Laboratory Experiments using Binary Pupil Masks for the *SPICA* Coronagraph Instrument

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ABSTRACT

We are currently involved in the development of stellar coronagraphs, with which the contrast between a star and a planet orbiting it can be improved, with the primary aim of the direct observation of exoplanets. We have carried out demonstrations of our mask design ideas for the pupil of *SPICA* and developed new free-standing masks (Mask-B and Mask-C) using thin sheets of nickel. Mask-B is intended to be used with a small inner working angle (*IWA*), and therefore, would be useful for direct observations of young Jovian planets very close to stars. With Mask-C a wide-field coronagraphic image is realized, so would be useful for efficient surveys of unknown exoplanets far from their stars and observations of diffuse targets such as circumstellar disks related to planetary formation. These mask have the general advantages of a binary pupil mask, i.e., (1) they are robust against pointing errors, and (2) they can, in principle, make observations over a wide range of wavelengths. Furthermore, the design of these masks gives them the following very important asset in that (3) they are applicable to the pupil of the *SPICA* telescope, which is partially obscured by a secondary mirror and support spiders. We obtained the first results of our laboratory experiments using Mask-B and Mask-C. The contrast of Mask-B close to the center was $\sim 10^{-4}$ and that of Mask-C over an extended field of view (6–23 λ/D) was $\sim 10^{-5}$–10^{-6}.

1. INTRODUCTION

It is important to directly observe exoplanets in order to understand the processes by which they were formed, evolved, and their diversity. However, the enormous contrast in flux between a star and a planet associated with it is the primary difficulty in making direct observations (Traub & Jucks 2002). Thus, the development of stellar coronagraphs, which can improve the contrast between the star and the planet, is needed. We are studying binary-shaped pupil mask coronagraphs, with the intention of applying them to the *SPICA* coronagraphic instrument (Enya et al. 2011). Space-borne telescopes have advantages as platforms for high contrast coronagraphs, because they are free from air turbulence and atmospheric infrared absorption. Working in the mid-infrared (mid-IR) region has the great advantage that the contrast between the sun and the planet is 10^{-6}, compared with visible wavelengths where it is 10^{-10}.

To demonstrate the principle, we have developed a checkerboard mask on a substrate, which is a type of binary-shaped pupil mask, and a large vacuum experimental platform, the High-dynamic range Optical Coronagraph Testbed (HOCT),

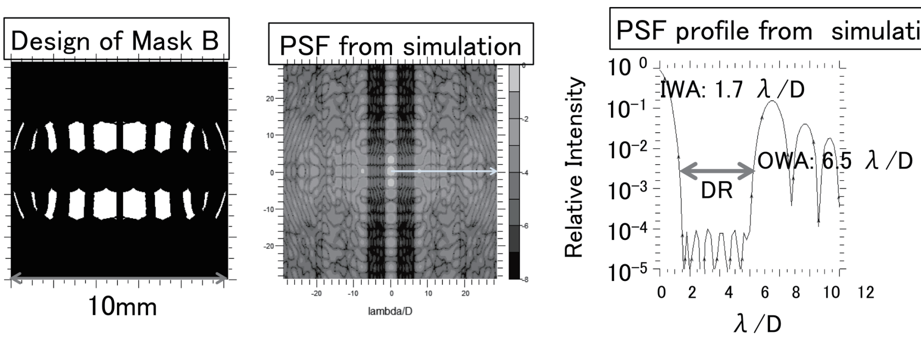

Figure 1. *Left:* Design of Mask-B. The transmissivities of the black and white regions are 0 and 1, respectively. *Middle*: Simulated coronagraphic PSF, which has 2 DRs near the core. *Right*: Simulated PSF profile along an arrow in the middle panel. The contrast, *IWA*, and outer working angle (*OWA*) are 10^{-4}, 1.7 λ/D, and 6.5 λ/D, respectively.

