A high-contrast imaging polarimeter with the stepped-transmission filters based coronagraph *

Cheng-Chao Liu^{1,2,4}, De-Qing Ren^{3,1,2}, Yong-Tian Zhu^{1,2}, Jiang-Pei Dou^{1,2} and Jing Guo^{1,2}

¹ National Astronomical Observatories/Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences, Nanjing 210042, China; ccliu@niaot.ac.cn

² Key Laboratory of Astronomical Optics & Technology, National Astronomical Observatories/Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences, Nanjing 210042, China

³ Physics & Astronomy Department, California State University Northridge, 18111 Nordhoff Street, Northridge, California 91330-8268, USA

⁴ University of Chinese Academy of Sciences, Beijing 100049, China

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Abstract The light reflected from the planets is polarized mainly due to Rayleigh scattering, while the star light is normally un-polarized. Thus it provides an approach to enhance the imaging contrast by inducing the imaging polarimetry technique. In this paper, we propose a high-contrast imaging polarimeter that is optimized for the direct imaging exoplanets. Combined with our recently-developed stepped-transmission filters based coronagraph. Here we present the design, calibration method of the polarimetry system and the associate test of its high-contrast performance. In this polarimetry system, two liquid crystal variable retarders (LCVRs) act as polarization modulator, which can extract the polarized signal. We show that our polarimeter can achieve a measurement accuracy of about 0.2% at the visible wavelength (632.8nm) with linearly polarized light. Finally, the whole system demonstrates that a contrast of 10^{-9} at $5\lambda/D$ is achieved, which can be used for direct imaging Jupiter-like planets based on space telescope.

Key words: instrumentation: polarimeter, coronagraph — techniques: polarimetric — methods: laboratory

1 INTRODUCTION

The search for the exoplanets is a hot topic and up to now more than 1924 exoplanets have been discovered by using different methods. However, most of them are detected by indirect methods, such as radial velocity or transit approaches. Although there is preliminary information on the statistics of mass and semimajor axis of exoplanets, the current catalogs suffer from incompleteness for masses below $0.3 M_J$ (the unit of mass equal to the total mass of planet Jupiter) and periods longer than 5.5 years (<http://exoplanet.eu>). Therefore, the direct imaging research will become significantly important and can be used to characterize the physical parameters of the planets, which will challenge the current theory of formation and evolution of planets. However, the direct imaging of exoplanets is extremely

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challenging due to the close angular separation and extremely high contrast ratio between the planet and its primary star. For example, a contrast of 10^{-10} is required to image earth-like planets in the visible wavelengths at a few λ/D from the parent star, where λ is the working wavelength, D is the aperture size of the primary mirror of the telescope.

A high-contrast coronagraph can be used to tackle starlight diffraction due to the telescope pupils (Guyon et al. 2006); and a complicated wave-front controlling system will be used to suppress the speckle noises to generate a dark hole (DH) due to the wave-front distortions from imperfection optics (Bordé & Traub 2006). The researchers in the Jet Propulsion Laboratory and Princeton University optimized a small local DH ($X=3\lambda/D$, $Y=6\lambda/D$) using two deformable mirrors (DMs) with a large number of actuators, where the contrast can reach the level of 10^{-10} (Trauger & Traub 2007; Kay et al. 2009). However, the DH created by current technique is too small to apply to the space telescope to direct image the earth-like planets.

In recent study, it has shown that the light directly from the star is normally un-polarized, while the reflection light from the planet's atmosphere or circumstellar disk is strongly polarized. In Stam's work, a numerical simulation shows that the degree of polarization can reach about 60% for Jupiter-like exoplanets for phase angles near 90° (Stam et al. 2004). Thus, it provides an approach to remove the speckle noises and enhance the imaging contrast by inducing the imaging polarimetry technique. Also the polarimetry can be used to characterize the planet, since the Stokes parameters of the reflected starlight depends strongly on the composition and the structure of the planet atmosphere (Graham et al. 2007).

