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A high-contrast coronagraph for direct imaging of Earth-like exoplanets: design and test *

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Abstract A high-contrast coronagraph for direct imaging of an Earth-like exoplanet at the visible band needs a contrast of 10^{-10} at a small angular separation of $4\lambda/D$ or less. Here we report our recent laboratory experiment that approaches these limits. Our test of a high-contrast imaging coronagraph is based on our step-transmission apodized filter. To achieve this goal, we use a liquid crystal array as a phase corrector to create a dark hole based on our dedicated algorithm. We have suppressed the diffraction and speckle noise near the point image of a star to a level of 1.68×10^{-9} at $4\lambda/D$, which can be used for direct imaging of Jupiter-like exoplanets. This demonstrates that a telescope incorporating a high-contrast coronagraph in space has the potential to detect and characterize Earth-like planets.

Key words: instrumentation: coronagraph, liquid crystal array — techniques: apodization — methods: laboratory

1 INTRODUCTION

Today, searching the universe for Earth-like exoplanets is one of the hottest topics in science. Up to now, more than 1000 exoplanets have been detected and confirmed. Most of them were discovered through indirect ways such as the transit method or radial velocity detection. These methods have not been demonstrated to be sensitive enough for the detection of Earth-like planets. The Kepler mission has recently discovered two Earth-sized planets by observing transits: Kelper-62, which is in the habitable zone, and Kepler-78b (Borucki et al. 2013; Pepe et al. 2013). However, direct imaging is needed to fully detect the signatures of life or biomarkers like O_2 and O_3 at visible wavelengths in exoplanets by using spectroscopic techniques. To realize this goal, the unwanted diffracted light from

the host star and speckle noise from the optical system must be efficiently suppressed using high-contrast imaging coronagraphs. A contrast of $\sim 10^{-10}$ is required for imaging Earth-like planets in visible wavelengths, which is a great challenge for current techniques. A critical issue in dealing with speckle noise, which is induced by any optical imperfections such as wavefront errors or surface roughness. Static speckle noise generally degrades the contrast of a coronagraph to a level on the order of $10^{-5} \sim 10^{-7}$ (Dou et al. 2010; Ren et al. 2010).

A common approach used by other research groups to achieve this high level of contrast is to correct the optical errors and generate a small local dark hole by using one or two deformable mirrors (DMs). This approach has been used by groups led by researchers at the Jet Propulsion Laboratory (JPL) and Princeton University (Trauger & Traub 2007; Kay et al. 2009). However, this approach needs a DM with a large number of actuators and a complicated phase retrieval algorithm. Although the contrast can reach the level of 10^{-10}, the regions created by the dark holes in devices constructed by these two groups are not large enough to apply to space telescopes in searching for exoplanets. In our group, we have successfully used the stochastic parallel gradient descent (SPGD) algorithm to efficiently suppress speckle noises by using the point spread function (PSF) on the imaging focal plane. This algorithm was first used in our extreme adaptive optics (ExAO) system to achieve high contrast in a ground-based system. This setup was utilized to successfully demonstrate that a small dark hole with an extra contrast gain of 65 improvement is achievable with a DM having 140 actuators (Ren et al. 2012). Recently, a new approach was used in our coronagraph, and the dark hole created by our approach was much larger than that created by other groups, which we will discuss in Section 3.

Ren and Zhu have developed a stepped transmission filter-based coronagraph (Ren & Zhu 2007). Recently, in our laboratory tests, the newly designed filter could achieve a contrast of 10^{-6} at a small angular separation down to $4\lambda/D$ (λ is the wavelength and D is the diameter of the telescope aperture).

Test results of the newly designed coronagraph, which incorporates both stepped transmission filters and our SPGD based dark hole correction, are presented in Section 2. In Section 3, we show the test optical system and experimental results. Finally, we present the conclusions and outline future developments.

