Optics Communications 285 (2012) 896–899

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Open loop adaptive optics testbed on 2.16 meter telescope with liquid crystal corrector

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ARTICLE INFO

Article history:
Received 28 March 2011
Received in revised form 10 October 2011
Accepted 18 October 2011
Available online 4 November 2011

OCIS:
230.3720
010.1080

Keywords:
Adaptive optics
Liquid crystal corrector
Open loop control

ABSTRACT

A novel liquid crystal wave front corrector (LCWFC) based open loop adaptive optics testbed for nonpolarized light was introduced in this paper. A polarizing beam splitter (PBS) was used behind the LCWFC to divide the reflected nonpolarized light into two orthogonal polarized lights with and without the modulation effect for high resolution imaging and aberration detection respectively. The alignment direction of LC molecules was parallel to the polarization direction of the light PBS reflected. This configuration was simple and easy for construction. It avoided the energy loss due to the use of polarizer for conventional LCWFC based closed loop adaptive optics system. Furthermore, it could be switched into closed loop configuration very easily, which was useful for quantitative system performance evaluation. The detailed construction and operation was reported in Section 2. In Section 3, this testbed was deployed at the coude focus of the 2.16 m telescope at the Xinglong Station of the Beijing Astronomical Observatory. The observation of star Arcturus was done. The Full Width Half Maximum (FWHM) resolution was improved from 2.12″ to 0.64″ successfully.

1. Introduction

Liquid crystal wave front corrector (LCWFC) is one of the most attractive wave front correction devices for adaptive optics system (AOS). The phase only modulation property for conventional nematic LC devices has been studied since the 1980s [1,2]. Compared with conventional deformable mirror device, the LCWFC has the advantages of low cost, reliability, low power consumption, low price, no moving mechanical components and high resolution [3–7]. It has millions of pixels, which makes it possible to use the phase wrapping technique to increase its modulation depth without any loss on spatial resolution [8]. The phase modulation procedure was performed by rotating the LC molecules under the driver of external electric field. For conventional parallel aligned LC device, which benefited for pure phase modulation, only the linearly polarized light with polarization direction parallel to the alignment direction of LC molecules could be fully modulated. Light with polarization direction perpendicular to its alignment direction had no effect. Conventional LCWFC based AOS usually use a polarizer to filter the incident nonpolarized light to match the alignment direction of LCWFC [5]. This polarization dependence results in nearly fifty percent energy loss for nonpolarized light due to the use of a polarizer.

For nonpolarized light with aberrated wave front, the LCWFC will have different influence due to its uniaxial property. This nonpolarized light could be separated into two orthogonal polarization components when transmitting through the LCWFC, shown in Fig. 1. The extraordinary component was represented by the red arrow lines with its polarization direction parallel to the alignment direction of LC molecules and the ordinary component was shown as the black arrow lines with its polarization direction perpendicular to the alignment direction of LC molecules. When the correction signal was added to the LCWFC, the extraordinary refractive index of LC will be changed according to the driving voltage while the ordinary refractive index stayed still. This correction signal was only effective for extraordinary component and had no impact on the ordinary component. In other words, light transmitted through the LCWFC remained nonpolarized but with modulated portion mixed in it.

In this paper, a PBS was introduced behind the LCWFC to separate these two components, shown in Fig. 1. The only need was to set the alignment direction of LC molecules parallel to one of the polarization states of the PBS. In Fig. 1, it was parallel to the P polarization state. So, the modulation signal was transmitted through PBS and the reflected light was still maintaining the original aberration. Under this configuration, light with polarization direction parallel to the alignment direction of LC molecules could be used for wave front correction. Another polarized light that could not be modulated by the LCWFC was used for wave front detection and the energy loss was avoided. The only challenge was that the whole system should be operated in an open loop configuration. It was difficult to use conventional deformable mirror WFC in open loop control due to its hysteretic and nonlinearity properties. But for LCWFC, this was possible. It has been proven to be a very high-precision corrector for generating a

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doi:10.1016/j.optcom.2011.10.054