Currently, many polarimeters have been developed and used as one of the main components in ground-based planet imaging systems, such as Gemini Planet Imager (GPI) on Gemini Telescope, which saw its first light in 2013, and the Zurich Imaging Polarimeter (ZIMPOL) built for SPHERE on VLT UT3, which achieved its first light in 2014 (Perrin et al. 2015; Roelfsema et al. 2010).

In this paper we propose our unique high-contrast imaging polarimeter coupled with a stepped-transmission based coronagraph. We describe the instrument design, principle and data acquisition in section 2. The instrument Mueller matrix and calibration approach are shown in section 3, and section 4 describes the polarimeter performance. We conclude our results and outline our future work in Section 5.

2 INSTRUMENT DESIGN

Figure 1 presents the schematic figure of the optical layout of our polarimetry system. In this system, it is composed of two main components. One is the apodized pupil and the other is the polarimeter. The circular stepped-transmission filter is placed in the optics pupil to suppress the diffraction light, which can achieve the contrast of the order 10^{-7} (Ren et al. 2010). Then a polarimeter is inserted after the pupil apodization system, which includes a calibration unit (a polarizer and a zero-order quarter waveplate) and two liquid crystal variable retarders (LCVRs). The LCVRs will be used as a polarization modulator. More details will be presented in Section 2.2.

2.1 Polarimeter coronagraph

Here we will mainly focus on the design and test of the polarimetry system, since we use the previous stepped-transmission based coronagraph. Thus we will make a brief review of the coronagraph and will not discuss it in detail. The amplitude of the electric field is variable among different steps for a stepped-transmission filter. However, it is constant in each step. The metallic material Inconel is deposited on a BK7 substrate and the transmission is controlled by the adjustment of thickness of the Inconel. The metallic coating filter consists of 50 steps along the aperture radius. The basic conception to use a stepped-transmission filter for pupil apodization is first proposed by Ren & Zhu (Ren & Zhu 2007). It can efficiently suppress the central star diffraction. The stepped-transmission filter coronagraph we use in this polarimeter can achieve a high contrast of $\sim 10^{-7}$ at $5\lambda/D$, which is fully demonstrated in 2010 (Ren et al. 2010).

Fig. 1 Optical concept of the polarimeter with the stepped-transmission filter coronagraph, which suppresses the light from the central star.

2.2 Modulation segment and the Stokes parameters acquisition

Fig. 2 The configuration of the modulation package. The two LCVRs mounted with their fast axis at 0° and 45° respectively.

Two nematic liquid crystal full-wave variable retarders (LCVRs) manufactured by Thorlabs, optimized for 350 to 700 nm, are used to modulate the incoming beam. We use LCVRs instead of waveplates, because this can reduce the effects of mechanical motion. Figure 2 shows the optical configuration of the polarization modulation package.

To obtain the Stokes vector, the polarimeter should take four images in four different modulation states. We adopt the IMaX method to find the Stokes polarization components (Martínez Pillet et al. 2004), in which the retardance of LCVR1 and LCVR2 corresponds to $(315^\circ \ 315^\circ \ 225^\circ \ 225^\circ)$ and $(305.246^\circ \ 54.736^\circ \ 125.246^\circ \ 234.736^\circ)$. The Stokes I, Q, U, V parameters can be derived from the fol-

Fig. 3 The calibration curves of two LCVRs. Left: LCVR1. Right: LCVR2.

lowing formula:

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{pmatrix} = \begin{pmatrix} 1 & 1/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \\ 1 & 1/\sqrt{3} & -1/\sqrt{3} & -1/\sqrt{3} \\ 1 & -1/\sqrt{3} & -1/\sqrt{3} & 1/\sqrt{3} \\ 1 & -1/\sqrt{3} & 1/\sqrt{3} & -1/\sqrt{3} \end{pmatrix} \cdot \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \quad (1)$$

The LCVR's phase retardance is generated by applied an associated voltage. However, the phase retardance and voltage relationship may be variable from LCVR1 to LCVR2, which is also a function of the wavelengths. We measured the actual phase retardance and voltage relationship at the test 632.8 nm wavelength in our laboratory. Figure 3 shows the calibration curves of two LCVRs measured in our lab, compared with that provided by the vendor Thorlabs at the same temperature ($T=23.4$ Celsius) (Wu et al. 1984; Shekwoga Baba & Boudreaux 2007). According to these curves we use the linear interpolation to work out the needed voltages for different kinds of phase retardance.

