A broad-band scalar vortex coronagraph

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Accepted 2013 July 16. Received 2013 July 16; in original form 2013 June 7

ABSTRACT

Broad-band coronagraphy with deep nulling and small inner working angle has the potential of delivering images and spectra of exoplanets and other faint objects. In recent years, many coronagraphic schemes have been proposed, the most promising being the optical vortex phase mask coronagraphs. In this paper, a new scheme of broad-band optical scalar vortex coronagraph is proposed and characterized experimentally in the laboratory. Our setup employs a pair of computer-generated phase gratings (one of them containing a singularity) to control the chromatic dispersion of phase plates and achieves a constant peak-to-peak attenuation below 1 × 10−3 over a bandwidth of 120 nm centred at 700 nm. An inner working angle of ∼λ/D is demonstrated along with a raw contrast of 11.5 mag at 2λ/D.

Key words: instrumentation: miscellaneous – planets and satellites: detection

1 INTRODUCTION

Direct imaging of exoplanets (Marois et al. 2008; Serabyn, Mawet & Burrrus 2010; Neuhäuser & Schmidt 2012) is one of the major scientific drivers behind the recent developments in stellar coronagraphy (Mawet et al. 2012). The possibility to distinguish the faint light of the planet amid the glare of the host star would eventually enable spectrometric characterization of their atmospheres (Janson et al. 2010), which is currently mostly possible for large-size transiting exoplanets (Charbonneau et al. 2002). In this regard, the thriving challenge is the detection of biomarkers in the exoplanet atmospheres (Lovelock 1965), and thus to ascertain the frequency of life in the Universe.

In traditional stellar coronagraphy (Vilas & Smith 1987), the light of the star is blocked in the image plane by means of an opaque screen and then filtered in the pupil plane by a second opaque mask (the Lyot stop; Lyot 1939), before the image is formed on the detector. This configuration gives good suppression of the starlight, at the expense of the inner working angle, i.e. the minimal distance from the attenuated star at which a faint neighbouring object can be observed. Recently, attention was driven to the possibility to use phase rather than amplitude masks to suppress efficiently the starlight while retaining an inner working angle close to the diffraction limit (Roddier & Roddier 1997). Many different types of phase mask coronagraphs have been suggested and experimented in the last decade (Mawet et al. 2012), the common denominator being that the phase mask is used to scatter the light of the central star outside the pupil aperture and thus be easily removed by a circular aperture used as Lyot stop. Particularly interesting in this regard are the so-called vortex phase mask coronagraphs (Foo, Palacios & Swartzlander 2005), which transform the starlight beam into an optical vortex, a ring-shaped beam with a null in the centre and a spiral wavefront (Allen et al. 1992).

Most of the proposed methods however suffer from strong chromaticism, due to the fact that a specific phase shift cannot be generated by a single mask for all wavelengths simultaneously (Swartzlander 2005). As a result, phase mask coronagraphs can attain high rejection of the central star only if operated with small bandwidths, certainly a limitation for the goal of spectroscopic investigation of exoplanets.

A solution to the problem of chromaticism has been proposed by Mawet et al. (2005) and consists in generating a polarization optical vortex by exploiting the form birefringence of sub-wavelength gratings (so-called vectorial vortex coronagraphs). While this method is possible for mid-infrared wavelengths (Delacroix et al. 2013; Mawet et al. 2013), for shorter wavelengths the nanotechnology for the development of the phase masks is not yet at the level required by scaling. Vectorial vortex coronagraphs at shorter wavelengths were fabricated by means of liquid crystal polymers technology (Mawet et al. 2009) and gave excellent broad-band contrasts in the laboratory (Mawet et al. 2011) and on sky (Serabyn et al. 2010).

In this paper, we propose a solution for the chromaticity of scalar optical vortex coronagraphy in the visible band by use of a method previously applied to femtosecond laser optics to generate broadband optical vortices. The peak-to-peak attenuation of our coronagraphic setup is constant below the 1 × 10−3 level over a bandwidth of at least 120 nm centred at the wavelength of 700 nm. The throughput of the vortex generating setup achieves a peak value of 75 per cent and is approximately constant for wavelengths between 640 and 800 nm.

