Status of Development for the AIC and the FQPM

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ABSTRACT

This paper presents the development of the Achromatic Interfero-Coronagraph (AIC) and the Four-Quadrant Phase Mask coronagraph (FQPM). Both coronagraphs have been tested in the lab and on ground-based telescope.

INTRODUCTION

Until about 10 years ago, only the classical Lyot coronagraph was used as a tool for high dynamical range imaging. In 1996, a new type of coronagraph, the Achromatic-Interfero Coronagraph (AIC), was proposed (Gay & Rabbia 1996). In 1997, Roddier & Roddier proposed to use focal phase plate as coronagraph. One of the most prolific phase mask coronagraph is the Four Quadrant Phase Mask (FQPM) proposed by Rouan et al. in 2000. Both AIC and FQPM have been tested on ground-based telescope in combination with Adaptive Optics system. The purpose of this paper is to recall the main results of these two coronagraphs, emphasizing on the laboratory and scientific results of the FQPM.

Achromatic Interfero Coronagraph

The Achromatic Interfero Coronagraph (AIC, Gay & Rabbia 1996, Baudoz et al, 2000a) was the first new type of coronagraph to be tested on a ground-based telescope (1.5 m telescope at the Observatoire de Haute Provence) combined with an adaptive optic (AO) system (Baudoz et al. 2000b). The test performed in the near Infrared (K band) demonstrated the principle of AIC (see Figure 1). The performance of the coronagraph was a attenuation of the star of about 50 mostly limited by residual atmospheric turbulence not corrected by AO. A detection of a faint component (difference of magnitude =3.5) was proven at a distance of only 1/3 of the telescope resolution (λ/D). This is the only coronagraph able to detect at such close angular distance to the star. Another prototype of AIC was installed on the 3.6 m Canada France Hawaii Telescope but the complexity of the optical train necessary to fit the CFHT beam, the mechanical instability of the Cassegrain focus, and the modest number of corrected mode of the AO system prevented the AIC to reach a better performance than at OHP. A new AIC that is less sensitive to the optical path difference is under development (Gay et al., private communication).

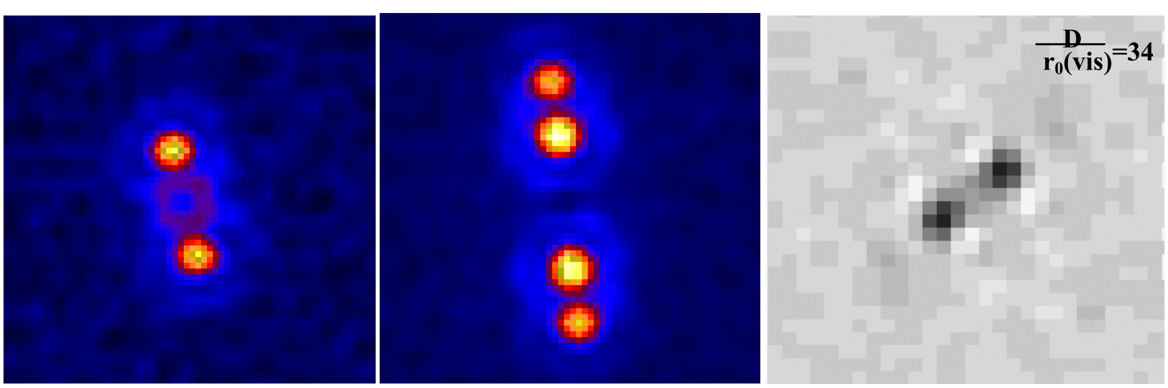


Figure 1: *Left: AIC image of a double star not centered on the coronagraph (low contrast between both star to show the effect of AIC). Middle: AIC image of the same double star centered on the coronagraph. Right: AIC image of a faint companion around a bright star. The difference of magnitude between the bright star and the faint component is 3.5 and the distance between the two star is only 1/3 of λ/D (see Baudoz et al. 2000b for more details).*

Four Quadrant Phase Mask Coronagraph

a. Visible

The first development and tests of the FQPM has been done in the visible range. Several techniques have been used to manufacture FQPM optimized for the visible wavelength. The simplest way to produce FQPM is to deposit an optical layer on a substrate of glass only on two opposite quadrants. The FQPM is then optimized for one wavelength. Riaud et al. 2003 have shown that contrast of 2.10^6 can be reached using a laser diode (wavelength adjustable between 630 and 640 nm, see Figure **2**). Several solutions have been studied to avoid the monochromaticity of a deposited layer. One of the solutions our group has implemented is the use of achromatic half-wave plates. Using 4 half-wave plates, 2 of them being rotating by 90° compared to the other is equivalent to get a FQPM achromatic (Mawet et al. 2006). The tests performed in the lab at visible wavelength have reached the performance (a contrast of 10^4 at 3 λ/D) expected from the theoretical point of view (see Figure **2**).

