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A high-contrast imaging coronagraph for segmented-mirror large aperture telescopes using a spatial light modulator

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Abstract: The primary mirrors of current and future large telescopes always employ a segmented mirror configuration. The small but non-negligible gaps between neighboring segments cause additional diffraction, which restricts the performance of high-contrast coronagraph. To solve this problem, we propose a coronagraph system based on a single liquid crystal spatial light modulator (SLM). This spatial light modulator is used for amplitude apodization, and its feasibility and potential performance are demonstrated using a laboratory setup using the stochastic parallel gradient descent (SPGD) algorithm to control the spatial light modulator, which is based on point spread function (PSF) sensing and evaluation and optimized for maximum contrast in the discovery working area as a merit function. The system delivers a contrast in the order of 10^{-6}, and shows excellent potential to be used in current and future large aperture telescopes, both on the ground and in space.

Keywords: Liquid crystal spatial light modulator; Amplitude apodized pupil; Large aperture telescopes

1. INTRODUCTION

The detection of exoplanets is a research hot topic in modern astronomy. In recent years, direct imaging and characterization of exoplanets have attracted increasing attention, which may help answer one of the most basic scientific questions: are we alone in the universe. Exoplanet detection methods include the indirect detection and direct imaging[1], with over 5 590 exoplanets having been detected before March 21, 2024. Among them, most of the planets have been detected through the indirect method, which mainly include the radial velocity, transit, microlensing, astrometry as well as pulser timing. It is difficult to directly obtain vital data such as the effective temperature and atmospheric characteristics of the planet. Direct imaging of exoplanets can measure their masses and orbits. Through further spectral analysis, important physical information such as the planet's atmospheric composition, surface gravity, and effective temperature can be studied, which are essential in searches for the characteristic signals of extrasolar life.

However, the difficulty of direct imaging detection lies in the fact that there is a huge difference in light intensity between planets and their host stars in general; for terrestrial planets, this contrast ratio can be as high as 10 billion[2]. Finding planets under such a huge difference in light intensity is a very difficult task, posing unprecedented challenges to existing optical detection technologies[3]. Consequently, it is necessary to develop high-contrast stellar coronagraph technology. In 2012, we proposed a new high-contrast imaging coronagraph, combining a liquid crystal array[4] (LCA) for active pupil apodization and a deformable mirror (DM) for phase correction[5]. Our LCA is a spatial light modulator (SLM) that is only used for amplitude modulation, and accurately calibrates and compensates for amplitude non-uniformity and nonlinear response[6]. We measured the imaging contrast of a coronagraph system using only LCA and no DM. At internal working angles of 2.5 and 5 λ/D, imaging contrasts of 10^{-4} and 10^{-5} can be achieved[7], respectively.

In the future, extremely large aperture telescopes, such as 30-meter class telescopes, will adopt a segmented-mirror splicing structure. To make full use of the spatial resolution and light-gathering capabilities of large aperture telescopes, current exoplanet detection plans will develop extreme adaptive optics (Ex-AO) and specifically designed coronagraphs optimized for the direct imaging of exoplanets. These include Exo-Planet Imaging Camera and Spectrograph (EPICS) for the 39-meter European Extremely Large Telescope at the European Southern Observatory, the Planetary Systems Imager (PSI) for the Thirty Meter Telescope in the United States, the Near-Infrared Spectrograph (NIRS) for the 24-meter Giant Magellan Telescope, and future space missions including the Cool Planet Imaging Coronagraph on the China Space Station Telescope and the Nance Grace Roman Space Telescope. Gaps between the many adjacent spliced segmented mirrors can cause a lot of complex additional diffraction, severely limiting the performance of high-contrast coronagraphs, rendering it necessary to conduct research on key technologies for stellar coronagraph[8].

To solve this problem, we propose a pupil modulation coronagraph system based on a single liquid crystal SLM. First, a laser emits a point source from an optical fiber, and after passing through a collimating lens and a special-shaped aperture, it can be approximated to the light passing through a telescope with a stitched, segmented mirror structure.

