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High-contrast coronagraph for ground-based imaging of Jupiter-like planets *

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Abstract We propose a high-contrast coronagraph for direct imaging of young Jupiter-like planets orbiting nearby bright stars. The coronagraph employs a step-transmission filter in which the intensity is apodized with a finite number of steps with identical transmission in each step. It should be installed on a large ground-based telescope equipped with a state-of-the-art adaptive optics system. In this case, contrast ratios around 10^{-6} should be accessible within 0.1 arcsec of the central star. In recent progress, a coronagraph with a circular apodizing filter has been developed, which can be used for a ground-based telescope with a central obstruction and spider structure. It is shown that ground-based direct imaging of Jupiter-like planets is promising with current technology.

Key words: instrumentation: high angular resolution — methods: laboratory, numerical — techniques: coronagraphy, apodization — planetary systems

1 INTRODUCTION

At present, over 300 extra-solar planets have been detected, mostly through the radial velocity technique. The detected candidates are either quite massive ($0.16\,M_J < M\sin i < 13\,M_J$) or very close to their primary stars (0.03–4 AU), whose properties are likely a result of observational bias (Ammons et al. 2006). A numerical simulation suggests that the actual population probably contains many planets including both terrestrial planets similar in size to Earth and giant icy planets in long-period orbits (Ida & Lin 2004). The exact mass of the planets cannot be determined through the radial velocity technique because of the declination angle. Together with the transiting approach, the radius and mass ($1.42\,R_J$, $0.69\,M_J$) of the planet orbiting HD 209458 are firstly determined (Henry et al. 2000). However, indirect detection techniques cannot perform spectroscopic measurements and therefore cannot determine whether or not there is life on another planet. Direct detection of an extra-solar planet's emitted or reflected light would finally provide us with information on some

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important physical parameters, such as chemical composition, and even the presence of possible life markers. This can also can enable us to put constraints on theories of planetary formation and migration.

It is extremely challenging to directly image an earth-like planet from the ground due to the large flux ratio contrast (10^{-10}) and its location very close to the primary star ($0.1''$). For NASA's Terrestrial Planet Finder Coronagraph, a contrast of 10^{-10} at an angular distance better than 4λ/D is required (Brown &Burrows 1990). However, direct detection of a young Jupiter-like planet may be possible using large ground-based telescopes equipped with a state-of-the-art adaptive optics (AO) system (Masciadri et al. 2005; Langlois et al. 2006). Hot Jupiters are supposed to still be self-luminous due to on-going accretion (Marley et al. 2007) and, therefore, are sufficiently bright for direct imaging. In 2008, three Jupiter-sized planets around their star HR8799 have been directly imaged using the 8-m Gemini and 10-m Keck telescopes (Marois et al. 2008). The flux ratio between these planets and their star is around 10^{-5}, making them possible to be directly imaged from the ground.

These planets were imaged through a traditional coronagraph system with AO plus image processing algorithms. Such a system cannot reach a very high contrast at present. By introducing a high-contrast imaging coronagraph to the traditional system, more faint extra-solar planets should be able to be directly imaged from the ground. In this work, we proposed a high-contrast coronagraph to directly image young Jupiter-sized planets. The coronagraph employs a step-transmission filter in which the intensity is apodized with a finite number of steps of identical transmission in each step (Ren & Zhu 2007). The coronagraph is designed to deliver contrast on the order of $10^{-6}\sim10^{-7}$ and $10^{-9}\sim10^{-10}$ as short and long term goals, respectively. At present, a stable laboratory experiment results demonstrated in the visible wavelength, and contrast on the order of 10^{-6} has been achieved at an angular distance of 4λ/D. The coronagraph should be installed on a large ground-based telescope (6–8 m class) with an AO system to correct for atmospheric turbulence, in which case contrast ratios around 10^{-6} should be accessible within $0.1''$ of the central star. Three kinds of observation candidates for such a coronagraph system are: a) a direct image of the three extra-solar planets that have been detected through the traditional imaging coronagraph; b) a direct image of the planet-hosting stars (PHS) to determine these unconfirmed extra-solar planet candidates; c) a direct image of some new planets with the most favorable contrast from their primary stars (probably PHS).

