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EXPERIMENTAL ADVANCES IN PHASE MASK CORONAGRAPHY

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Abstract. Stellar coronagraphy is a key technology for current and future instruments for exoplanet imaging and spectroscopy, both on the ground and in space. We pursue the research on coronagraphs based on circular phase-masks and report in this paper on recent advances in terms of the trade between spectral bandwidth and achievable contrast. Circular phase masks combined with colored apodizations prove to be promising options in such coronagraphic systems to reach high contrast gains within the search area over a wide band of wavelengths.

Keywords: high angular resolution, coronagraphy

1 Introduction

Detection by direct imaging and spectral analysis of the exoplanets represent some very exciting but challenging issues in contemporary astronomy. Once very high angular resolution images obtained, downstream high contrast imaging techniques are required to observe faint sources close to bright stars. In this context, several coronagraphic concepts were proposed these past few years to remove the light of an observed star.
Coronagraphs using phase masks prove to be very promising concepts since high contrast levels can theoretically be achieved with them at very small separations from an observed bright star. In particular, circular phase masks present the advantage to be less sensitive to the telescope central obscuration than other phase mask concepts, like the sectorised phase mask family (e.g. see Lloyd et al. 2003). The Roddier & Roddier phase mask (RRPM) was the first circular phase mask concept proposed within this approach (Roddier & Roddier 1997). In its apodized version, it can completely suppress the diffraction pattern of a monochromatic point source (Soummer et al. 2003a). This concept is however greatly limited when it deals with large spectral bandwidths. The Dual Zone phase mask (DZPM, Soummer et al. 2003b) constitutes an improvement of this RRPM since it was conceived to overcome the limits met by the RRPM in the presence of a polychromatic point source. The first design of the DZPM coronagraph has been realized considering a grey (or achromatic) apodization.
In this paper, we report an improvement of the DZPM coronagraphic design, replacing the grey by a colored (or chromatic) apodization, to increase the performance of the DZPM coronagraph over the whole considered spectral bandwidth. Theoretical contrast levels achieved by the colored apodized DZPM coronagraph will be compared with those of the grey apodized DZPM coronagraph and manufacturing aspects will be analyzed.

2 The DZPM coronagraph

Roddier & Roddier (1997) proposed an improvement of the classical Lyot coronagraph by replacing the opaque occulting mask by a small and transparent π-phase shifting mask (also called RRPM). They showed that if the core of the stellar diffraction pattern is delayed by a π-phase change, the original object wave and the wave diffracted by the phase mask interfere destructively within the geometrical pupil image, displacing most of the starlight into a halo surrounding the pupil. The rejected stellar light can be removed with the Lyot stop, leading to an important reduction of diffracted starlight in the final image projected onto a detector. A perfect starlight

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extinction can theoretically be reached in the monochromatic case with the addition of an optimized entrance pupil apodization(Soummer et al. 2003a).

Soummer et al. (2003b) proposed to modify the mask design to reach a quasi-perfect suppression of the star image over a large spectral bandwidth. He introduced a second annular phase mask to the initial phase mask, what leads to the design of a so-called dual-zone phase mask (DZPM) with two non π phase shifts. As for the RRPM, the contrast gain reached with the DZPM is improved by adding an entrance pupil apodization. The introduction of an entrance pupil apodization allows one to smooth the direct wave and make it match well with the sum of the waves diffracted by the two zones of the DZPM. The addition of a phase apodization typically in the form of mask defocus also leads to a closer null sum of the waves and then, an improvement of the coronagraphic performance.

In order to keep on improving the DZPM coronagraph performance, we propose to replace the grey by a colored apodization and thus, optimize the apodization transmission function at each wavelength within our spectral bandwidth.

