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Advancements of the optical vortex coronagraph

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ABSTRACT

The optical vortex coronagraph is a promising scheme for achieving high contrast low loss imaging of exoplanets as close as $2\lambda / D$ from the parent star. We describe results using a high precision vortex lens that was fabricated using electron-beam lithography. We also report demonstrations of the coronagraph on a telescope employing a tip-tilt corrector.

Keywords: coronagraph, exoplanet, high contrast, optical vortex

We have designed a prototype stellar optical vortex coronagraph using an optical vortex lens [1]. This device may be used on a terrestrial telescope to enhance the imaging of low contrast systems. Atmospheric correction is achieved using a small aperture telescope and a tip-tilt adaptive optics corrector. This system, which employs a vortex lens fabricated with e-beam lithography, is expected to achieve a Strehl ratio of 99% and a contrast enhancement of 10,000 at $4\lambda / D$. This system will function as a testbed, allowing us to uncover potential systematic design problems.

The optical vortex lens is a transmissive glass optical element, depicted in Fig. 1. It has a specific step height, or pitch, that corresponds to one wave of phase delay across each step [2]. The vortex lens has a transmission function given by

$$t = \exp(im\theta). \tag{1}$$

where m is the so-called topological charge. In this report we have designed the lens to produce a value of $m = 2$ at a wavelength of 785 nm.

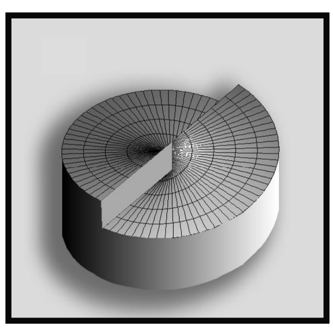

Figure 1. The optical vortex lens with two steps where each step height corresponds to 1 wave of phase delay.

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The optical vortex is useful because it creates a black hole in the beam. Without the vortex in place, the image of the star is simply the Fourier transform of the Airy disc, i.e., a *cyl* function shown in Fig. 2(b). However, when a charge 2 vortex is in the image plane of the star, the image in the pupil plane is the Fourier transform of the star Airy disc multiplied by the transmission function of the vortex lens, which gives a pattern known as the ring of fire shown in Fig. 2(c) [1,3].

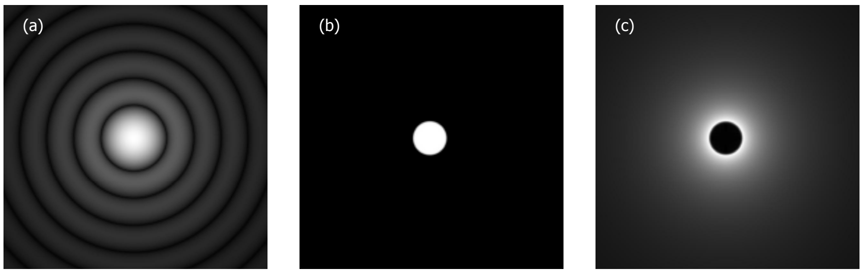

Figure 2: (a) The Airy pattern of the star, defined by $f(r) = somb(r)$. (b) The function in the pupil plane of the coronagraph without the vortex lens in place, defined by $FT[f(r)] = cyl(r')$. (c) The function in the pupil plane of the coronagraph with the vortex lens in place, defined as $FT[f(r)\cdot\exp(im\theta)]$.

The optical vortex coronagraph is a Lyot type coronagraph [4] with a phase mask in the image plane, rather than an occulting disc, as shown in Fig. 3.