To directly image the extra-solar planet, a monolithic mirror telescope is preferred to eliminate the diffraction of each segment mirror. However, ground-based telescopes are not an off-axis design. The central obstruction and spider structure will introduce a serious diffraction, which will greatly degrade the performance of existing coronagraph systems. To overcome such a problem, we have been developing a coronagraph based on a circular-step-transmission filter that is suitable for a ground-based telescope with a central obstruction and spider structure. Such a coronagraph can effectively suppress the diffraction lights along the four diagonal directions according to the theoretical simulation. The target contrast for the newly designed coronagraph is set to be $10^{-6.5}$ at 5λ/D. With such a contrast, the new coronagraph system will possess the potential to directly image Jupiter-sized planets based on current ground-based telescopes such as Subaru or Gemini.

The outline of the paper is as follows. In Section 2, the principle of operation is presented. In Section 3, we propose the development of the step-transmission coronagraph. In Section 4, potential extra-solar planet candidates to be observed are discussed. The conclusions and future developments are given in Section 5.

2 PRINCIPLE OF OPERATION

The light of the star combined with that of the planet candidates from the sky will enter the following basic instruments:

Telescope⟶AO system⟶Coronagraph system⟶Detector

To directly image an extra-solar planet that is very close to its star, a 6–8 m class telescope is preferred for such a ground-based observation which can gain high spatial resolution. On the other hand, the planet detectability is also affected by the halo of scattered light which mainly comes from atmospheric turbulence. Detection of a planet that is roughly 15 mag fainter than its host requires a halo 10^4 times fainter than the central image peak. Introducing a high precision AO system can greatly reduce the diffraction halo (Langlois et al. 2006). After AO correction, light signals will enter the coronagraph system, which is composed of collimated and imaged mirrors, and then pass through a high-quality step-transmission filter and a cross-shaped mask. At a given wavelength, the star's diffraction pattern can be effectively represented as the point spread function (PSF) image center. As a result, most of the energy will be distributed in the central part of the PSF image, making the planet's faint light location detectable up to several arc seconds away from its star.

The main advantage of the step-transmission filter based coronagraph lies in the fact that it can reach a much higher dynamic range than traditional coronagraphs. The intensity of its step-transmission filter is apodized with a finite number of steps with identical transmission in each step. Such a design simplifies the transmission pupil manufacture and a high precision of transmission can be achieved by adopting the "measurement before coating" procedure (Ren & Zhu 2007). Another advantage of the step-transmission filter-based coronagraph is its high throughput, over 40%, which will greatly reduce the exposure time for a practical observation.

3 DEVELOPMENT OF THE STEP-TRANSMISSION CORONAGRAPH

3.1 General Requirements for a Coronagraph

For ground-based direct imaging of young Jupiter-sized planets, a coronagraph must provide high-contrast imaging with a contrast from 10^{-4} to 10^{-6}, applicable in both the visible and near infrared (NIR) wavelengths. High spatial resolution is another critical requirement for the coronagraph to directly image a planet very close to its primary star. For our coronagraph, the inner working angle (IWA) is set to be around 4λ/D. Correspondingly, for an 8-m class telescope, the detectable planet distance from its star will be 0.05$''$ in the visible (0.5 μm) and 0.2$''$ in the NIR (2 μm) wavelengths, respectively.

3.2 Principle of Using the Coronagraph for Extra-solar Planet Imaging

The coronagraph is still based on the principle of a step-transmission filter as proposed by Ren and Zhu two years ago (Ren & Zhu 2007), but some slight changes have been made to the new filter development. Here, we briefly review the principle of the coronagraph.

The electric field of the electromagnetic wave at the pupil plane for the coronagraph system can be expressed as:

$$E_{\rm pupil}(u,v) = A(u,v)\,, \tag{1}$$

where $A(u,v)$ is the entrance pupil function of the coronagraph system.

The electric field of the starlight on the focal plane is the Fourier transform of the electric field on the pupil plane. The associated intensity of the PSF image is the square of the complex modulus of the electric field on the focal plane and is given as:

$$I(x,y) = |\boldsymbol{F}[E_{\rm pupil}(u,v)]|^2\,, \tag{2}$$

where $\boldsymbol{F}$ represents the Fourier transform of the associated function.

The intensity distribution of the PSF image can be changed by choosing different pupil functions. In this work, the pupil of the coronagraph is apodized with a finite number of steps with identical transmission in each step. By optimizing the transmission for each step of the pupil, the greatest energy of the focal plane image will be distributed in the PSF center accordingly.