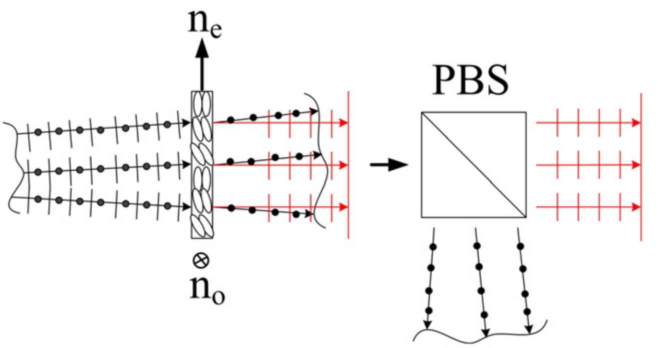


Fig. 1. The modulation property of parallel alignment LCWFC for nonpolarized light.

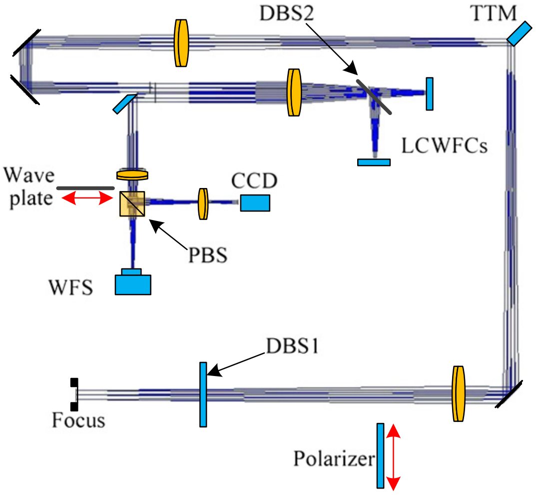


Fig. 3. The optical layout of the LCWFC based open loop AOS.

desired wave-front, which benefited for open loop control [9–12]. Furthermore, open loop control was also a requirement for advanced AO concepts for future giant telescopes [13–15].

According to this, an open loop LCAOS testbed was designed in this paper. The configuration and its operation were introduced in Section 2. Finally, it was deployed at the focus of a 2.16 meter telescope to demonstrate the concept on-sky.

2. System design and operation

Compared with conventional closed loop AOS, which was shown in Fig. 2 (a), the concept of open loop LCAOS was shown in Fig. 2 (b). PBS was the pivotal device in this system. It divided the incident nonpolarized light into two orthogonal polarized lights for wave front detection and correction respectively. Under this configuration, the incident nonpolarized light could be used entirely.

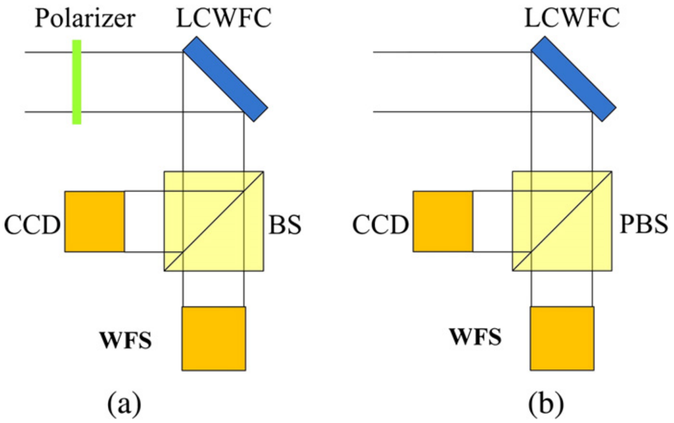
The testbed designed was shown in Fig. 3. Light gathered by the telescope was collimated and reflected by the tip-tilt mirror (TTM). Then, all the light was emitted onto the LCWFC. After the reflection of LCWFC, the light was still nonpolarized but contains a modulated polarization component, which was parallel to the alignment direction of LC molecules and the S polarization direction of the PBS. It could be reflected by the PBS for high resolution imaging. The P polarized light transmitted by the PBS preserved the aberration information, which could be used for wave front detection. Compared with previously introduced open loop AOS either with deformable mirror [16] or LCWFC [12], this configuration was the simplest, which was benefit for system fabrication and operation.