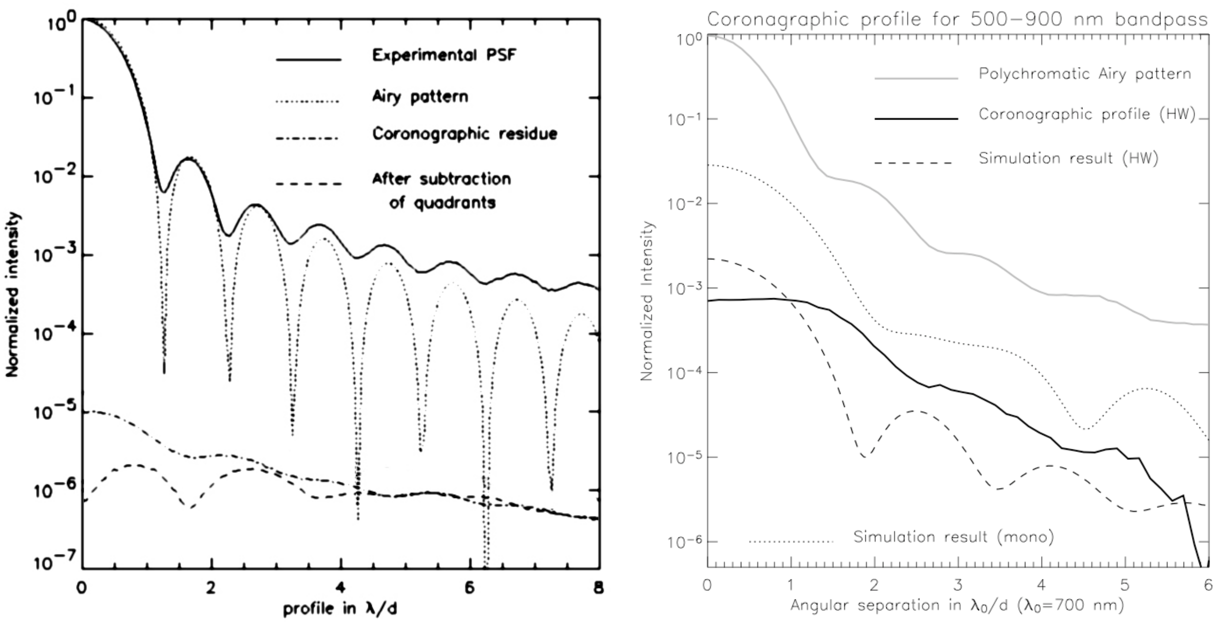
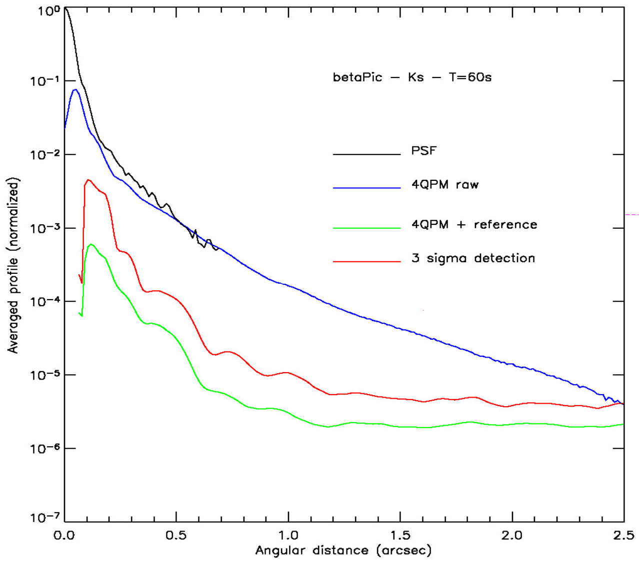