We have identified several contrast-limiting errors in recent laboratory experiments (Dou et al. 2009a). Among them is the "non-straight" shape of the overlap between two neighboring steps, which is a limitation of the existing coating procedure. As a result, several bright spots randomly occur in the PSF image. Correspondingly, the contrast in these regions cannot reach its theoretical result. To overcome this problem, a thin straight stripe with no light pass is introduced between each of the two neighboring steps, which will restrict the diffraction along one direction (for instance, diffraction can only be along the vertical direction with a horizontal apodization). Such a design will not affect the theoretical contrast of the coronagraph. A contrast on the order of 10^{-6} should still be achieved at an angular distance of $3\sim4\lambda/D$. However, the throughput will be reduced from 41.5% to 36.1% due to existing stripes. In this work, we increase the step number from 13 to 15 to gain a larger outer working angle (OWA), which is roughly equal to λ/D times the step number of the filter. Figure 1 shows the transmission amplitude pattern of the newly designed filter and a photograph of the actual filter.

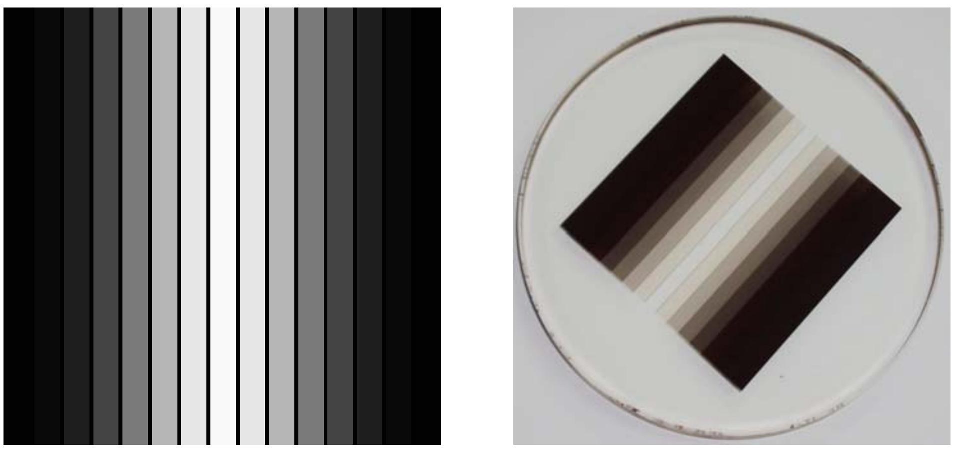

Fig. 1 *Left*: Transmission amplitude pattern of the newly designed filter, a 50 μm straight stripe is introduced between each two neighboring steps; *Right*: Photograph of the actual filter.

3.3 Recent Laboratory Experimental Results

In this sub-section, we present the latest laboratory experimental results of the coronagraph in visible wavelengths. The coronagraph employs a new 15 step-transmission filter according to the design discussed above (see Fig. 1). The configuration of the experimental system can be found in a recent paper (Dou et al. 2009a). Figure 2 shows the PSF images under different exposure times of 0.09, 2.7, 36 and 360 s, respectively. It is shown that these randomly distributed speckles have been effectively removed and the diffraction is restricted along the vertical direction due to the straight stripes. As a result, a high contrast of 10^{-6} has been achieved at an angular distance of $4\lambda/D$ along the diagonal direction. The tested contrast plot along the diagonal direction is shown in Figure 3.