2 RESULTS OF TESTING THE NEW STEPPED FILTERS AND CORRECTION WITH A DARK HOLE BASED ON THE SPGD ALGORITHM

2.1 New Filters and the Testing Results

Ren & Zhu (2007) first proposed a coronagraph based on stepped transmission filters. This kind of coronagraph can be mounted in an off-axis space-based telescope. This can be part of a future space mission which can directly image Earth-like exoplanets. In our previous papers, we demonstrated the feasibility of this project that included a high-contrast imaging coronagraph (Dou et al. 2009). Recently we have designed and manufactured five new filters with the goal of achieving better contrast over a larger field of view.

Here we briefly discuss the design and testing that were done in our laboratory. For each filter, the diffraction is only suppressed along one direction (x or y), depending on the orientation of light that is attenuated when it passes through the filter. On the coronagraph focal plane, the complex amplitude of the electric field is the Fourier transform of the complex amplitude of the pupil. The theoretically designed contrast for one filter should reach 10^{-6} at an angular distance from the peak intensity of the PSF that is equal to or larger than $4\lambda/D$. In this design, two filters can also be combined together in sequence such that they are perpendicular to each other. In this case, diffraction along the two perpendicular directions of x and y is suppressed, and a theoretical contrast of 10^{-8} should be achievable at an angular distance of $4\lambda/D$ or larger.
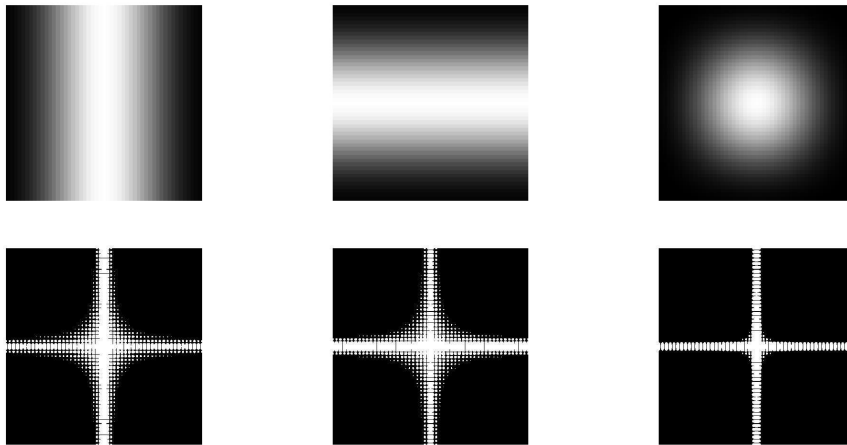
Fig. 1 Transmission patterns of the filters (*top*) and their associated PSFs (*bottom*).
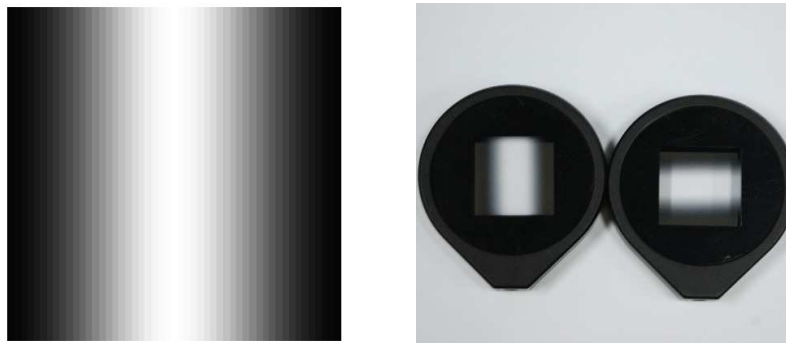

Fig. 2 The theoretical transmission filter with 51 steps and a photograph of the two real filters.

However, in practice a coronagraph cannot achieve its theoretically-predicted contrast. Because the transmission of the filter is affected by an uneven metallic coating, which introduces variations in thickness along the optical path, the resulting beam has varying phases. The high contrast generated by this transmission filter, based on the principle used by a coronagraph, is achieved by implementing a so-called apodized pupil. Due to transmission through the apodized pupil, the transmission coefficient for each filter is 0.498.