3 Numerical simulations

For our numerical simulations, a circular aperture with $D = 42\,\mathrm{m}$ diameter and $\eta = 30\%$ central obscuration (E-ELT case) is considered. We assume a central wavelength $\lambda_0 = 1.65\,\mu\mathrm{m}$ and a bandwidth of 25.4% (H-band case). Concerning our optimization, the monochromatic intensity of the coronagraphic and non coronagraphic images is calculated at 5 wavelengths: $1.49\,\mu\mathrm{m}$, $1.57\,\mu\mathrm{m}$, $1.65\,\mu\mathrm{m}$, $1.73\,\mu\mathrm{m}$ and $1.81\,\mu\mathrm{m}$. For each wavelength λ, we average the intensity of the coronagraphic and non coronagraphic images over an annulus from $2\,\lambda_0/D$ to $10\,\lambda_0/D$ from the main optical axis. The averaged attenuation is obtained calculating the ratio of these mean intensity values. Once this done, we compute a merit function to estimate the quadratic sum of the averaged attenuations reached at each wavelength. A numerical least-squares method is used to obtain the DZPM parameters that maximize our merit function and therefore, achieve the best attenuation for simultaneously all the wavelengths of our study.

3.1 Numerical models analyzed for this study

Five numerical models for the DZPM coronagraph are studied here and involve several parameters. The mask diameters d_1 and d_2 and the phase steps, given in optical path difference OPD_1 and OPD_2, constitute the common characteristics to all of our concepts. The other parameters are related to the amplitude and phase apodization of the entrance pupil and can be grey (achromatic) or colored (chromatic) depending on the considered model. For the phase apodization, we work with radially symmetric aberrations of the first order and therefore, it can be obtained physically by defocussing the mask.

–The 1^{st} and 2^{nd} models are related to a grey apodized DZPM coronagraph. Their apodization parameters are then constant and estimated considering the best on-axis starlight extinction and the merit function defined above, for the 1^{st} and 2^{nd} models respectively.

–The 3^{rd} model is a colored apodized DZPM coronagraph and thus, the apodization parameters are chromatic and optimized independently at each wavelength of our study considering the merit function defined above.

–The 4^{th} and 5^{th} models constitute possible physical implementations of the 3^{rd} model. For the colored apodizer of the 4^{th} and 5^{th} models, we adopt a design using an absorbing material like color filter glass and an assembly based on a metallic thin film deposited on a silica substrate respectively.

3.2 Choice of the metal for the 5^{th} model

Preliminary studies have been realized to determine the choice of the metal for the 5^{th} model, see Figure 1. We have considered the chromatic extinction coefficient of different metals and a controlled thin film thickness of the used metal for different normalized radial distances r. Figure 1 is limited to the case $r = 0.324$ but results are quite similar for other radial distances and lead to the same conclusion. Using silver allows us to reach the closest amplitude apodization to that obtained with the 4^{th} model for all the wavelengths of our study. In the following, silver will be the metal considered for our simulations.

