Adaptive optics technique to overcome the turbulence in a large-aperture collimator

Quanquan Mu,[1,2] Zhaoliang Cao,[1,2] Dayu Li,[1] Lifa Hu,[1] and Li Xuan[1]

[1]State Key Lab of Applied Optics, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin, 130033, China

[2]Graduate School of the Chinese Academy of Sciences, Beijing, 100039, China

*Corresponding author: Xuanli@ciomp.ac.cn

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A collimator with a long focal length and large aperture is a very important apparatus for testing large-aperture optical systems. But it suffers from internal air turbulence, which may limit its performance and reduce the testing accuracy. To overcome this problem, an adaptive optics system is introduced to compensate for the turbulence. This system includes a liquid crystal on silicon device as a wavefront corrector and a Shack–Hartmann wavefront sensor. After correction, we can get a plane wavefront with rms of about 0.017λ ($\lambda = 0.6328\,\mu\text{m}$) emitted out of a larger than 500 mm diameter aperture. The whole system reaches diffraction-limited resolution.

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1. Introduction

In astronomical observation and space object detection, larger-aperture telescopes are necessary to get very high resolution. Testing of such a large telescope system becomes unavoidable. A collimator with a large aperture and long focal length may be suitable for such a job. Some problems that were not previously serious for small collimators will occur. Specifically, air turbulence in the collimator will limit system performance and reduce resolution. One effective way to overcome this problem is to impose vacuum conditions inside the collimator. However, an airproof window is hard to manufacture because it is difficult to ensure that the window maintains a flat state under vacuum conditions. The adaptive optics (AO) technique, which was first suggested by Babcock in 1951 [1], has been used to compensate for the air turbulence that restricts the performance of ground-based telescopes. Compared with the turbulence that telescopes suffer, turbulence is weak and slow in a collimator. It is reasonable to compensate for collimator turbulence with a liquid crystal device because of its low cost, low power consumption, and high pixel density [2–5]. Although it is a little slow, it is fast enough for weak turbulence [6].

2. System Design

Different from ground-based telescopes, which are imaging systems, the collimator is a light emitting system. The light source and testing targets are located at the entrance side of the collimator. The systems under test are positioned at the exit port, where the outgoing light should be a plane wavefront. To accomplish this, we designed an AO system mounted onto the collimator to compensate for the real-time air turbulence, which will improve the collimator's performance and reduce the requirements for the operational environment. The main principle is that we put a correction device between the light source and the collimator to precompensate for the turbulence that will be induced in the collimator, to ensure that the outgoing light remains a plane wavefront after it propagates through the collimator. In order to detect the aberration in the collimator, we have to place a window at the exit port of the collimator to reflect

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part of the light back into the Hartmann–Shack (HS) wavefront sensor at the entrance side.

3. Optical Configuration

Previous work has proved the possibility of using an AO system with a collimator to overcome air turbulence and get a correction precision of rms 0.072λ ($\lambda = 0.633\,\mu$m). The initial system is shown in Fig. 1. We used a liquid crystal on silicon (LCOS) device (LCR2500, Holoeye Corporation) as wavefront corrector. Its phase stroke at a wavelength of $0.6328\,\mu$m is $2.2\,\pi$ without phase wrapping, as measured with a ZYGO interferometer. The phase modulation depth actually used was 2π after gamma correction [7]. A HS wavefront sensor was used to detect the aberration. The detail parameters for both the wavefront corrector and the sensor are listed in Tables 1 and 2. M2 was the primary mirror of the collimator. Mirror M1 represents the window to reflect light back into the AO system. In this configuration, the light propagated in the collimator twice before it reached the sensor. So the corrector compensated for the air turbulence in the collimator twice to make sure that the residual aberration that the HS sensor detected remained smallest when we started the closed loop. If M1 were replaced by a window that has a fixed reflectance, the outgoing light of the collimator for testing would no longer be a plane wavefront because of overcorrection; so we could not actually use this system directly. In this configuration we used a double-focus scheme to avoid the use of a beam splitter, to minimize the energy loses. We designed a wide-view-angle lens L3 and used it in off-axis mode to make sure that the incident and the reflected light from the LCOS device at the focal plane were separated by a small distance to split them.

In this paper, some improvements have been introduced and a new simplified optical system was built to ensure that it is practicable and compact. Figure 2 showed the optical layout of the new AO system with the collimator. Light emitted from the light source is reflected by beam splitter BS1 and mirror M1 and is then collimated by lens L1 into parallel light. After the precompensation by LCOS, the light is refocused by L1 and coupled into the collimator at the focus of

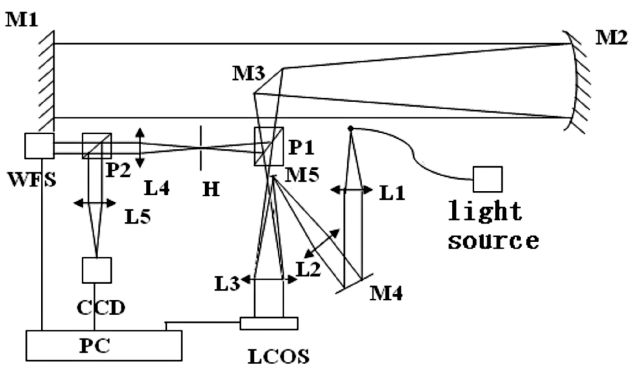


Fig. 1. Diagram of the AO system for the collimator. M, mirrors; WFS, wavefront sensor; L, lenses; PC, computer; P1, P2, beam splitter.