The transmittance of the special pupil is then modulated by controlling the liquid crystal SLM to suppress diffracted light. To test this system, we use the SPGD[9] algorithm to control the SLM and a CCD-based scientific camera to collect the PSF at the focal plane as an evaluation function. Based on the SPGD algorithm, we design a pupil gradient modulation technique that optimizes the maximum contrast performance in the working area through the perception and evaluation of the PSF. The single SLM system can achieve a contrast of 10^{-6}, indicating that the system can be used for exoplanet detection in current and future ground-based and space-based large telescopes[10].

2. PRINCIPLES OF THE CORONAGRAPH SYSTEM

After passing through the optical system, the pupil function of the starlight is given by

$$p(x,y) = A\mathrm{e}^{-\mathrm{i}\varphi}, \tag{1}$$

where A represents the amplitude of the pupil, and φ represents the phase.

The PSF at the focal plane of the CCD can be expressed as

$$I_{PSF} = \left|F\left[p(x,y)\right]\right|^2, \tag{2}$$

where F is the Fourier transform, i.e. the PSF is the square of the modulus of the Fourier transform of the pupil function. As shown, the PSF, I_{PSF}, is related to the amplitude A. The amplitude-type SLM is able to change the energy distribution of light by altering its amplitude.

This article will discuss the circular aperture. The coronagraph system obtains high-contrast dark regions by optimizing the amplitude at the pupil plane, using the evaluation function,

$$J = \frac{\sum I_o(x,y)}{\sum I_i(x,y)}, \tag{3}$$

where, $I_i(x,y)$ is the energy intensity of the central region and $I_o(x,y)$ is the energy of the high-contrast imaging region, as shown in Fig. 1. This evaluation function is used to find the minimum value of the energy of the imaging region relative to the central region energy, i.e. the smaller the evaluation function, the better the contrast performance.

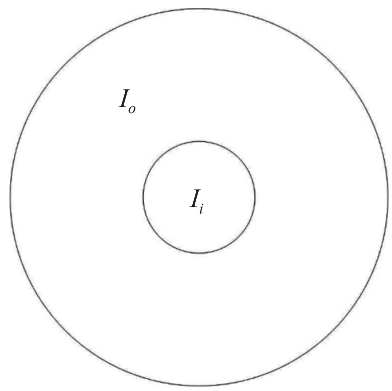

Fig. 1. Definition of the evaluation function region.

There are many different algorithms for objective function optimization, such as genetic algorithms and stochastic parallel gradient algorithms[11]. Here, we use the SPGD to iteratively optimize the amplitude and phase. The SPGD algorithm is an improved version of the well-known steepest descent algorithm, which applies arbitrarily small random perturbations to all variables simultaneously and then evaluates the gradient changes in system performance metrics. This algorithm will not be discussed further here.

In this study, we use liquid crystal SLMs for amplitude modulation of light. The liquid crystal array is based on the birefringence of its nematic liquid crystal molecules. These cigar-shaped molecules are uniaxial crystals with an optical axis parallel to the direction of the molecules. The long axis of the molecules defines the direction of the extraordinary refractive index; since the extraordinary refractive index can vary with the voltage applied to the liquid crystal, the polarization direction of transmitted light will rotate by a specific angle. Sandwiched between a polarizer and a light splitter, the LCA acts like a SLM, which can adjust the transmitted light of each pixel in the array by setting the applied voltage. Here, the polarizer and analyzer are selected to be 0° and 90° polarizers, respectively, to perform pure amplitude modulation of starlight.

3. EXPERIMENT AND RESULTS

This study presents an optimization method for pupil modulation in telescopes with segmented mirror structures. A laser is used to emit a point source from an optical fiber, which passes through a collimating lens and a specially shaped aperture. This can be used to simulate the light of a telescope with a segmented mirror structure. The entire experimental system[12] is shown in Fig. 2, while the pupil is depicted in Fig. 3. By controlling the transmittance of a liquid crystal SLM to achieve the purpose of suppressing diffraction light, a camera is used to collect PSFs at the focal plane as evaluation functions. Based on the SPGD algorithm[13], we designed a pupil gradient modulation technique[14].