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2 GENERATION OF BROAD-BAND OPTICAL VORTICES

2.1 Optical vortices and coronagraphy

An optical vortex is an optical field containing a point where the phase is undefined, usually referred to as the phase singularity. In this point, the optical field has exactly 0 amplitude. The circulation of the phase transverse gradient around a path γ around a phase singularity is an integer multiple of $2\pi$ and is addressed as the topological charge of the optical vortex:

$$\oint_\gamma \nabla \phi(x, y) \cdot dl = m2\pi.$$  \hspace{1cm} (1)

Here, $\phi(x, y)$ is the phase in the transverse plane perpendicular to the propagation direction of the field. For a field $U_V$ with cylindrical symmetry, we may write the optical vortex in the following form:

$$U_V(r, \theta, z) = A(r) \exp(ik_0 z) \exp[-i\phi(\theta)]$$

$$= A(r) \exp(ik_0 z) \exp(-im\theta),$$  \hspace{1cm} (2)

where $A(r)$ is a radial amplitude function with a null in the origin $r = 0$. The wavefront of the vortex field (focus of points with the same phase) has the shape of a screw of step $2\pi/k_0$. Phase singularities can be written on a generic field $A(r)$ by means of a phase mask, i.e. a plate where the local optical path is given by $n\theta/k_0$. Particularly interesting for astronomical applications is the case in which $m = 2$ and $A(r) = J_1(r)/r$, such as in the case of an aberration-free telescope with circular pupil focusing starlight on the centre of the phase plate. It can be demonstrated (Mawet et al. 2005; Swartzlander 2005) that in the pupil plane the field $U_V$ is transformed in the following form:

$$U_V(r, \theta) = FT \{ U_V \} = \exp(-i2\theta) \begin{cases} 0 & r < R_p \\ (R_p/r)^2 & r \geq R_p. \end{cases}$$  \hspace{1cm} (3)

The equation shows that the light is scattered outside the radius $R_p$ of the pupil (the so-called ring of fire). This property, which is shared by vortices with even topological charge (Mawet et al. 2005), can be exploited to dim the light of the star efficiently. Indeed, by placing a circular aperture with radius $R < R_p$ in the pupil plane, we can in principle reject the whole light of a central star, while retaining most of the light from a weak companion which, focused outside the vortex region of the phase plate, will be distributed over the area of the pupil. A final pupil transformation (Fourier transform) will allow us to image just the companion. In practice, the ring of fire is smoothed by aberrations and some light of the central star is scattered within the pupil.

Another practical limitation of this scheme is that phase plates work only for a fixed wavelength (Swartzlander 2005) and operation in polychromatic regime degrades considerably the contrast of a phase plate coronagraph (Swartzlander et al. 2008). As we shall see in the next paragraph, a pair of holographic phase plates can resolve the problem.

2.2 Off-axis vortex holographic phase plates

The effect of the chromaticity of on-axis vortex phase plates gives rise to the superposition of vortices of various topological charges in the field transmitted by the phase plate (Swartzlander 2005). This problem is solved by using an off-axis phase plate hologram.

A hologram is a recording of an optical field (Goodman 2005). By illuminating the hologram with an appropriate reference wave, the recorded field can be reconstructed and used for various applications. The hologram can be encoded in amplitude or phase. In many applications, the hologram is generated numerically and transferred with photolithographic techniques to an optical substrate. We thus speak of computer-generated holograms (CGH). In phase holograms, local variations of the thickness or refractive index of a transparent substrate are used to encode the phase of an optical field.