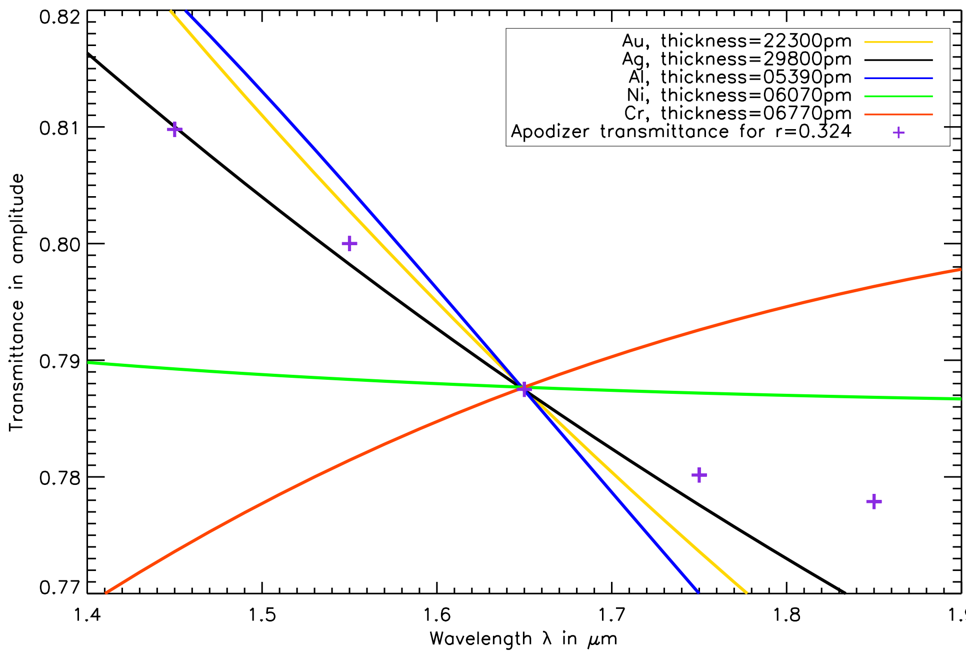

Fig. 1. Amplitude transmission values obtained with the assembly and the 4^{th} model as a function of the wavelength. Different metals with optimized thickness have been considered here for the assembly to obtain transmission values close to those of the 4^{th} model. These results are given for a normalized radial distance $r = 0.324$.

3.3 Results in the image plane

As a first approximation, we have considered the sum of the monochromatic images obtained at each wavelength of our study to simulate polychromatic images reached with each concept. Radial intensity profiles of the polychromatic images obtained in the presence or not of the DZPM have been calculated for all of our models, see Figure 2 left plot. The non coronagraphic profiles achieved with the different models are almost identical one to each other since the amplitude apodizations used for each concept present very similar transmission functions and throughput T of about 58%, see Figure 2 right plot. A summary of the performance for all of our models is given in Table 1. For each concept, we have calculated the intensity level reached at three different angular separations from the star: $2\,\lambda_0/D$, $5\,\lambda_0/D$ and $8\,\lambda_0/D$. Model 3 is our best possible design using an optimization of the apodizer chromaticity. The contrast at $5\,\lambda/D$ is improved by a factor 4-5 or more compared the gray apodizer design. Model 4 & 5, represent a practical implementation using color filter glass and a silver deposit for the apodization resp. Contrast performance is within a factor 2 of the theoretical optimal solution from model 3 (at $5\,\lambda/D$).

Table 1. Comparison of the contrast levels theoretically achieved with the different models of DZPM coronagraph.

Model	**Level at**		
	$2\,\lambda_0/D$	$5\,\lambda_0/D$	$8\,\lambda_0/D$
1	1.39×10^{-5}	5.33×10^{-7}	1.03×10^{-7}
2	1.11×10^{-5}	4.56×10^{-7}	9.59×10^{-8}
3	5.02×10^{-6}	1.10×10^{-7}	1.70×10^{-8}
4	5.55×10^{-6}	1.61×10^{-7}	2.79×10^{-8}
5	5.10×10^{-6}	1.96×10^{-7}	3.69×10^{-8}