Table 1. Parameters of LCR2500 LCOS Device

Parameter	Value	Unit
Active area dimensions	19.5 × 14.6	mm
Display resolution	1024 (H) × 768 (V)	pixels
Pixel pitch	19 × 19	μm
Gray Levels	256 (8 bit)	
Optical efficiency: Reflectance	> 75%	
Aperture ratio	> 93%	
Liquid crystal type	45° twisted nematic	
Max. refresh frame rate	75	Hz
Cell gap	5.5	μm
Phase stroke	1.1	λ (= 0.6328 μm)

Table 2. Parameters of HASO32 HS Sensor

Parameter	Value	Unit
Aperture dimension	5 × 5	mm^2
Number of subapertures	32 × 32	
Tilt dynamic range	$> \pm 3(520\lambda)$	°
Focus dynamic range	± 0.025 to $\pm\infty(200\lambda)$	m
Repeatability (rms)	< 1/200	Wavelength
Spatial resolution	~160	μm
Max acquisition frequency	77	Hz

the collimator. Most of the light will be transmitted by the window to be used for testing other systems. Part of the light will be reflected back into the AO system and be compensated again by LCOS before it reaches the HS sensor and the imaging CCD camera, which are used to detect the residual wavefront error and the image, respectively. Different from the light reflected by the window, which is returned into the AO system, the outgoing light propagates in the collimator only once, and the correction is also performed only once. This makes sure that the light emitted from the collimator will remain plane wavefront when the AO system is closed loop.

The experimental system is shown in Fig. 3. Here we used a collimator that has a focal length of 13 m. The aperture for compensation was nearly 500 mm in diameter because of the mirror size we used here, which represents the window. The active area of the LCOS device was nearly 11.5 mm in diameter, corresponded to a 3.8 mm pupil at the HS sensor entrance port with a conjugated relationship. Approxi-

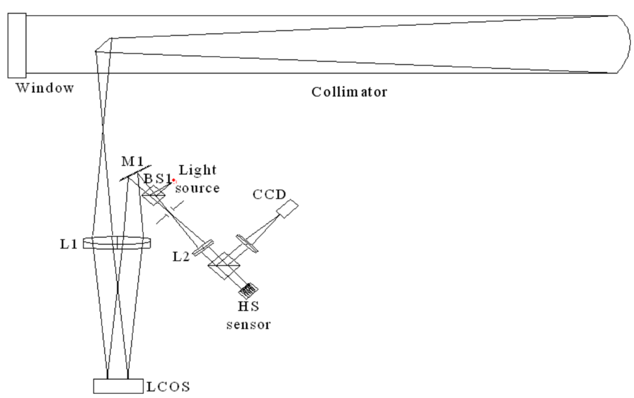


Fig. 2. New AO system with collimator.

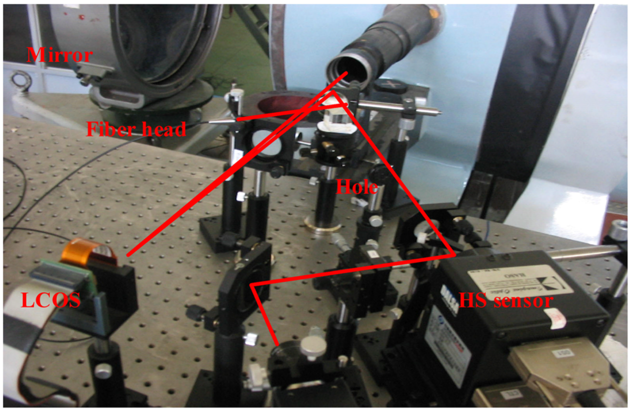


Fig. 3. (Color online) Optical layout of the AO system in the laboratory.

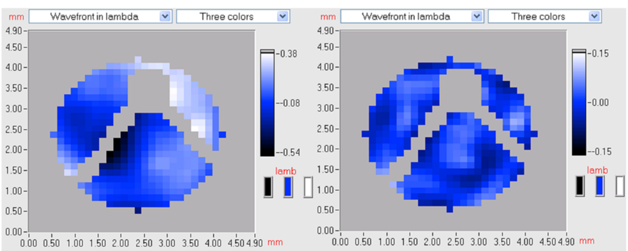
mately 340 microlenses of the HS sensor were actually used here. A halogen light coupled with a fiber bundle was used as the light source.