An off-axis vortex phase CGH can be generated by extracting the phase of the product between a phase singularity $(U(\theta) = \exp(-im\theta))$ and a reference plane wave $U_k = \exp(-iak_0x)$ propagating at an angle $\alpha$ from the optical axis. The spatially resolved phase delay of the plate for $m = 2$ is illustrated in Fig. 1. We see that the hologram is akin to a diffraction grating with a period $g = 2\pi/(ak_0)$ and a phase singularity in the centre (three lines converge into one). By illuminating the hologram with an optical field, we will in general scatter the light over different diffraction orders of the grating. The field scattered at diffraction order $n$ is a vortex with a topological charge $nm$. At the design wavelength, the phase hologram will be scattering the light in the first order of diffraction only. When the phase plate is illuminated by light at a different wavelength, light will be scattered also to other diffraction orders, but preferentially to the first order. Therefore, the superimposed grating will sort spatially the contribution of the parasitic topological charges which represent the problem of the on-axis phase plate (Swartzlander 2005).

However, the diffraction angle at the first order will be proportional to the wavelength. Therefore, by illuminating the hologram with white light, we will obtain a superposition of monochromatic copies of the optical vortex, each propagating at a slightly different direction according to its wavelength. This is a manifestation of the angular dispersion introduced by the grating. A way to overcome this problem is to illuminate the hologram with angularly dispersed light propagating along the direction of its first diffraction order.
Light will be mainly scattered at order $+1$ of the vortex hologram and the angular scattering will be cancelled leaving a white-light optical vortex beam. A practical implementation of the scheme is illustrated in Fig. 1(c) (see also Bezuhanov et al. 2004). A first grating (Fig. 1b) introduces angular dispersion in the white-light beam. The first diffraction order is selected by a lens and a slit aperture and reimaged by a second lens onto the vortex hologram, which exhibits a grating with the same periodicity as the first grating. The vortex hologram will add the topological charge to the beam and for the diffraction order $+1$ will also re-compose the degeneracy of the propagation directions of the various colours, so that a white-light vortex is formed. Note that all defects of the vortex induced by the chromaticity of the phase plate will propagate at different diffraction orders which will be rejected. Thus, the inability of the vortex phase plate in generating pure charge vortices for broad bandwidth will be transferred to a throughput inefficiency of the setup.

3 EXPERIMENTAL SETUP

The setup for our laboratory test of the broad-band optical vortex coronagraph is composed by three main functional units and is depicted in Fig. 2. The first functional unit is used to simulate the diffraction pattern of an obstruction-free telescope. We used light either from an HeNe laser ($\lambda_0 = 633$ nm) or from a broadband white-light source ($\lambda_0 \geq 640$ nm) coupled into a single mode fibre to simulate a point-like source. The light from the optical fibre was collimated by an $f = 11$ mm aspheric lens (L1) and used to illuminate a pinhole (PH1) of diameter $D = 75$ $\mu$m which simulates the pupil of a telescope. An $f = 40$ mm lens (L2) was used to generate an airy disc with radius $r = 420$ $\mu$m (first minimum radius, $\lambda = 640$ nm) at the input of the second functional unit (broad-band optical vortex generator).

The scheme of the broad-band optical vortex generator is the replica of that illustrated in Fig. 1 implemented with $f = 100$ mm lenses and blazed phase diffraction gratings with period $g = 50$ $\mu$m. The gratings (Fraunhofer Institute, Jena) were prepared by replicating on a thin polymer layer (10 $\mu$m) a master hologram obtained by grey tone laser lithography. They are optimized for the wavelength of $\lambda_0 = 650$ nm and have a maximum diffraction efficiency in the first order exceeding 90 per cent. The vortex hologram (CGH) was placed in the focus of the L3 on an $x$-$y$ micrometric translation stage which allowed us to align precisely the phase singularity of the grating with the optical axis of the setup. An iris blind was used to select just the first diffraction order of the first grating.

In the third functional unit (Lyot stop), the image plane is transformed back into the pupil plane by an $f = 400$ mm achromatic lens (L4). A ring of fire with inner radius of 350 $\mu$m and maximum intensity at 410 $\mu$m was formed in the back focal plane of the lens. In this plane, we placed a $d = 700$ $\mu$m pinhole which corresponds to 93 per cent of the magnified diameter of the entrance pupil (750 $\mu$m). Finally, lens L5 transformed back the optical field into the image plane, which was recorded with an 8 bit CCD camera.