Figure 1 shows the theoretical transmission patterns of the designed filters (top panels) and their associated PSF images (bottom panels). The top panels show images of one filter (in the top-left panel), another filter with a $90°$ orientation (in the top-central panel), and the combination of these two filters (in the top-right panel).

Figure 2 shows the theoretical transmission of one transmission filter with 51 steps and a real image generated by the two filters at an orthogonal orientation. Images of the PSF generated by the coronagraph, with the combination of these two filters that have an orthogonal orientation, taken with different exposure times of 0.15, 15 and 1500 s and their associated contrast plot, are shown in Figure 3. A 16-bit SBIG camera was used to take these images.
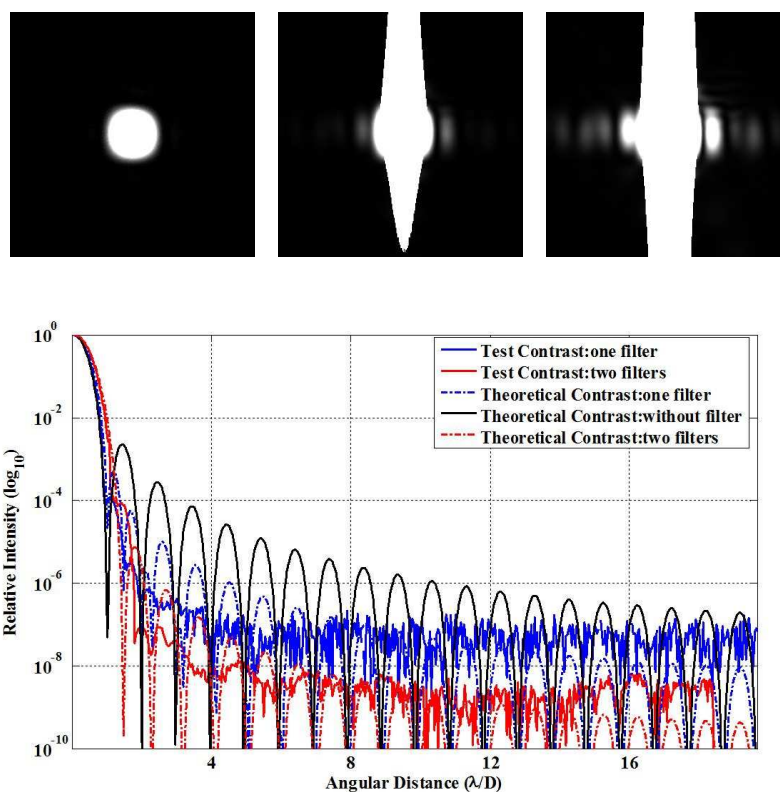
Fig. 3 The top panels show the PSF images of the coronagraph that has two filters under different exposure times. The bright vertical pattern in the central and right panels is due to blooming in the CCD image. The bottom panel shows a comparison between the test and designed PSF contrast along the diagonal direction.

2.2 The Dark Hole Correction Based on SPGD Using a Liquid Crystal Array

In a previous paper, we proposed and demonstrated that the SPGD algorithm can be applied to a high-contrast coronagraph to reduce speckle noise induced by imperfections in the optics (Dong et al. 2011). We used a DM to provide an optimal phase to create a dark hole in the target region and the theory behind the SPGD algorithm has been discussed in detail (Ren et al. 2012). The DM used in that previous test had 140 effective actuators arranged in a 12×12 grid (excluding those in the four corners). The actuators at the corners are restrained and cannot move freely. The dark hole had a small area because of the small number of actuators. Considering that a DM (32×32 or 64×64 actuators) is too expensive to be used in our tests, in our most recent test, we used an XY nematic series spatial light modulator (SLM) as a phase corrector to replace the DM. The SLM is manufactured by BNS and has 512×512 pixels, with an 83.4% fill factor. In the test, the pixels are divided into a number of groups and each group is binned as an effective pixel consisting of 8×8 pixels. The XY nematic series SLM is optimized to provide a full wave (2π) of phase stroke upon reflection at the nominal design wavelength.