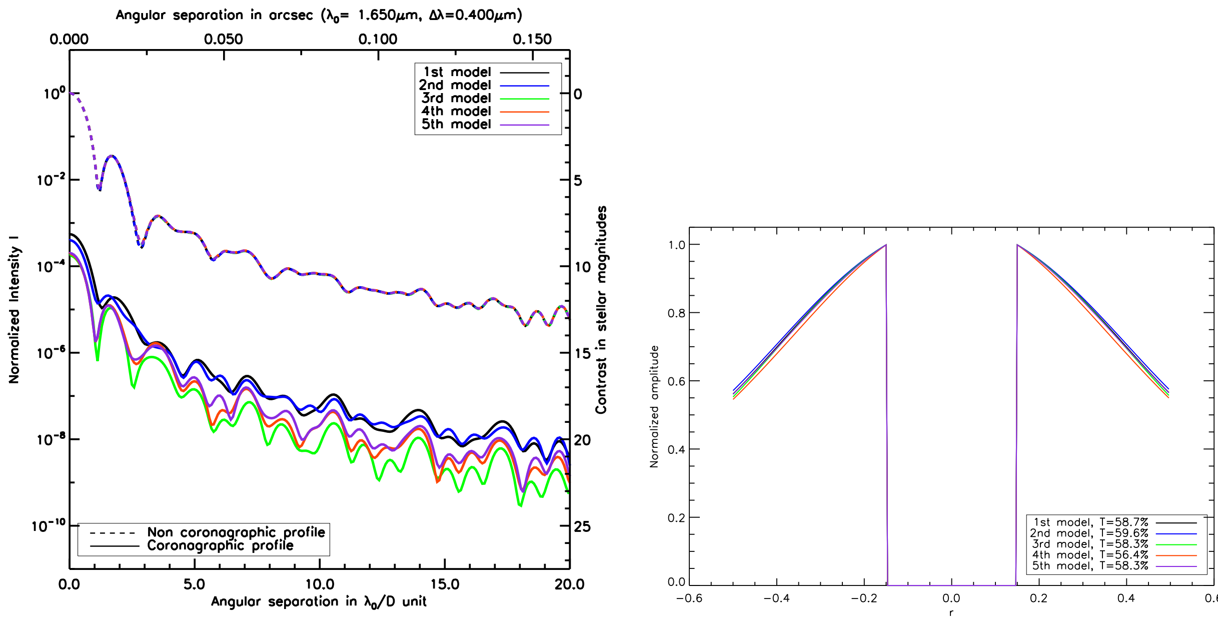

Fig. 2. Left: radial profiles of the images achieved in the presence or not of the DZPM for the different models of our study. **Right**: radial profiles of the amplitude apodization at $\lambda = 1.65\,\mu$m for each of our models. Values of the throughput T is given for each model.

4 Manufacturing aspects

In the following, we analyze manufacturing aspects related to the 5^{th} model. Concerning the phase masks, DZPM prototypes with good quality profiles have been manufactured by SILIOS Technologies. They will soon be tested in our laboratory in Marseilles. To manufacture the apodizer of the 5^{th} model and obtain the required amplitude transmission function for it, we consider the utilization of a typical silver ion exchange process (Findakly 1985) in a glass substrate through an aluminum mask which thickness gradually increases from outside the center of the substrate. Experiments are currently performed at the CCADET of UNAM. Finally, colored phase apodization is also used with the 5^{th} model and expressed as a radially symmetric aberration of the first order. This can be obtained physically by using a powerless lens doublet combined with a mask at the focus. The doublet characteristics are: an infinite focal length at λ_0, glasses with the same refractive index, the same Abbe number and very different partial dispersion.

5 Conclusion

In the context of high contrast imaging, the Dual Zone phase mask (DZPM) stellar coronagraph is a promising concept to remove starlight efficiently over a large spectral bandwidth. The focal plane mask, phase and amplitude apodizations constitute the characteristic elements of this coronagraph. The objective of this paper has consisted in reporting the last improvements made to optimize the performance of the DZPM coronagraph. We have replaced the grey by a colored apodization to increase the starlight attenuation within the search area of substellar mass companions. Afterwards, a physical model of this DZPM coronagraph with colored apodization, based on silver thin film deposited on a fused silica substrate, has been proposed. Encouraging performances have been reached numerically with this concept; some contrast levels of $5.10{\times}10^{-6}$ at $2\,\lambda_0/D$ and $1.96{\times}10^{-7}$ at $5\,\lambda_0/D$ can theoretically be achieved. This represents a mean gain in contrast of 1.23 mag with respect to the DZPM coronagraph using a grey apodizer and proposed by Soummer et al. (2003b). This result has been obtained considering a 25.4% spectral bandwidth (H-band case) and a centrally obstructed circular aperture (E-ELT case). Manufacturing aspects have also been analyzed here and prove to be very encouraging for the fabrication of the DZPM coronagraph.

These advanced studies are the prelude of experiments on the optical bench that we are currently mounting in our laboratory to test the DZPM coronagraph. Results are expected to be presented in a forthcoming paper.

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