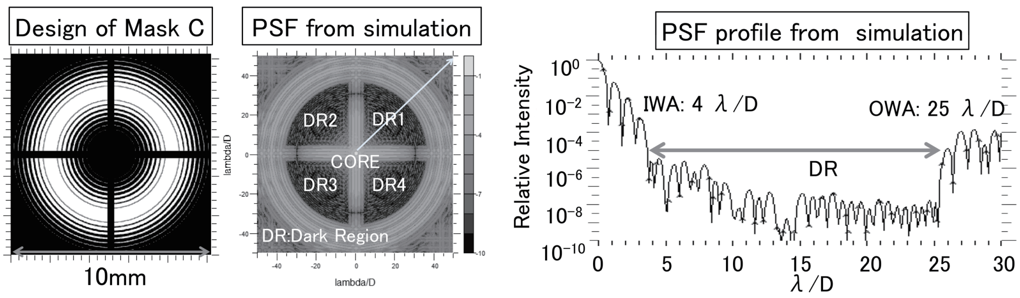

Figure 2. *Left*: Design of Mask-C. The transmissivities of the black and white regions are 0 and 1, respectively. *Middle*: Simulated coronagraphic PSF, which has 4 DRs near the core. *Right*: Simulated PSF profile along an arrow in the middle panel. The contrast is $10^{-4.5}$ at $4\,\lambda/D$ and 10^{-7} between $12\,\lambda/D$ and $25\,\lambda/D$.

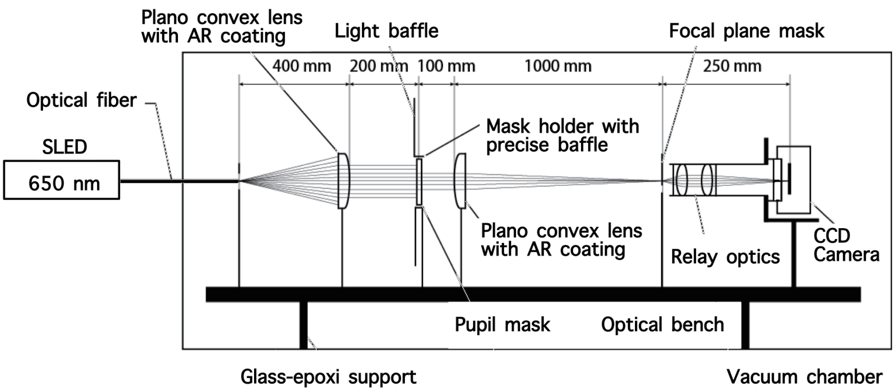

Figure 3. The configuration of the experimental optics.

which provides high thermal stability for the experimental equipment. Using visible light sources, we demonstrated that subtraction of the Point Spread Function (PSF) has potential benefits for improving the contrast of a binary-shaped pupil mask coronagraph, that the contrast with this coronagraph can be significantly improved using multicolor/broadband light sources, and that the new free-standing mask provides superior performance in improving the contrast in the infrared region (Haze et al. 2009, 2011; Haze 2012).

Adopting a checkerboard design, we systematically developed various masks including free-standing masks and masks on substrates with various materials and thicknesses and demonstrated their coronagraphic performance, reaching a contrast of $\sim 10^{-7}$ at visible wavelengths. Experiments at visible wavelengths are easier than in the mid-IR, but reliable enough to check errors in the mask shape, and more sensitive to wavefront errors than in the mid-IR. No significant correlation was found between the contrast and the mask properties (made of copper or nickel with thicknesses of 2, 5, 10, and 20 μm). Wavefront errors are the major limiting factor in the contrast of a coronagraph (Enya et al. 2012).

2. NEW MASK DESIGNS (MASK-B AND MASK-C)

We have started demonstrating our mask design ideas for the pupil of *SPICA*. Figures 1 and 2 show the designs of Mask-B and Mask-C, respectively. The central brightest region of the PSF is called the "core", and the regions near to the core, in which diffracted light is reduced, are called the "Dark Regions (DRs)". Mask-B is intended to be used with a small inner working angle (*IWA*). The contrast for this is 10^{-4} at an $IWA = 1.7\,\lambda/D$, where λ is the wavelength and D is the pupil diameter. The mask is useful for direct observation of young Jovian planets very close to the star. With Mask-C a wide-field coronagraphic image is obtained. The contrast for this is $10^{-4.5}$ at $4\,\lambda/D$ and 10^{-7} between $12\,\lambda/D$ and $25\,\lambda/D$. This mask is useful for efficiently surveying unknown exoplanets far from the stars they orbit and for observations of diffuse targets such as a circumstellar disks related to planetary formation. These masks have the general advantages of binary pupil masks: (1) They are robust against pointing errors. (2) They can, in principle, make observations over a wide range of wavelengths. These particular masks have a particular important asset: (3) The design makes them applicable to the pupil of the *SPICA* telescope, which is partially obscured by a secondary mirror and support spiders.