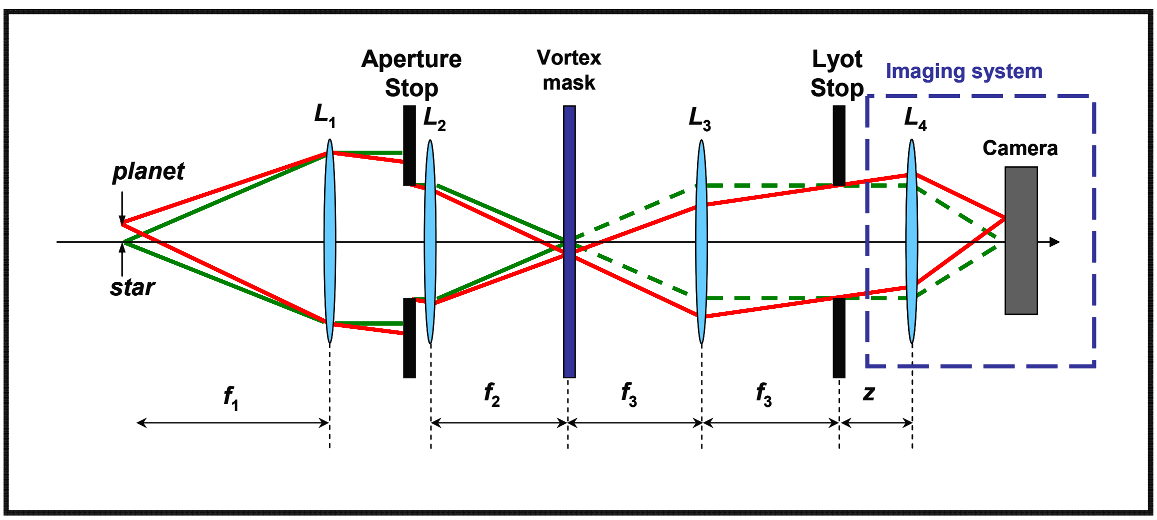

Figure 3: Layout of the optical vortex coronagraph. The vortex mask replaces the occulting stop of the original Lyot coronagraph.

The starlight is shown in green (on-axis) and the planet light in red (off-axis) in Fig. 3. The light from each is collimated by lens L_1, and then passes through the entrance pupil of the coronagraph. The light is focused by lens L_2 onto the vortex mask and re-collimated by lens L_3. In the Lyot plane (the exit pupil of the coronagraph) the green starlight forms the ring of fire. The planet light, however, is off axis. When focused onto the vortex mask, it does not hit the center of the spiral and therefore does not obtain the transmission function of the vortex. The planet light is approximately a tilted circ function at the Lyot stop, uniformly filling the Lyot stop. Fig. 4 shows an experimental image at the Lyot stop when both the red and green beams illuminate the system.

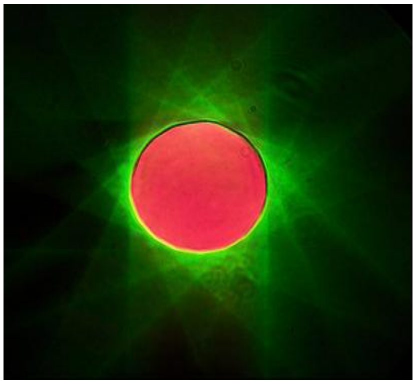

Figure 4: Laboratory image from the Lyot plane of the coronagraph. The green light represents the starlight and forms the ring of fire. The red light represents the planet light and passes through the ring of fire as a plane wave.

In the Lyot plane, a stop is placed to block out the ring of fire from the star. In contrast, the planet light passes through the aperture and is refocused onto the camera. The entire working system is shown below in Fig. 5.