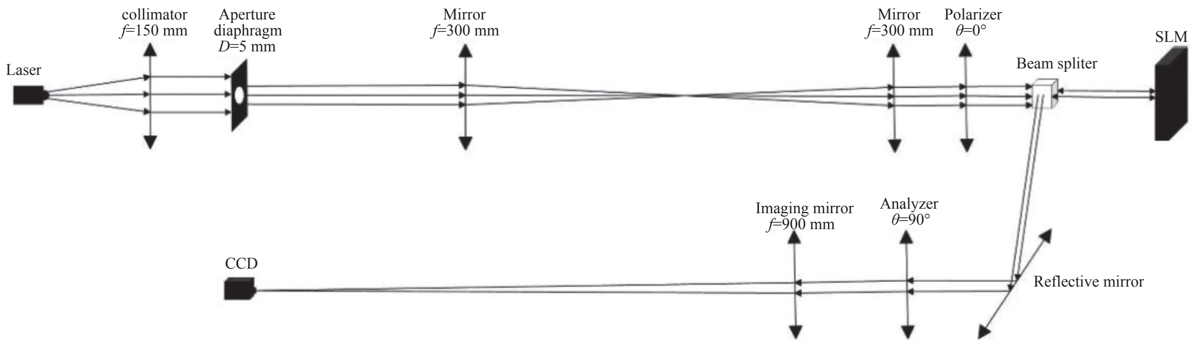

Fig. 2. Schematic diagram of the coronagraph system.

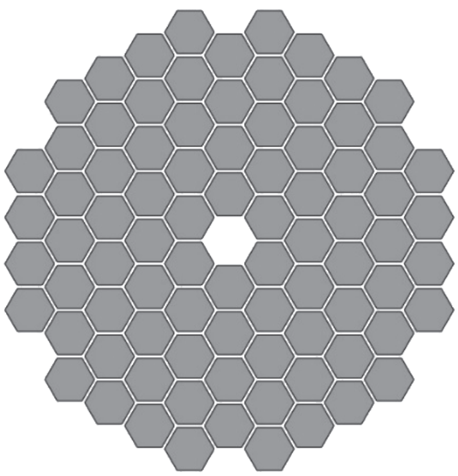

Fig. 3. Schematic diagram of the mirror surface with a segmented mirror splicing structure.

In this study, we use the annular pupil transmittance modulation technique to determine the number and width of the modulated annuli based on the aperture. The product of the number of annuli and their widths can be determined manually, with the limitation being the physical dimensions of the telescope aperture. According to the Nyquist sampling theorem[15], the number and width of the annuli can be flexibly set within a certain range. Using the SLM, the PSF image is divided into annuli of equal width along the radial direction of the pupil, with consistent transmittance for each annulus[16].

In the experiment, the initial value of the transmittance of each annulus is set according to the system settings, and there are N transmittance values for N annuli. Among them, the initial value of the transmittance of the annulus in the optimization region is set to a low value between 0 and 1, according to the experimental optical path, which is used as the starting point for optimization. Then, the amplitude of the light is changed by the SLM to change the transmittance of each annulus, achieving the goal of improving the imaging contrast. The SPGD algorithm is used to dynamically adjust the transmittance of each annulus in the optimization region. According to the trend of the objective function, we can determine whether the contrast performance is improving. If the overall objective function gradually decreases, it represents a continuous improvement in contrast performance, and the algorithm can be used for continuous iterative optimization. Conversely, an overall objective function that continuously increases shows decreasing contrast performance, and the control parameters should be changed for the re-experiment. The PSF images of the focal plane before and after modulation are shown in Fig. 4 and Fig. 5, respectively. It can be clearly seen from the figures that our optimization effect is very significant. The images observed on the pupil plane before and after modulation are shown

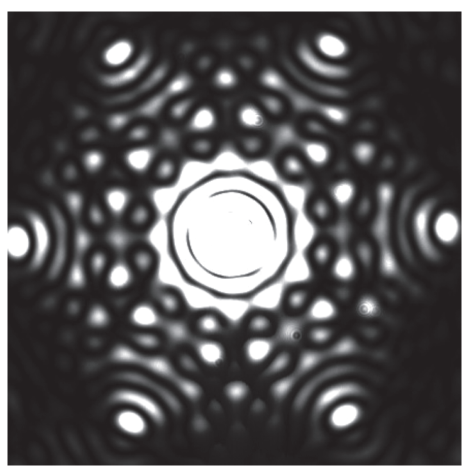

Fig. 4. PSF image of the focal plane before modulation.