In this test, we use the SPGD optimization algorithm, which measures the wavefront error according to the PSF on the focal plane, and the acquired information is used to directly control the phase of the liquid crystal array (LCA) to create a dark hole.

3 CONFIGURATION OF THE DARK HOLE CORRECTIVE OPTICS SYSTEM

3.1 The Intensity Calibration of Starlight and Planet Light

Since a 16-bit CCD camera can only measure contrast up to $1/65536$ (about 10^{-4}) and the contrast that we will measure is out of this range, we need to use a neutral density (ND) filter to attenuate the starlight. Two laser light sources (laser 1 and laser 2) are used to simulate the starlight and the planet light, respectively, with the optical configuration of intensity calibration shown in Figure 4. We need to know the contrast resulting from these two beams. Therefore, before running the optimization code, we firstly calibrate the intensity of the star and planet light sources. The stepped transmission filters must be removed. An ND filter with an attenuation of $1/1000000$ in intensity is inserted into the starlight beam. With two individual exposures, we adjust the camera exposure time to make the light intensity from the planet and the star equal to each other.

Figure 5 shows the images resulting from two different exposure times. According to the exposure times and ND attenuation, the contrast between the two beams should be $85/0.5 \times 1000000 = 1.7 \times 10^8$. Once the contrast between the two sources is known, it can be used to calculate a higher contrast achievable by the coronagraph. When the intensity calibration is accomplished, we run the SPGD optimization code.
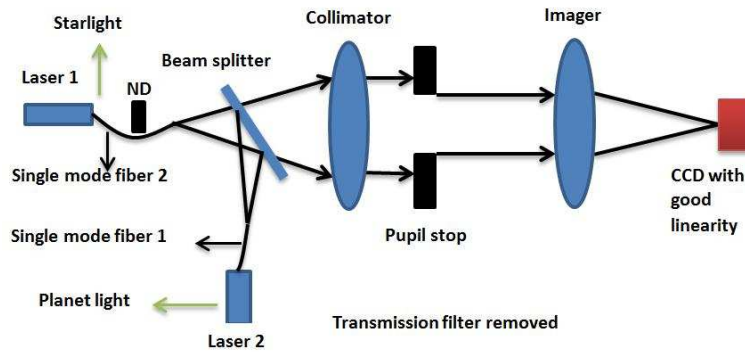

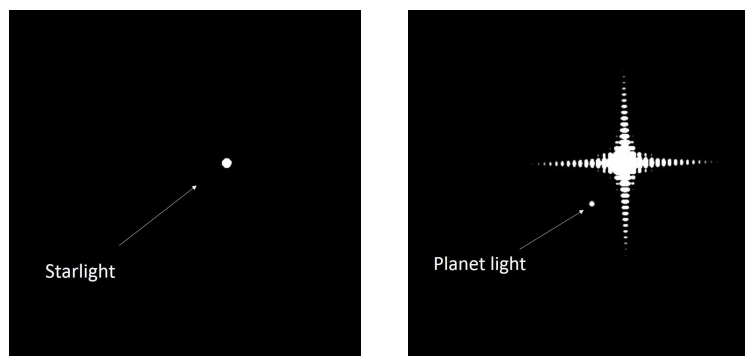**Fig. 4** The optical configuration of intensity calibration.