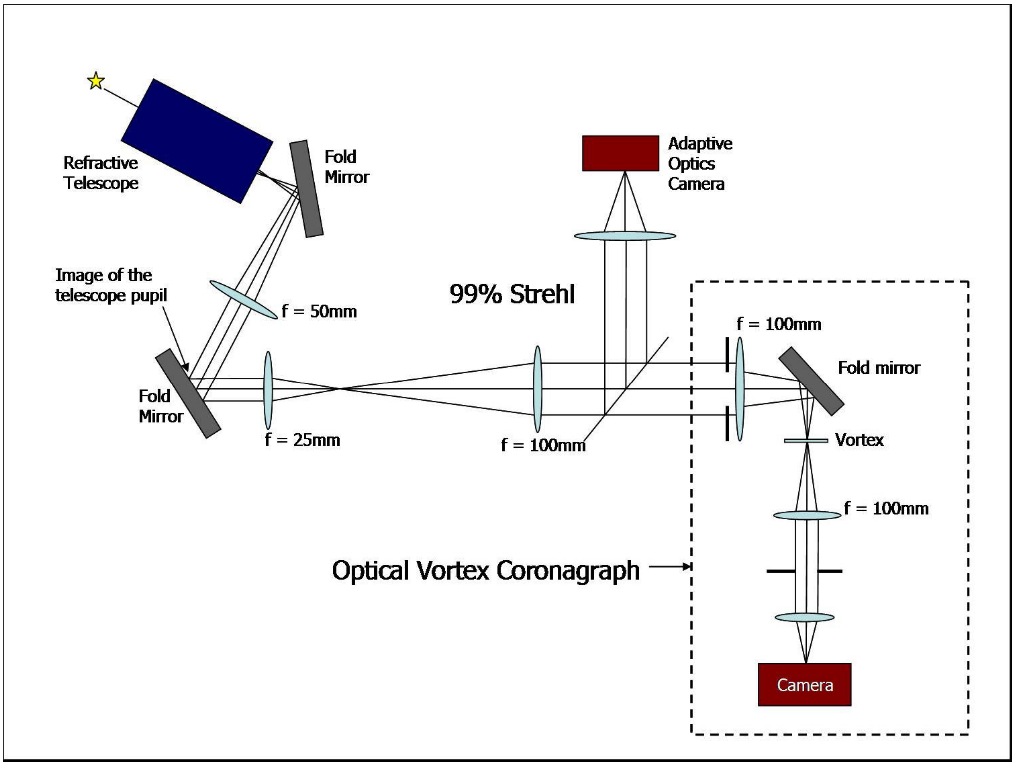

Figure 5: Experimental setup of the system, including the adaptive optics system that connects the telescope to the coronagraph and corrects for atmospheric turbulence.

The starlight is collected by a one inch diameter telescope and re-collimated by the 50 mm lens. The telescope pupil is imaged onto the second fold mirror. The light is then passed through an afocal re-imaging relay that passes the pupil of the telescope to the entrance pupil of the coronagraph. A beam splitter sends part of the light to an adaptive optics camera that controls the tip/tilt of the second fold mirror to correct for atmospheric perturbation. The rest of the light passes through the entrance pupil of the coronagraph and is focused onto the vortex lens. The light is re-collimated by the lens after the vortex. At the Lyot plane the Lyot stop blocks the starlight so that only the planet light is left to be focused onto the camera. The tip-tilt adaptive optics system was measured to produce a 99% strehl ratio.

Preliminary results measured using a 785nm laser in the laboratory are shown in Fig. 6. The figures below show the exit pupil image without and with a vortex lens in place, respectively. The red circle indicates the portion of the pupil passed by the Lyot stop. The intensity ratio of the light passed by the Lyot stop with vortex out vs. vortex in is 63. Figure 7 shows the point spread functions in the final image plane without and with the vortex lens in place. The peak ratio of the vortex out to the vortex in is 69.

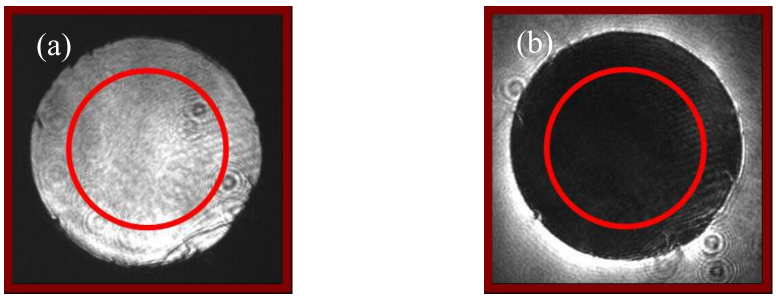

Figure 6: Laboratory images from the above system, taken in the Lyot plane (a) without and (b) with the vortex lens in place.

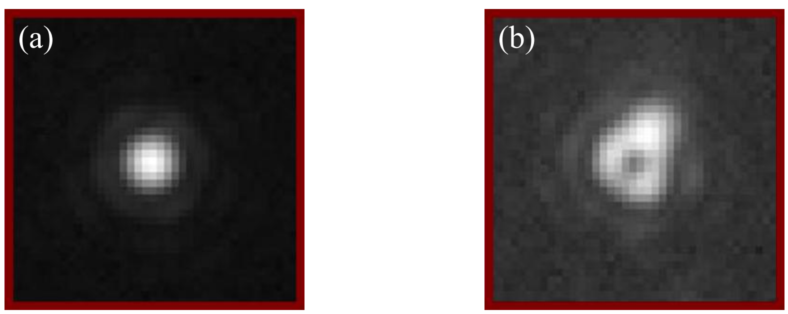

Figure 7: Laboratory images from the above system, taken at the final image plane (a) without and (b) with the vortex mask in place.

In order to interpret these results, characterization of the vortex lens created using e-beam lithography by Jet Propulsion Laboratory was necessary to give a baseline for comparison. To do this, the vortex lens was measured using a profilometer at Veeco, Inc. Figure 8(a) is a topological image of the vortex mask. The patchwork patterning shown in the image is due to stitching errors of the e-beam pen. This is expected to negatively impact the results. Additionally, there is a profilometer ambiguity at the center of the image where the vortex central features cannot be resolved. In order to use this image to calculate theoretical results, the ambiguity must be corrected by interpolating the data to create the vortex center.