3 THE METHOD FOR DETERMINING INSTRUMENTAL MUELLER MATRIX AND CALIBRATION

The optical elements of the whole instrument will induce additional polarization (up to 5% at visible wavelenths) and influence the measurement accuracy (de Juan Ovelar et al. 2014; Perrin et al. 2010). Therefore, we should calibrate the instrument to derive the Mueller matrix of the instrument, which represents the impacts of the polarimeter on the incident polarized starlight. In this part, we use a calibration unit, which is shown in Fig. 1, consisting of a linear polarizer and a Thorlabs zero-order quarter waveplate optimized for 632.8 nm. The calibration unit can generate a series of different known polarization states.

3.1 Instrumental calibration

The input Stokes vector (I, Q, U, V) , S , of the light and the measured Stokes vector, S' , satisfy the following equation:

$$S' = M_n \cdot \dots \cdot M_2 \cdot M_1 = M_i \cdot S \quad (2)$$

Here, $M_1 \dots M_n$ represent the Mueller matrices of n optical elements. M_i is a 4×4 Mueller matrix of the instrument, which we need to determine. When the calibration unit is inserted in the optical system,

Fig. 4 Stokes vector calibration result. Measured data (red), theoretical input (green) and the best fit values (black).

the measured output, S' , can be expressed by

$$S' = M_i \cdot M_r(\theta_i) \cdot M_p(\theta_p) \cdot S \quad (3)$$

Where $M_r(\theta_i)$ and $M_p(\theta_p)$ denote the Mueller matrix of the waveplate retarder and the linear polarizer, respectively. S , $(I_0 \ 0 \ 0 \ 0)^T$, is the input Stokes state. The linear polarizer is fixed ($\theta_p = 0$) and the quarter waveplate retarder (θ_i) is rotated from 0° to 180° in 10° steps representing one Stokes parameter at a time. Therefore, the input Stokes states:

$$S_{in} = M_r(\theta_i) \cdot M_p(\theta_p) \cdot S = I_0/2 \cdot (1, \cos^2 2\theta_i, \sin 2\theta_i \cos 2\theta_i, \sin 2\theta_i)^T \quad (4)$$

So far, we know the input states S (4×19) and also we can measure the output states S' (4×19). The instrumental Mueller matrix can be solved by a singular value decomposition.

Figure 4 shows the differences among the measured vector, theoretical input and the computed value by the instrumental Mueller matrix. We note that the fit input Stokes vector is in good agreement with the ideal input vector. From Eq. 3 and Fig. 4 we can find that the instrumental Mueller matrix is:

$$M_i = \begin{pmatrix} +1 & -0.0089 & -0.0237 & +0.0174 \\ -0 & +1.0214 & -0.0020 & -0.0367 \\ -0 & -0.0589 & -0.9860 & -0.2177 \\ +0 & +0.0068 & +0.0552 & +1.0270 \end{pmatrix} \quad (5)$$

After computing by above Mueller matrix, for an input beam linearly polarized, the accuracy of the polarization measurement can reach at the level about 0.2%. From Fig. 4 we find that the improvement of the accuracy after such calibration is significant.

4 THE PERFORMANCE OF THIS POLARIMETER USED IN EXOPLANET DETECTING

This section describes the overall system test and its performance. Two lasers simulate the star and the planet, respectively. The light from the planet laser is polarized by a liner polarizer. Our goal is to detect the faint polarized signal of the planet from the unpolarized star light and to quantify the level of the contrast the polarimeter can achieve.