Previous research has been realized that the distortion correction of LCWFC was restricted in a narrow waveband nearly 100 nm in visible. In order to expand the spectral coverage of this testbed, a dual-LCWFC configuration was proposed [17]. Each LCWFC was responsible for the correction at different wavebands and then beams after correction were combined to realize the high resolution imaging in the whole waveband.

In this testbed, two dichroic beam splitters (DBSs) are used to divide the broadband beam of 600 nm–900 nm into two sub-wavebands, each of which can be corrected by one LCWFC. The 600 nm–900 nm waveband is acquired by using a long-wave pass filter (DBS1) with cutoff point at 600 nm. DBS2 is a long-wave pass filter with cutoff point at 700 nm, which divided the whole waveband into two wavebands and sent them to different LCWFCs. Using this method the light efficiency was improved observably to a level of applicability.

For open loop AOS, the alignment and calibration become more challenging. Key to the operation of any open loop AOS is the ability to register the open loop WFS to the WFC. In Ref. [16], an additional scoring WFS and a LED calibration source were utilized to achieve this registration. In Ref. 12, some accessional relay optics system and wave plates were used to establish a closed loop subsystem between the WFS and LCWFC. Both of them make the whole system complex and hard to operate.

In this testbed, only a half wave plate was needed before the PBS to establish a closed loop subsystem, shown in Fig. 3. This half wave plate was configured with its optical axis in a direction which makes an angle of 45° with the alignment direction of LC molecules.



(a) (b)

Fig. 2. Closed loop and open loop configuration of LCAOS.

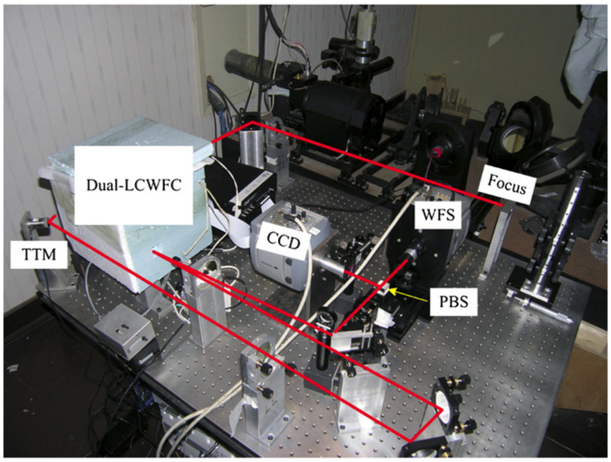


Fig. 4. The open loop LCAOS testbed.

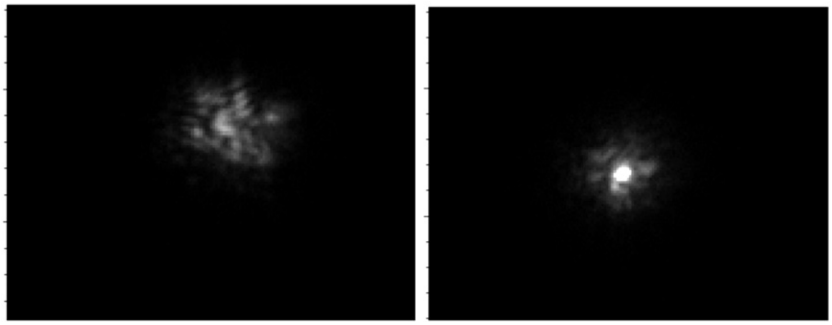


Fig. 5. Images of Arcturus before and after correction.

Then, the polarization direction of the component which was matched with the alignment direction of LC molecules will be rotated 90° after being transmitted through the half wave plate. The S polarized light with modulation signal became P polarized and could be received by the WFS to measure the response of LCWFC. Furthermore, a point source was also needed to act as a local target. It was located at the focus in Fig. 3. This light source could also be used for TTM calibration. This configuration was simple and do not need to do any change on the main part of the AOS.