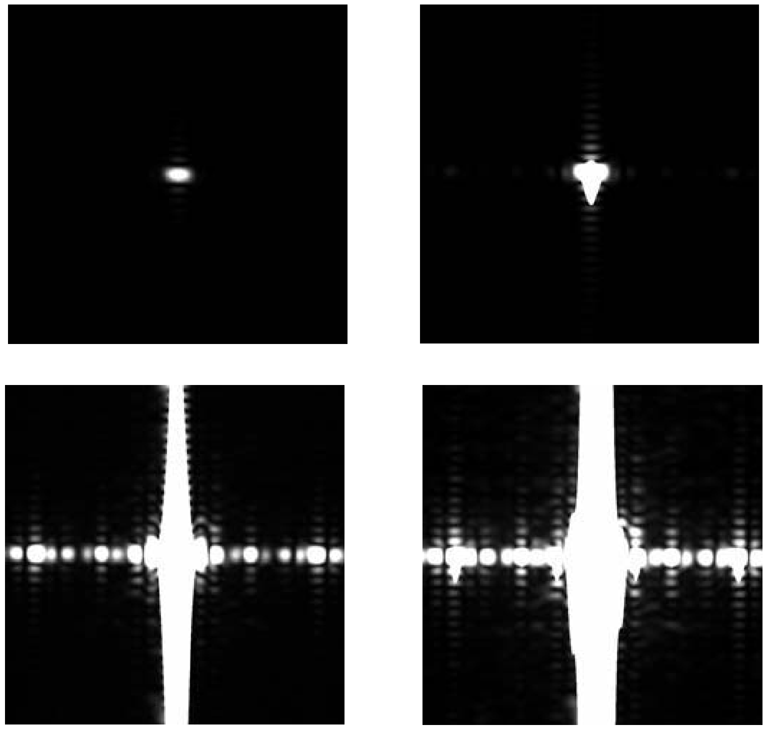

Fig. 2 PSF images under different exposure times.

3.4 Coronagraph Development for Ground-based Observation

At present, most of the ground-based telescopes do not use an off-axis design. The central obstruction and spider structure will introduce serious diffraction, which will greatly degrade the actual performance of existing coronagraph systems. To overcome this problem, we have been developing a coronagraph that can be used for a ground-based telescope with a central obstruction and spider structure. In this sub-section, we briefly present its theoretical design and performance.

Here, we set the central obstruction of the telescope to be 12.5%. The width of the spider arms is set to be 1.6% of the primary mirror diameter (for instance, 13 cm for a telescope with an 8-m primary mirror, which is thick enough). In this work, the coronagraph employs a step-transmission filter with finite circular steps. In each circular step, the transmission value is the same. The employment of a step-transmission filter significantly simplifies the manufacture of the transmission pupil, making high-precision transmission achievable for the filter.

Using a step-transmission filter to achieve high-contrast imaging, our goal is to find the optimum transmission value T_n for each circular step, where n is the step number. The optimization problem involves minimizing the energy in a target region R and maximizing the total throughput as well. It can be formulated as a 2-D constrained nonlinear minimization problem:

$$\text{minimize} \quad \sum_{(x,y)\in R} |C(x,y) - C_{\mathrm{t}}|\,, \quad \text{subject to} \quad 0 \le T_n \le 1, \tag{3}$$

where C is the the approximate contrast of the system and C_{t} is the target contrast.

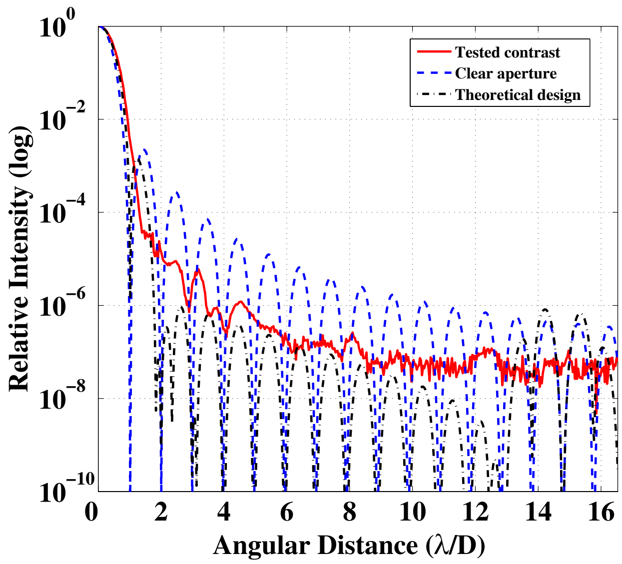

Fig. 3 Contrast plot along the diagonal direction for a clear aperture (*blue dashed line*), theoretical filter apodization (*black dash-dotted line*) and practical test results (*red solid line*) (see electronic version).

Here, we normalize the intensity of the PSF image by dividing the intensity maxima, and then we gain the contrast:

$$C(x, y) = \frac{I(x, y)}{\max[I(x, y)]}\,. \tag{4}$$

The target contrast for the newly designed coronagraph is set to be $10^{-6.5}$ at 5λ/D. The solution obtained for IWA= 5λ/D and OWA=135λ/D is shown in Figure 4. The throughput is 32.5%. It is shown that the extra diffraction caused by the central obstruction and spider structure has been effectively suppressed along the four diagonal directions. To demonstrate its theoretical performance, in Figure 5, we show the PSF contrast plot from 5λ/D to 50λ/D.