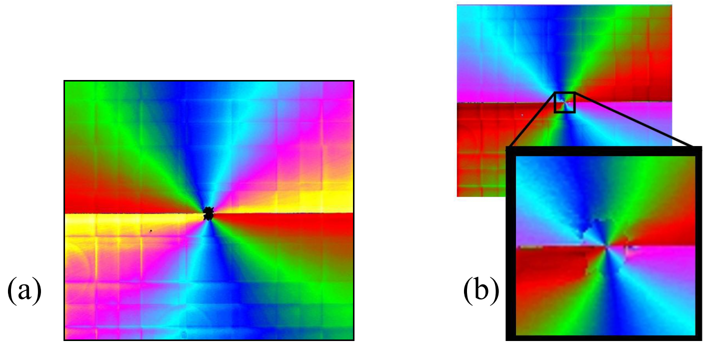

Figure 8: (a) A topological map of the surface of the vortex lens. (b) Correction of the central features that could not be resolved by the profilometer.

For numerical analysis, the vortex image data was placed into a 4096x4096 numerical array as shown in Fig. 9(a). When the airy pattern of the star is imaged onto the vortex lens, the phase changes as shown in Fig 9(c).

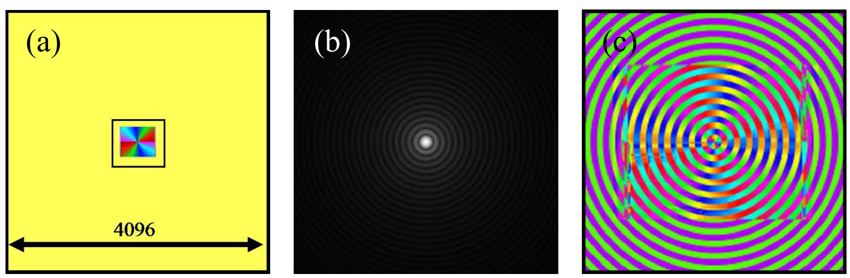

Figure 9: (a) The relative size of the vortex mask in the numerical array used for theoretical testing of the mask quality. (b) Size enhanced image of the theoretical Airy pattern to be focused onto the vortex lens. (c) The change in phase exhibited due to the affects of the vortex lens.

The numerical processing predicts that, with a *cyl* function at the entrance pupil and a Lyot stop in place, the vortex lens produced should give an integrated intensity ratio of 72. This is in fair agreement (e.g. a 13 percent difference) with the experimentally measured value of measured in the lab. Therefore it is likely that mask fabrication errors are limiting the performance of the system. A second generation e-beam mask is in process at Jet Propulsion Laboratory.

Plots of the amplitude in the final image plane are shown in Fig. 10. The grey line shows the on-axis starlight with no vortex in place. The black line shows the attenuation of the on-axis starlight with the vortex in place. The blue lines are the planet light, with and without the vortex in place. It is apparent that the vortex has very little effect on the off-axis planet light. These measurements give us a contrast of 10^4 at a distance roughly $4\lambda / D$ from the star.

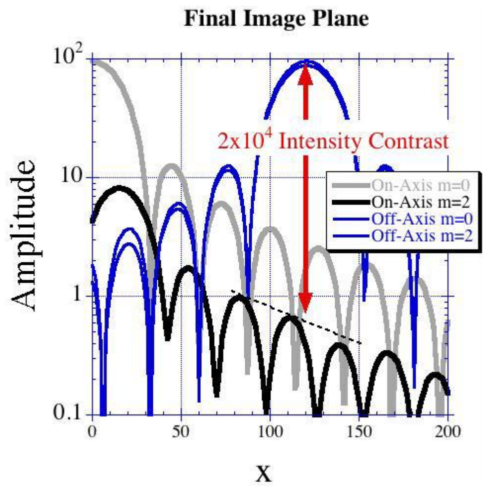

Figure 10: A plot of amplitude in the final image plane of the coronagraph shows a 10^4 contrast at $4\lambda / D$.

In summary this optical vortex coronagraph is designed to couple to a telescope for viewing the sky. To decrease the effects of atmospheric turbulence, a tip-tilt adaptive optics system is used with performance of 99% strehl. The vortex lens in the system was created by Jet Propulsion Laboratory using e-beam lithography. The fabrication issues have been identified and prove to be the limiting factor of the current setup. Even with this shortcoming, we expect a contrast of 10^4 at $4\lambda / D$. This is an improvement factor of 250 compared to our earlier verification of the vortex coronagraph concept [5].

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