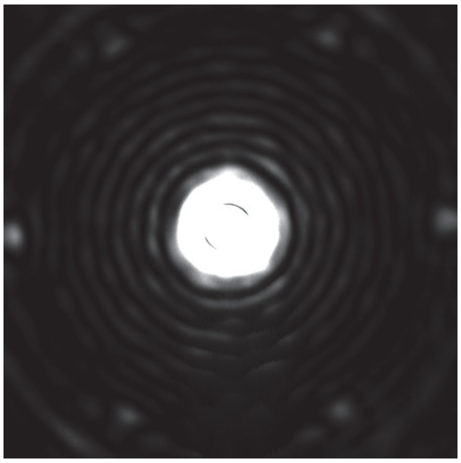

Fig. 5. PSF image of the focal plane after modulation.

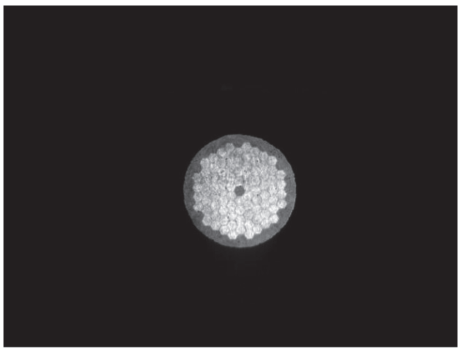

Fig. 6. Pupil surface image before modulation.

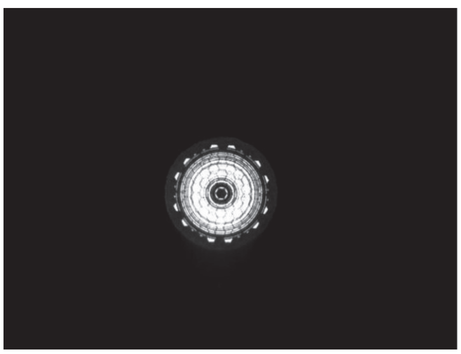

Fig. 7. Pupil surface image after modulation.

in Fig. 6 and Fig. 7. After approximately 3000 steps of modulation, we achieve a contrast performance of more than 10^{-6} in the working angle range of 4–12 λ/D. The contrast curve after modulation is shown in Fig. 8, and the plot of modulation steps and evaluation function is presented in Fig. 9.

4. CONCLUSION

This study aims to improve the contrast performance of future extremely large aperture telescopes with segmented mirror stitched structures using liquid crystal SLMs to perform pure amplitude modulation on the special pupil generated by the stitched mirrors, and using the SPGD algorithm to control the iterative optimization of

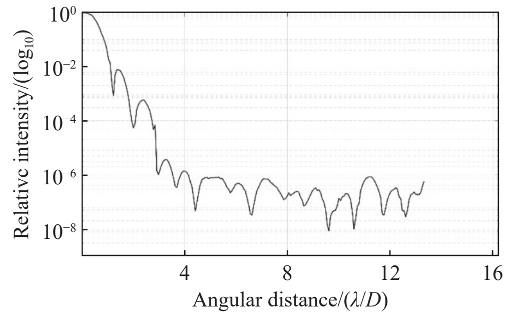

Fig. 8. Contrast curve after modulation.

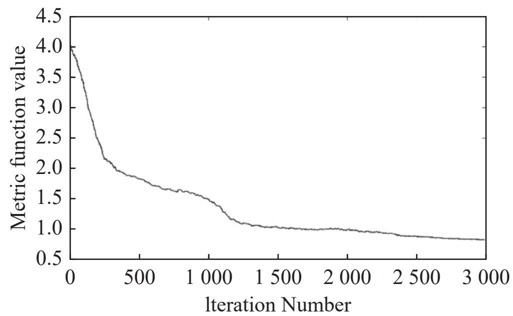

Fig. 9. The curve of the evaluation function during modulation.

the SLM. However, this study did not perform phase correction[17-19], and in future work, an additional SLM can be added for improved phase[20] correction to further enhance the overall contrast performance[21].

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AUTHOR CONTRIBUTIONS

Jiangpei Dou played a pivotal role in the conceptualization of the coronagraph's framework and methodology, and designed the coronagraph algorithm. Additionally, Jiangpei Dou reviewed and edited the manuscript. Huanyu Dong conducted the experimental work, validation work and data curation, and wrote original draft. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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