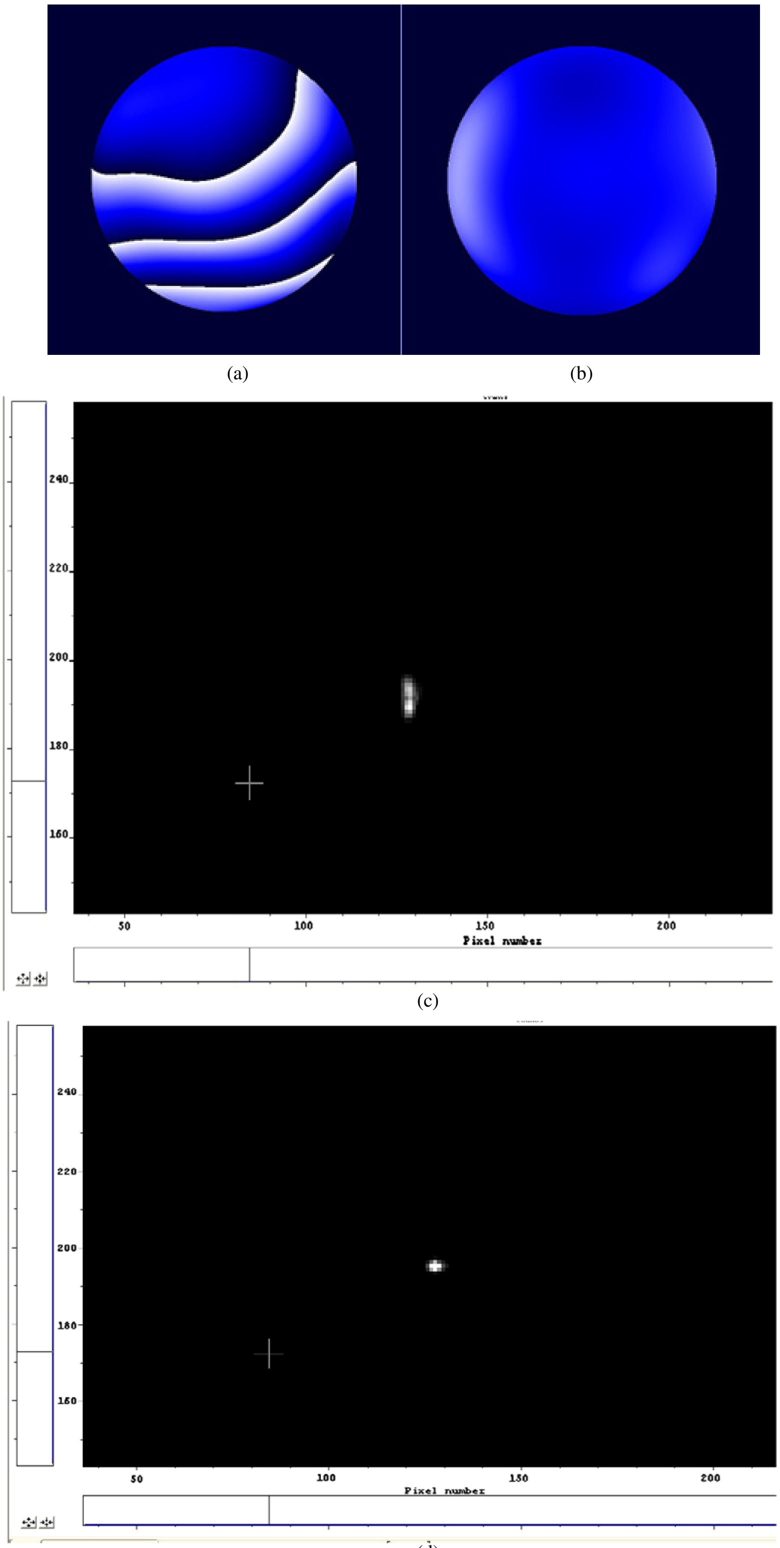


Figure 3. Wavefront correction of unpolarized light with an LC adaptive optics system: (a) wavefront before correction; (b) wavefront after correction; (c) image of the light source before correction; (d) image of the light source after correction.

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