4 POTENTIAL EXTRA-SOLAR PLANET CANDIDATES

4.1 Candidates

Our coronagraph should be installed on a large ground-based telescope (6–8 m class) with AO systems to correct for atmospheric turbulence. In this case, contrast ratios around 10^{-6} should be accessible within $0.1''$ of the central star. To test the feasibility of such a coronagraph for ground-based observations, we plan to use it firstly to directly image the three detected planets (Marois et al. 2008). Since the location of these planets has already been confirmed, it is much easier for us to quickly ascertain the actual performance of the coronagraph. Table 1 shows the basic properties of the three planets around the primary star HR8799. Using the coronagraph, higher contrast should be achieved than traditional coronagraph systems and, therefore, these planets are supposed to be seen much clearer.

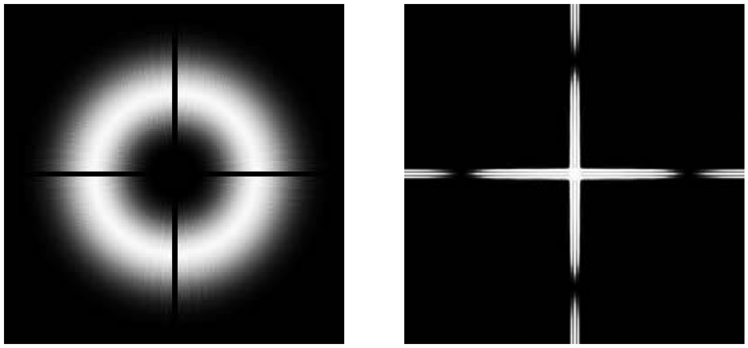

Fig. 4 Amplitude pattern for the circular-step-transmission filter (*left*); associated PSF with four dark regions achieved along diagonal directions (*right*).

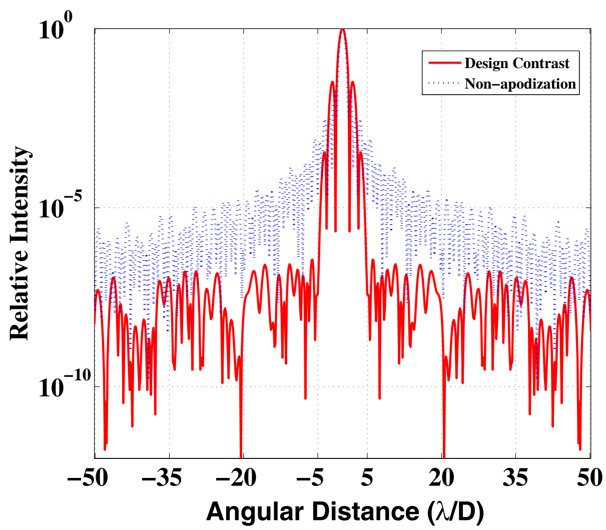

Fig. 5 PSF contrast plot: a contrast on the order of $10^{-6.5}$ can be achieved in the four diagonal regions.

Table 1 Basic Properties of the HR8799 System

Star	Distance from Earth	T_{eff} [K]	
HR8799	38∼40 pc	7505∼7305	
Planets	Distance(Angular)	T_{eff} [K]	Contrast
HR8799 b	24 AU (0.63″)	900–800	$10^{-7}\sim10^{-5}$
HR8799 c	38 AU (1″)	1100–1000	$10^{-6}\sim10^{-4.5}$
HR8799 d	68 AU (1.8″)	1100–1000	$10^{-6}\sim10^{-4.5}$

As a subsequent application, our coronagraph could be used to image extra-solar companions that have not been confirmed as planets. In Lagrange's recent paper, a probable giant planet has been imaged in the β Pictoris disk by using AO plus image processing algorithms. Such a companion could be the first extra-solar planet ever imaged so close to its primary star (Lagrange et al. 2009). Adding the coronagraph to existing systems would provide higher contrast (10^{-6}) and spatial resolution (within $0.2''$), which will help to determine planet candidates. On the other hand, mass determination of some planets is obtained through theoretical models rather than from observation (Neuhauser et al. 2005). Using such a coronagraph, direct imaging of these planets becomes promising and their actual mass and other important physical parameters could finally be precisely measured. Table 2 shows some physical properties of the planets or planet candidates (Ducourant et al. 2008; Lagrange et al. 2009).