Fig. 5 The intensity of starlight with an exposure of 0.5 ms (*left*) and the intensity of planet light with an exposure of 85 ms (*right*).
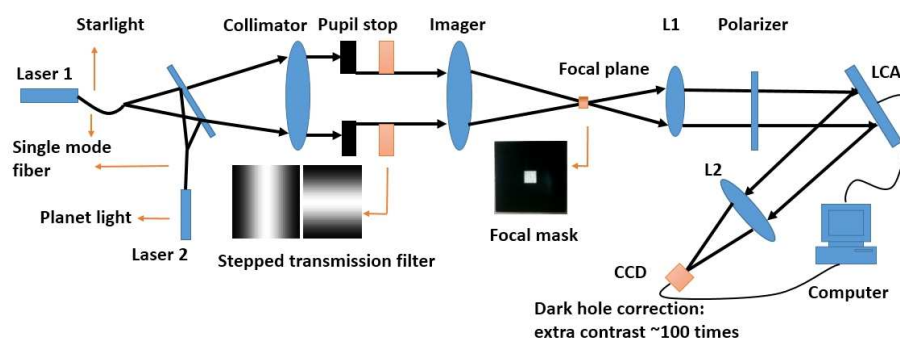
Fig. 6 The whole optical system with the dark hole correction.

3.2 Optical Layout of the Whole System

Figure 6 shows the layout of the optical system used by the coronagraph during the test. The starlight and planet light are simulated by two point sources using two laser light sources ($\lambda = 632.8$ nm), whose contrasts are calibrated in advanced. When we run the SPGD optimization code, the laser used to simulate the planet light will be blocked. The starlight is suppressed when the light passes through the pupil stop and two orthogonal stepped transmission filters.

Due to the constraint of having a small number of DM actuators, it is not possible to create a large dark hole. In addition, a DM with a large number of actuators is expensive. Therefore, we use an LCA to replace the DM in our current test. In this test, only one quadrant is used for high contrast imaging. A focal mask composed of a square aperture is located on the first focal plane (before lens L1), which blocks three quadrants of the focal plane image and only allows the image from one quadrant to go through the optical system to achieve high-contrast imaging.

The LCA is located on a plane conjugate to the pupil. A polarizer should be placed before the LCA in order to control the polarization state of incident light; the LCA works as a phase-only modulator when the input light source is linearly polarized along its vertical axis. The phase of the incoming linearly polarized light can be modulated by the LCA as the light passes through it. Finally, the light is imaged by a lens (L2), and a fast CCD camera takes images of the PSF.

The PSF images are taken by a 16-bit fast CCD camera and saved on a computer in real-time. Then using the PSF image, the SPGD algorithm evaluates the energy in the target region of interest. According to the results of the evaluation, the SPGD will control the voltage of each effective pixel in the LCA to provide an overall phase that minimizes the energy in the target field of view. Through multiple iterations, the expected dark hole can be generated. Finally, the computer saves the optimal voltages for the LCA, which correspond to the associated phase and generate an extra improvement in contrast. The dark hole can be stably produced in the lab environment for at least 6 hours, which is long enough for imaging Jupiter-like exoplanets.