4.1 Intensity calibration

The method to calibrate the intensity has been proposed by us in our previous paper (Liu et al. 2015). As we know the detecting range of a 16-bit CCD camera is only from 0 to 65536. The contrast (10^{-9}) we measure is definite out of this range. Therefore, we insert the neutral density (ND) filters to attenuate the star light. In our test the overall level of attenuation is 10^{-8} . Firstly, the part of the polarimeter,

Fig. 5 Left panel shows the starlight intensity with an exposure of 0.1s. Right panel shows the planet light intensity with an exposure of 1s.

the stepped-transmission filter and all the linear polarizers should be removed before calibration. Then, move the positions of the star and planet to the same pixels. Finally, we adjust the exposure time to make the intensity of the star (attenuated by the NDs) and the planet's equal to each other. From Fig. 5 we can figure out the contrast of two beams: $0.1/10^8 = 10^{-9}$ (Ren et al. 2010). Once this intensity calibration is done, we will use the polarimeter to detect the dim planet light.

4.2 Detection of the faint polarized light reflected by the planet

Fig. 6 Left: Total intensity of the PSF (without transmission filter). Middle: The PSF suppressed by transmission filter. Right: linear polarized intensity of the PSF. The whole angular distance from the central star to the edge is $10\lambda/D$.

According to the Section 2.2, we need to take four images under four different modulation states to obtain the Stokes vector. Fig. 6 shows the original PSF without transmission filter (left), the PSF suppressed by the filter (middle) and linear polarized intensity (right) after data reduction. We can see that the dim planet can not be detected in the bright star (left and middle). The planet (red circle, left panel) emerges at $5\lambda/D$, while the unpolarized starlight is suppressed by the polarimetry.

This test demonstrates our polarimeter has the ability to directly detect the exoplanets or the debris disks and also it can improve the contrast by a factor of 100 at least, because the coronagraph can give a contrast of $\approx 10^{-7}$. Due to the instrumental polarization and the noise, there is some residual polarized intensity (right). The noise (such as detector read noise) becomes relevantly larger with increasing separation from the central star.

5 CONCLUSIONS

The polarimetry technique will become a powerful approach to characterize the faint exoplanets and the circumstellar disk in the visible wavelength, where the reflection light is dominated, rather the self luminous light in the infrared. In this work, we have presented the design and performance of our high-contrast polarimeter integrated with a coronagraph for high-contrast imaging. We insert the calibration unit to determine the instrumental Mueller matrix by rotating the quarter waveplate. This improves the measurement accuracy to the level of $\approx 0.2\%$ for the linear polarization components. The polarimeter can provide an extra contrast of ≈ 100 times at an inner working angular distance of $5\lambda/D$, and the polarimeter and coronagraph combination can reach at a contrast of 10^{-9} at 632.8 nm. Also the high-contrast region from $5/D$ to $10/D$ on the entire imaging focal plane is larger, which is of great importance to be applied to space telescope. Also the high-contrast region from $5\lambda/D$ to $10\lambda/D$ on the entire imaging focal plane is larger than the dark holes created by other groups such as the JPL and Princeton University, which is of great importance to be applied to space telescope.

This paper demonstrates that the combination of a polarimetry and a coronagraph is a promising technique for imaging of cold planets including Jupiter-like or earth-like planets with future giant segmented mirror telescopes (GSMTs) such as Thirty Meter Telescope (TMT) or Europe Extremely Large Telescope (E-ELT) as well as space based telescopes. Since the telescope optics will affect the polarization partially, more factors should be considered in the practical observations. Meanwhile, a steady-temperature system is necessary, because the LCVR is affected by the temperature variation. Our ultimate goal is to improve the contrast to the order of 10^{-10} or better on the entire imaging focal plane by solving these problems. Further progress will be discussed in the future papers.

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