Figure 2: *Left: Laboratory tests of the FQPM in the visible and with monochromatic source (see Riaud et al. 2003 for more details). Right: Laboratory tests of achromatic FQPM with a 400 nm bandpass (see Mawet et al. 2006 for more details).*

b. Near-IR

While laboratory results in the near-IR reach the expected theoretical performance (Baudoz et al. 2004), the most interesting results in the near-IR are the scientific observation done on the VLT. Indeed, a FQPM has been installed inside the near-IR +AO camera NACO (Rousset et al. 2003) on UT4 at the VLT in 2003. Several scientific runs using this coronagraph have brought series of high dynamical range observation in different astrophysical areas. The tests performed on the sky have shown that a companion of a few 10^{-5} could be detected at 0.6″ (see Figure 3). Its high dynamical range combined with its small inner working angle enables it to reach information close to the star where no other instrument could observe at a given wavelength. This is the case for observation of the innermost part of the Beta Pictoris disk observed with the FQPM (Boccaletti et al. in preparation). This is also the case for the detection of the disk structure of the weak T Tauri star PDS 70 (Riaud et al. 2006). The FQPM also proved to be very useful for extragalactic observation because several structures that were never seen in the near-IR could be observed around NGC 1068 thanks to the FQPM (Gratadour et al. 2005, see Figure 4).



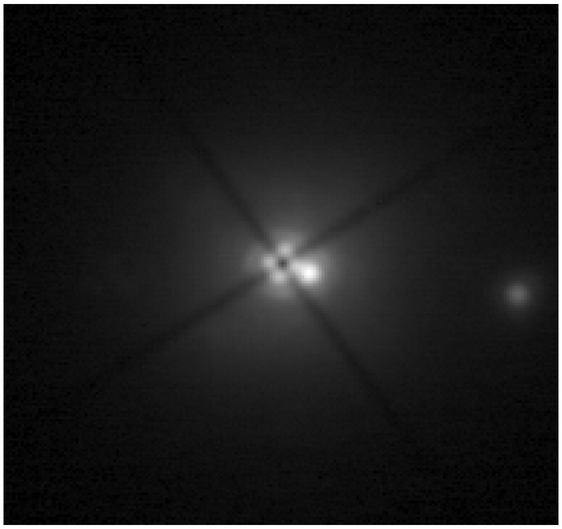


Figure 3: *Left: example of detection performance using the FQPM actually installed on VLT. The red curve shows the 3σ detection level (Boccaletti et al. in preparation). Right: Image of the visual triple star HIP 1306. The two faint components are respectively 1.6 and 3.5 magnitudes fainter than their star and located at distances of 0.13" and 1.0" (see Boccaletti et al. 2004)*

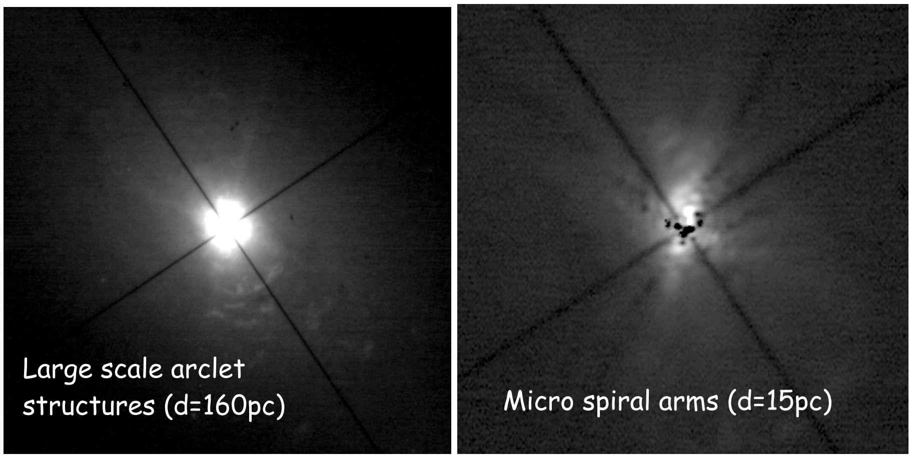


Figure 4: *The Active Galactic Nucleus NGC 1068 observed in Ks with FQPM on NACO. Left: FOV 11.7" where large scale arclet structure can be seen on the south side. Right: FOV 3.5" where we can see micro arms close to the center as well as aligned knots on the north side (see Gratadour et al. 2005 for more details).*

c. MID-IR

Our group is developing the three FQPM and the Lyot coronagraph that will take place in the Mid-IR Camera of the JWST (MIRI instrument). To validate the feasibility of such coronagraph, we manufactured coronagraph in the thermal infrared using different materials and fabrication techniques. We demonstrated that the behavior of the FQPM in the mid-IR and at very low temperature (12K) corresponds to the expected performance. The effective results of the FQPM in terms of contrast and attenuation (see Figure 5) are much better than what is specified for MIRI (Baudoz et al. 2006). In fact, the limitations from the James Webb Space Telescope (defocus, pupil shearing, jitter, aberrations, pupil geometry) are largely dominating over the intrinsic defects of the manufactured FQPM (see Figure 5). Thus, we can hope to reach the sensitivity estimated by simulations where the JWST limitations are taken into account. In that case, an Extrasolar Giant Planet orbiting at 10 AU around its parent star should be detected down to 400 K in one hour.