3. EXPERIMENTS AND RESULTS

We developed these new free-standing masks using thin sheets of nickel. The effective area of the masks is contained within an area of 10 mm × 10 mm. The thicknesses of Mask-B are 5 and 20 μm and the thickness of Mask-C is 25 μm.

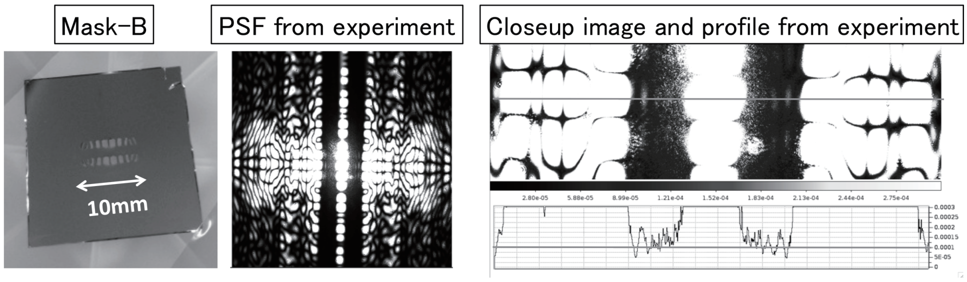

Figure 4. *Left*: Mask-B formed of nickel laminate. The effective region is within a 10 mm × 10 mm area. *Middle*: Observed PSF of Mask-B. *Right*: Close-up image and observed PSF profile of Mask-B.

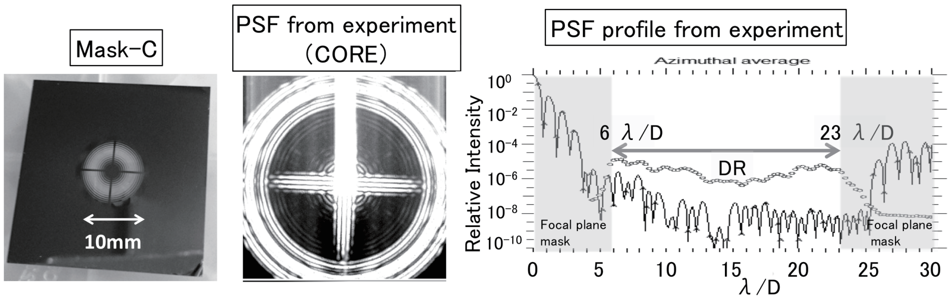

Figure 5. *Left*: The Mask-C formed of nickel laminate. The effective region is within a 10 mm × 10 mm area. *Middle*: Observed PSF of Mask-C. *Right*: Observed PSF profile of Mask-C. We used a focal plane mask which limited the coverage of the DRs.

In the production of Mask-C, it was difficult to form long accurate structures, but we succeeded in making free-standing masks by modifying the parameters. These masks were made with HOWA SANGYO, CO., LTD and Photo Precision Co., Ltd.

Figure 3 shows the experimental platform (HOCT) used for this work. A coronagraphic optical system was set up on an optical bench in HOCT. A Super luminescent Light Emitting Diode (SLED) with a center wavelength at 650 nm was used as the light source. The core was observed with 0.3 s exposure using neutral density filters with an optical density of 4. The dark region was observed with 200 s exposure.

We obtained the first experimental results with Mask-B and Mask-C, as shown in Figures 4 and 5. These obtained shapes of the PSF cores and DRs are quite consistent with the expectations from theory, as shown in Figures 1 and 2. The contrast obtained with Mask-B was around 4 orders of magnitude. The patterns near the *IWA* were not seen, because of light scattered from the core. Thus a focal plane mask suitable for the PSF of Mask-B is needed. The contrast obtained with Mask-C was $\sim 10^{-5}$–10^{-6} over an extended field of view (6–23 λ/D), which is less than the theoretical value. Speckles are the major limiting factor. The results show that the contrast obtained with these masks is significantly better than that obtained using non-coronagraphic optics. In order to improve the contrast by PSF subtraction, it is beneficial to have a highly stable environment. For this purpose, we have completed the fabrication of a super-invar optical bench for HOCT.

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