3.3 Dark Hole Creation

The dark hole obtained using our SPGD optimization algorithm is shown in Figure 7. A dark hole (between $4\lambda/D$ and $21\lambda/D$) is created in a quadrant on the focal plane that is larger than JPL's (between $4\lambda/D$ and $10\lambda/D$) and Princeton's ($X = 7 - 10\lambda/D$ and $Y = -3 - 3\lambda/D$) (Pueyo et al. 2009). After 1000 iterations of the phase correction, the speckle noise in the original PSF has been effectively removed. Once the dark hole is created, we turn on the laser light and generate the optimized LCA phase. Then the planet image stands out from the speckle noise in the dark hole
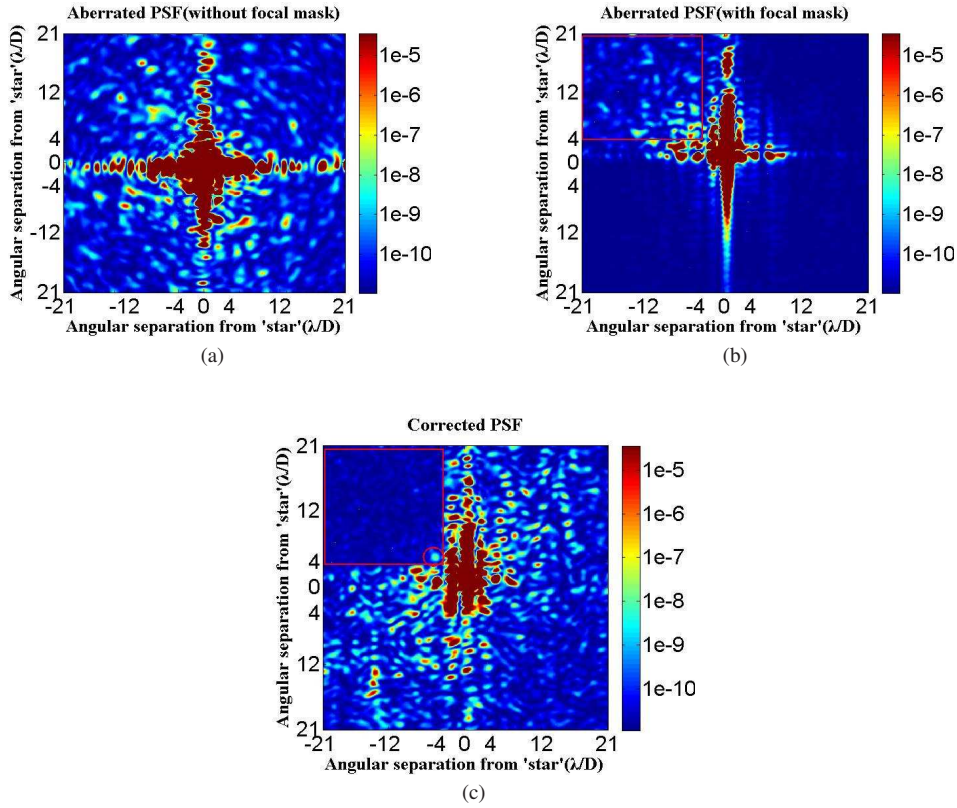
(a)

(b)

(c)

Fig. 7 Aberrated and corrected PSFs used in our tests. Panel (a) shows the PSF without a focal plane mask, while Panel (b) shows the PSF with a focal mask. The focal plane image after the dark hole correction is presented in Panel (c). In Panel (c), the planet image (indicated by a red circular region) stands out from the speckle noise in the red rectangular target region defined by the dark hole, with the length of one side being $X = Y = 4\lambda/D - 21\lambda/D$. This monochromatic experiment is done at a wavelength of 632.8 nm.

region, and can be seen clearly, as shown in the right panel of Figure 7. In fact, the intensity of the planet is about 3.5 times brighter than the residual speckle noise in the dark hole. Therefore, the contrast in the dark hole increases from 1×10^{-7} to 1.68×10^{-9} at $4\lambda/D$, which demonstrates an extra gain in contrast of two orders of magnitude through the contribution of the dark hole using the LCA.

4 CONCLUSIONS AND FUTURE WORK

In this paper, we have presented the test results of our new transmission filters with 51 steps used in our high-contrast coronagraph. According to the test, the contrast can reach 10^{-7} at $4\lambda/D$, without phase correction. Then we used the LCA to generate a dark hole based on our SPGD algorithm with the new filters. In the region around the dark hole, an extra contrast of $\sim$100 times has been achieved. Therefore, our high-contrast coronagraph with the stepped transmission filters achieves a contrast of 10^{-9} in the region around the dark hole. Our approach has the following advantages: the wavefront

control algorithm is simple and is computed only based on the focal plane PSF; the dark hole region that is created is larger, and does not need a large number of actuators in the DM.

This paper demonstrates that our coronagraph is a promising technique for space-based imaging of Earth-like planets. For future works, we will use a DM (32×32 or 64×64 actuators) whose precision ($\lambda/10000$) for phase correction is better than that of the LCA ($\lambda/100$), and the experiment will be carried out in a space-like environment inside a vibration-isolated vacuum chamber. Based on these two points, the contrast should be able to reach or be better than 1×10^{-10}. Further progress related to this project will be discussed in future publications.

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