4. Results and Discussion

The LCOS device we used here was a 45° twisted nematic liquid crystal device. Thus we could not use it directly as a pure phase-only correction device. To overcome this problem, we drove the LCOS device with a blazed-grating gray-scale map. A 40 μm tilt was applied to the x and y dimensions of LCOS by a phase wrapping method to separate the first-order light from zero order [7]. Most of the light will be concentrated into the first order, which can be modulated the in adaptive correction. The light that remains zero order cannot be modulated. A small hole was used to reject other light and just allow the first-order to pass through and be emitted into the HS sensor and the imaging CCD camera. Because of the dispersion induced by the blazed grating, we have to use a narrow-bandwidth color filter centered at 633 nm to make sure that the final image is clear, just as we did in previous work [6,8]. In order to correct the aberrations well that the HS sensor detects, we have to register the LCOS corrector to the HS sensor by the interaction matrix algorithm [9]. Each Zernike mode with a normalized coefficient was generated and sent to the LCOS device and detected by the HS sensor. Then the command matrix was calculated. We used 36 Zernike modes here, which are restricted by the HS sensor. This algorithm makes sure that the LCOS device registers well with the HS sensor. After the detection of an aberrated wavefront in the dynamic correction process, we calculate the conjugated phase map represented by a Zernike polynomial with up to 36 modes used to compensate it and add it onto the blazed grating map, which is represented by the tip-and-tilt Zernike mode, resulting in final phase map sent to the LCOS device. Finally, the wavefront diffracted from the first order will be a flat wavefront, and the first order image will become clear.

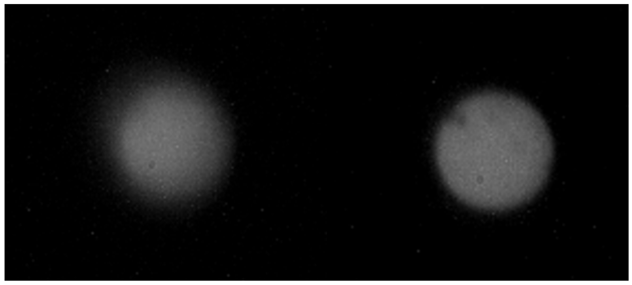
The wavefront maps for the collimator before and after adaptive correction are shown in Fig. 4. The rms error was 0.178λ; after we started, the correction was reduced to 0.035λ rapidly. The image of the fiber spot is shown in Fig. 5. It obviously changed. Also, we measured its modulation transfer function (MTF) in this correction process as shown in Fig. 6. It nearly reached diffraction-limited performance (the upper, green curve) after the AO correction. The critical frequency was nearly 50 cycles/mm.

We knew that the HS sensor was positioned at the entrance port of the collimator. It detected the aberration twice compared with the aberration that the outgoing light suffered. In other words, the rms error for the outgoing light, which was used for testing other systems, was 0.089λ. After correction the error



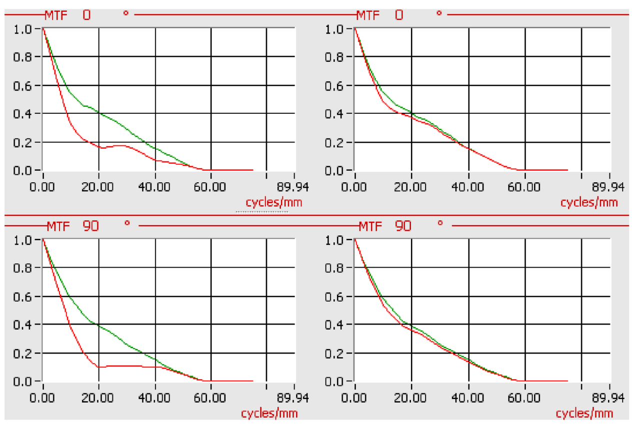
(a) (b)

Fig. 4. (Color online) Wavefront maps detected by the HS sensor before and after correction. (a) Aberrated wavefront, (b) corrected wavefront.



(a) (b)

Fig. 5. Images of the spot source (a) before and (b) after AO correction.



(a) (b)

Fig. 6. (Color online) MTF of the whole system (a) before and (b) after AO correction.

was reduced to nearly 0.017λ over a 500 mm diameter circle, which was half of the residual error that the HS sensor detected. This correction precision is high enough for optical system testing.

Because of the limitation of the AO system, such as the dispersion and the anisoplanatism, it can be used only for monochromatic testing and cannot be used for a large viewing angle that exceeds the isoplanatic area of the AO system. Many optimizations and improvements are still needed.

5. Conclusion

A simple adaptive optics (AO) system has been investigated to compensate for the air turbulence in a large-aperture and long-focal-length collimator. A LCOS device was used as a wavefront corrector. After this correction we can get very highly accurate plane wavefront output from the collimator over a 500 mm diameter circle aperture. The residual rms error was only 0.017λ after the wavefront correction. The whole system reached its diffraction-limited performance, which has a critical frequency of nearly 50 cycles/mm. Owing to the dispersion induced by the LCOS device and the anisoplanatism limitation of AO, this technique can be used only for part of the collimator testing systems. There are still many improvements left to do.

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