Table 2 Still Undetermined Basic Parameters of Planets or Planet Candidates

Planets	Distance (Angular)	$T_{\rm eff}$ [K]	Age [Myr]	Mass [$M_{\rm Jup}$]
GQ Lup b	103 AU($0.7''$)	2520–1600	≤ 2	1–50
2M1207 b	46 AU($0.8''$)	2000–1100	8	3–10
AB Pic b	275 AU($6''$)	2400–1600	30–40	11–70
β Pic b	8 AU($0.4''$)	1600–1400	8–20	6–12

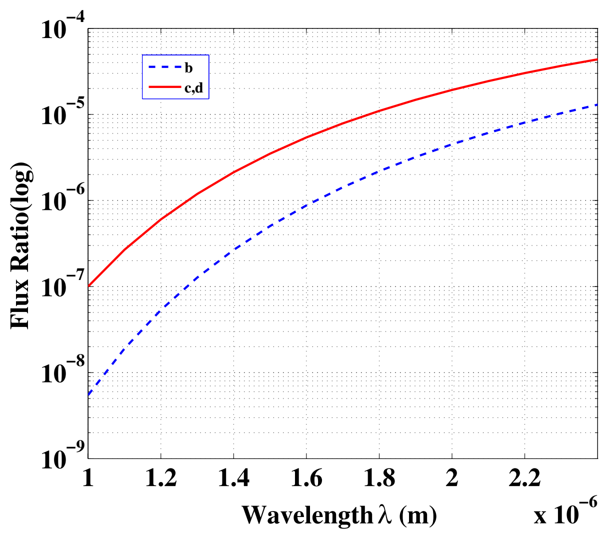

Fig. 6 Simulation flux ratio for the HR 8799 system in different wavelengths.

Another possible application of our coronagraph is to directly image the nearby region of those favorable stars. As Mark Marley (private communication) suggested, the most favorable contrast would arise from a young, massive Jupiter orbiting an M star. We may use our coronagraph to directly image regions around some young M stars. In that case, we hope to discover some new planets that have never been detected through existing techniques, which will enrich the population of extra-solar planets.

4.2 Observational Wavelength

To demonstrate the optimum wavelength for observation, we calculate the flux ratio between the three detected planets and their primary star HR8799. These planets are very young and still self-luminous; hence we use black-body radiation theory to do the simulation. Figure 6 shows the simulation results of ratio contrast in different wavelengths, which are consistent with the observation results. For HR8799 c and d, the contrast ratio is about $10^{-4.5}$ in the K band and 10^{-6} in the J band, respectively. It is obvious that the contrast difference is lower in IR than in the visible wavelength, which makes long wavelength observations favorable. On the other hand, the spatial resolution will be reduced when increasing the wavelength since the IWA of the coronagraph is proportional to λ/D. For an 8-m class telescope, the detectable planet distance from its star will be $0.05''$ in visible and increase to $0.2''$ in the K band. Although direct imaging of planets in Mid-IR is much easier than in NIR from the ratio contrast perspective, we will use the coronagraph to directly image the extra-solar planet close to its parent star in NIR wavelengths.

5 CONCLUSIONS AND FUTURE DEVELOPMENTS

In this work, we show that ground-based direct imaging of young Jupiter-sized planets is promising with current technology. Now, a step-transmission filter-based coronagraph has been developed in our institute. It has reached a stable contrast on the order of 10^{-6} at 4λ/D in the visible wavelengths, which is one of the best laboratory results compared with other research groups around the world. Using such a coronagraph, direct imaging of Jupiter-like planets around nearby stars in NIR wavelengths becomes possible. In recent progress, we have been developing a coronagraph which is suitable for a ground-based telescope with a central obstruction and spider structure. Numerical simulation shows that such a coronagraph can reach a mid-to-high contrast in the four diagonal regions. In this paper, we mainly discuss a coronagraph optimized for ground-based telescopes with monolithic mirrors. A coronagraph that can be used for segmented mirror telescopes will be discussed in future work.

At present, the actual performance of the coronagraph is limited by the wave-front error caused by imperfect manufacture of the optical components for an optics system, which induces speckle noise (Ren & Wang 2006). The wave-front error is a major contrast limiting factor and, therefore, the current coronagraph cannot reach a contrast better than 10^{-7} in the laboratory. As a follow-up effort, we will introduce the simultaneous differential imaging technique to remove speckles in order to gain an extra-contrast of 10^{-2}. In the long term, a deformable mirror that has been manufactured will be used to introduce a specific phase to the coronagraph system (Dou et al. 2009b), which should deliver a better performance with a contrast of 10^{-10}. Such a coronagraph will be installed on a space-based telescope and will finally be used for direct imaging of Earth-like planets. Further results will be discussed in our future publications.

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