To achieve high dynamic range with the CCD, we exploited the 12 bit dynamics of the shutter speed. High-dynamic-range images are obtained by (1) taking several shots with different shutter speed, (2) removing the saturated pixels, (3) applying the dark correction, (4) scaling the pixel values to the shutter speed and (5) combining the resulting partial images by the weighted average. Thereby, the combination is done pixel by pixel and the flux after step (3) is used for the weighting; hence, we avoid the upsampling of dark current noise because of the low weight of faint pixels. The linearity of both the pixel and shutter speed dynamics was tested. The estimated overall dynamics of our images is the product of the dynamic of the camera with the dynamic of the shutter, thereby $2^{20} \approx 10^6$.

4 RESULTS

To gauge the performance of the coronagraph, we measured first the peak-to-peak attenuation, defined as the ratio between the maximum flux in the on-axis radial profile and the maximum flux in the off-axis radial profile. To this end, we built two high-dynamic images of the final focal plane with (1) the phase singularity of the CGH centred on the optical axis of the instrument and (2) with the phase singularity shifted off-axis by several $\lambda/D$. In the first case, the ring of fire of the artificial star will be blocked by PH2, while in the second case, the light of the artificial star will be transmitted through PH2.

Fig. 3 shows the azimuthally integrated profiles of these two images for an artificial star created with an HeNe laser and a $\Delta \lambda = 120$ nm broad-band light source. The broad-band light source
was achieved by setting seven equally spaced channels covering the wavelength range from 640 to 760 nm in our programmable white-light source. For both light sources a peak-to-peak attenuation to $\sim 5 \times 10^{-4}$ was observed, showing the intrinsic achromatic behaviour of our coronagraph. In the broad-band case, the attenuation at $\lambda/D$ converts to 9.2 mag, while the attenuation at $2\lambda/D$ reaches a level of $2.4 \times 10^{-5}$ (11.5 mag), a performance comparable to the laboratory tests of the vectorial vortex coronagraph (Delacroix et al. 2013).

The dependence of the peak-to-peak attenuation on the bandwidth of light centred at 700 nm is shown in Fig. 4. As before, the bandwidth was achieved by selecting appropriately the eight channels available at our white-light source in steps of 10 or 20 nm. In the covered range of bandwidths, the peak-to-peak attenuation is constant within the measurement errors to a value of $(0.037 \pm 0.004)$ per cent. At the maximum bandwidth (120 nm), the relative bandwidth $\Delta \lambda / \lambda$ is 17 per cent, enough to cover the band of an astronomical filter. We notice however that our experiments were not able to investigate the maximal bandwidth of our coronagraphic setup since we were limited by the wavelength range of the white-light source (emitting for wavelengths $\lambda \geq 640$ nm, but efficiency drops for $\lambda > 780$ nm). There is no reason for the peak-to-peak attenuation to drop at even bigger bandwidths. The only limit is given when the different orders of the first grating begin to overlap. For the wavelength to overlap between the first and second order of diffraction, we need to have wavelengths $\lambda < 434$ nm and $\lambda > 870$ nm, thus allowing a spectral range of $\sim 430$ nm centred at 650 nm. This remarkable bandwidth range will include the $V$ and $R$ bands while covering half of the $B$ band and most of the $I$ band.

A potential limitation of our setup is however that the blazing of the grating and CGH may lose diffraction efficiency for wavelengths strongly detuned from the design wavelength. We show however that this is not the case for the investigated wavelength range. Fig. 5 shows the throughput of the vortex generator functional unit, i.e. comprising the optical components from the grating to the hologram (see Fig. 1). The weighted average transmission is 75 per cent, and it is constant over the wavelength range of 160 nm. Longer wavelengths could not be explored due to low efficiency of the white-light source and detector. Note that the grating and hologram were not coated with antireflection layer, hence reflection losses are expected to occur at these surfaces. Assuming a conservative reflectivity of 4 per cent at each surface, losses of $\sim 16$ per cent occur, meaning we could push the throughput of the whole system to 90 per cent by using antireflection coating.