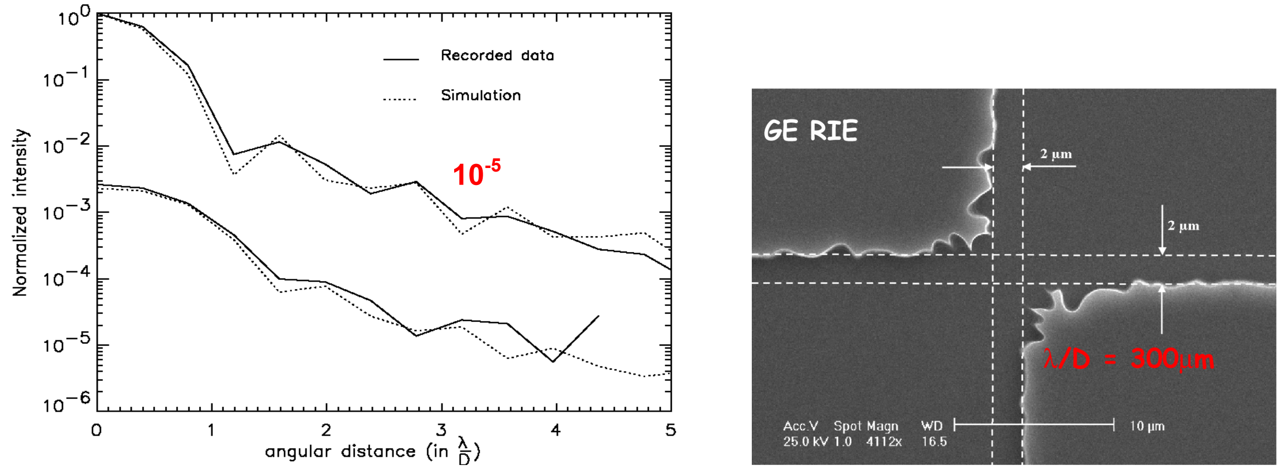


Figure 5: *Left: The solid lines show the radial profiles of the laboratory results with FQPM (lower curves) and without FQPM (upper curves). Dotted lines show the radial profiles calculated with the numerical code simulating the actual bench. Right: Electron microscope image of one of the FQPM manufactured out of Ge and using Reactive Ion-etching. The effect of the finite size of the transition between quadrants is negligible compared to other telescope limitations.*

CONCLUSIONS

The development of prototype of FQPM around the projects JWST and SPHERE has enabled the manufacturing of a number of different type of FQPM. The FQPM is the only coronagraph, aside of the classical Lyot coronagraph, that has been manufactured and validated in the laboratory and on the sky at so many spectral bands. The visible development of the FQPM shown that high rejection rate could be reached in monochromatic light. Achromatic FQPM were also tested in the visible using half-wave plates. In the mid-IR, the three FQPM that will take place in MIRI/JWST will mark a stone toward other coronagraph combined with space telescope. In the near-IR, the FQPM that has been installed on the VLT produced very promising results. A new system will be implemented at the VLT by Feb. 2007 and that will be combined to the Simultaneous Differential Imager (Biller et al. 2005). Even though the performance will be higher, it will still be limited by the quality of the correction of NAOS, the adaptive optics actually mounted on the VLT. To reach higher dynamical range, we are involved in the development of a 2nd generation ground-based instrument at the VLT. The instrument, called SPHERE (Beuzit et al. 2006), is probably the first high contrast imaging system to be fully optimized for the direct detection and characterization of exoplanets. Unlike all the coronagraphs that have been put on the sky before (AIC, FQPM), the design of this instrument is made altogether with the development and design of the coronagraph. Although TPF-C has a much challenging objective than SPHERE, this project could benefit of the many developments we made on the prototyping of coronagraphs and on the experience we gain at designing an instrument altogether with a coronagraph (system analysis, end-to-end simulation, …).

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