Another advantage of this system was it could be changed into closed loop configuration very easily, which was valuable for quantitative system performance evaluation. In order to accomplish this procedure, a polarizer and a quarter wave plate were needed to insert before the TTM and PBS respectively, shown in Fig. 3. The polarization direction of the polarizer was set parallel to the alignment direction of LC molecules. The optical axis of the quarter wave plate was set at 45°. It was used to convert the linearly polarized light modulated by the LCWFC into circular polarized light. This circular polarized light could be divided into two parts by the PBS. Both of them contain the correction signal and can be used for residual wave front error detection and high resolution imaging respectively.

3. Experiments and result

In this section the testbed was deployed at the coude focus of the 2.16 m telescope at the Xinglong Station of the Beijing Astronomical Observatory. There, we have the benefit of a thermally isolated, gravitationally constant environment for our instrument. The aperture we actually used was 1.8 m. The optical layout of this LCAOS was shown in Fig. 4. All of them were mounted on a 900 × 1200 mm platform.

The LCWFCs were manufactured by Boulder Nonlinear Systems (BNS) Corporation. Both had an aperture of 6.14 mm × 6.14 mm, 256 × 256 pixels. The central wavelength was set to 633 nm and 785 nm respectively. The response time was limited by the slow device, which was nearly 5 ms at 40 °C working temperature. A heat preservation system (the blue box shown in Fig. 4) with heater in it was designed to make sure the LCWFCs keep their working temperature under different environment. The WFS has a 500 Hz acquisition frequency and a 3 mm aperture with 20 × 20 microlenses. Under open loop control, the control loop frequency could be optimized to nearly 200 Hz with parallel control [18].

The experiment was done on May 22nd, 2010. The night was clear. Images of the Arcturus ($R = 0.3$ [19]) before and after correction were shown in Fig. 5. The resolution improved obviously. Fig. 6 illustrated the three dimensional profiles. We measured the Full Width Half Maximum (FWHM) of Arcturus which was decreased from 2.12″ to 0.64″, which corresponds to an $r_0 = 8$ cm and 30 cm at 780 nm wavelength respectively. All this result demonstrated that this system configuration was feasible, although the result was still far from the diffraction limited resolution of the telescope. The control loop bandwidth of this system was the main restriction of its performance, which was mainly induced by the slow response of LCWFC. In a relatively early study, Greenwood derived an expression for the bandwidth of an AOS used for astronomical imaging. For what he termed the bandwidth of AOS should equal to the greenwood frequency of the turbulence to achieve a nearly 1 rad wave front error for diffraction limited resolution [20]. For a medium strength atmospheric turbulence with greenwood frequency nearly 40 Hz, the correction frequency of AOS should be no more than 250 Hz. In order to improve the correction frequency, new WFS with 1 kHz acquisition frequency and a new LCWFC with high speed LC materials were under design for next generation of LCAOS.

4. Conclusion

In conclusion, a novel LCWFC based open loop AOS was introduced in this paper. It consists of a PBS located behind the LCWFC. The alignment direction of LC molecules was parallel to the polarization direction of the light PBS reflected. This configuration was simple and easy for construction. It avoided the energy loss due to the use of polarizer for conventional LCWFC based closed loop AOS. Furthermore, it could be switched into closed loop configuration very easily, which was useful for quantitative system performance evaluation. Finally, a testbed was designed and deployed at the coude focus of the 2.16 meter diameter telescope at the Xinglong Station of the Beijing Astronomical Observatory. The observation of star Arcturus was done. The FWHM resolution was improved from 2.12″ to 0.64″ successfully.

Acknowledgments

This work is supported by the National Natural Science Foundation (No. 60736042, No. 60578035, No. 50703039).

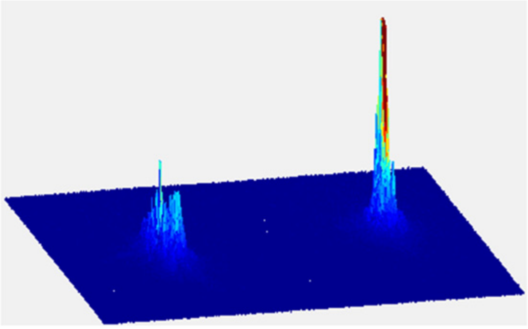


Fig. 6. Three dimensional profiles of Arcturus before and after correction.

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