Finally, we simulate the effect of the CGH on a close companion by measuring the transmission of our setup while moving the CGH off-axis. Fig. 6 shows the normalized transmission of the brightest spot plotted against the off-axis position of the CGH. At an angular separation $\lambda/D$ about 50 per cent of the light is suppressed while a companion at separation $\geq 2\lambda/D$ is nearly unaffected by the phase singularity in the CGH. This result is in line with the expectations of the narrow inner working angle of the vortex coronagraph. The data also show that the inherent stability of the angular separation between the beam and the CGH singularity should be maintained below 0.044 $\lambda/D$ in order to ensure a contrast better than $10^{-3}$.

**5 CONCLUSIONS AND PERSPECTIVES**

In conclusion, we have performed the laboratory characterization of a broad-band optical vortex coronagraph. We showed that a high contrast over large bandwidth is reachable, which is a key point to do spectroscopy on faint companions.

Compared to other schemes of scalar vortex coronagraphy (Swartzlander et al. 2008), the proposed setup has the advantage of providing very high attenuations of the central star over much larger bandwidths. We experimentally verified that the contrast can be kept constant over a bandwidth of 120 nm centred at the wavelength of 700 nm, enough to cover a transmission bandwidth of the atmosphere. As mentioned, however, the setup can in principle...
provide high peak-to-peak attenuations of the central star also for larger bandwidths albeit with a lower throughput. We note that the laboratory performance of our setup is comparable to that of the vectorial optical vortex coronagraph (Delacroix et al. 2013) in terms of relative bandwidth and peak-to-peak attenuation. Indeed, our setup exhibits a contrast nearly 10 times better than the vectorial vortex coronagraph. In principle, our setup can be extended to the near- or mid-infrared, where for both young and old exoplanets the brightness difference to their host stars is much smaller than in the visible. Assuming that we can achieve the same efficiency of the broad-band scalar vortex coronagraph in the mid-infrared, we notice that a peak-to-peak attenuation below ≈0.1 percent in combination with a camera dynamics of 10^4 and image processing techniques (Lafrenière et al. 2006) would allow us to detect objects as faint as 10^{-6}–10^{-7} (Δm ≈ 15–17 mag) compared to the central star, thus permitting to image directly the old exoplanets.

As for the other vortex coronagraphs based on the generation of charge 2 vortices, the inner working angle has been shown to be λ/D, while the field of view will be limited only by the field of view of the initial image plane. Note that our scheme is also suitable for the generation of vortices with topological charge greater than 2. As known (Guyon 2007; Jenkins 2008), higher order vortex coronagraphs are less sensitive to low-order aberrations (e.g. tip tilt) and intrinsic stellar disc size, the trade-off being represented by larger inner working angles. In the case of CGH, the resolution of the fabrication method (in our case 1 μm) will be the limiting factor for the realization of holograms with topological charge larger than 2, since the definition required to write a singular point increases with the topological charge of the vortex. Work is in progress to assess the impact of the resolution of the phase mask on the contrast.

The price to pay for a large operation bandwidth of the proposed coronagraph is the fact that the imprint of the vortex on the optical wavefront requires a relatively complex setup as compared to the single mask approach. The presence of two lenses and alignment degrees of freedom may introduce additional scattering sources and aberrations that may limit the achievement of even higher attenuations than already demonstrated. It may be worth noting that a simplified setup for a similar broad-band vortex generation was proposed and tested by Mariyenko, Strohaber & Uiterwaal (2005).

We believe our results represent a significant step towards the realization of high-performance, broad-band coronagraphs for the next-generation telescopes equipped with extreme adaptive optic systems which will enable routine imaging and spectroscopy of exoplanets and other faint features around stars.

ACKNOWLEDGEMENTS

We thank the referee, Dimitri Mawet, for careful and helpful reading of this paper.

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