

An off-axis Four-Quadrant Phase Mask (FQPM) coronagraph for Palomar: high-contrast near bright stars imager

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ABSTRACT

Direct detection of planets around nearby stars requires the development of high-contrast imaging techniques because of the high difference between their respective fluxes. This led us to test a new coronagraphic approach based on the use of phase mask instead of dark occulting ones. Combined with high-level wavefront correction on an unobscured off-axis section of a large telescope, this method allows imaging very close to the star. Calculations indicate that for a given ground-based on-axis telescope, use of such an off-axis coronagraph provides a near-neighbor detection capability superior to that of a traditional coronagraph utilizing the full telescope aperture.

Setting up a laboratory experiment working in near infrared allowed us to demonstrate the principle of the method, and a rejection of 2000:1 has already been achieved. Deploying an instrument on an existing ground-based telescope is the second step to test the feasibility of near-neighbor science with our new off-axis approach. We thus developed a FQPM-based coronagraph to be installed at the Palomar observatory, using existing facilities as much as possible for cheap and rapid demonstration. The off-axis design addresses all the requirements that have to be fulfilled for close imaging: a coronagraph to improve the companion/star flux ratio, very good wavefront correction for scatter reduction through a high-level adaptive optics system in the off-axis aperture, and an unobscured aperture. We present the laboratory and on-sky experiments design as well as results obtained so far.

Keywords: Coronagraphy, phase mask, Terrestrial Planet Finder.

1. Introduction

The exciting scientific goal of exoplanet detection imposes the development of new measurement techniques to meet the requirements of missions such as Terrestrial Planet Finder (TPF) or Eclipse. Imaging a faint companion close to a much brighter star requires being capable of observing with high contrast ratio at small inner working distance (IWD). Practical issues are limiting the coronagraphs based on the classical "Lyot" techniques (use of an opaque disk to block the on-axis light): large IWD, diffracted and scattered light. Different novel approaches are thus studied to overcome these limitations.

This led us to develop a novel high-contrast coronagraph to allow for detection in the very-close region of a bright star. This coronagraphic method uses a Four-Quadrant Phase Mask in place of the opaque disk of a classical coronagraph, and uses it with an off-axis section of the telescope to ensure high rejection. The advantages of this new approach are the capability of detecting companions very close to the parent star, together with a geometrical design that is wavelength independent.

2. FQPM principle

Figure 1 presents the principle of the coronagraph using a Four Quadrant Phase Mask. The general setup is identical to the one of a classical Lyot coronagraph, but here the opaque occulting mask has been replaced by a transparent phase-mask providing a π phase shift on chosen parts of the incoming electric field.

The circular unobscured pupil of the telescope (a) gives an Airy disk (b) on a focal plane, which is focused at the exact crosshair of the mask (c). The mask is composed of four quadrants, two of them placed on a diagonal being phase-shifted by π compared to the two other ones. In the next pupil plane (d), instead of a uniformly lighted circular disk, we get a flux repartition where all the light is on the area surrounding the pupil, which is now visible as a dark disk. A Lyot

stop (e), slightly smaller than the pupil size allows then blocking all the light (the intensity scales for images d and e are different for better clarity). When focusing the electric field obtained after the Lyot stop, one gets an image (f) where the flux in the center has been attenuated by a huge factor.

This attenuation occurs only for an object perfectly centered on the mask crosshair. Any off-axis object or structure in the nearby region of a star centered on the mask will thus not suffer this effect and remain visible. One advantage of this concept of phase mask is its symmetrical and achromatic design, compared to circular phase masks where the size of the mask has to be adapted to each wavelength. This concept also allows measurements very close to the parent star (one Airy radius or lower), where classical amplitude masks have a dark region of a few (4 to 10) Airy radius.

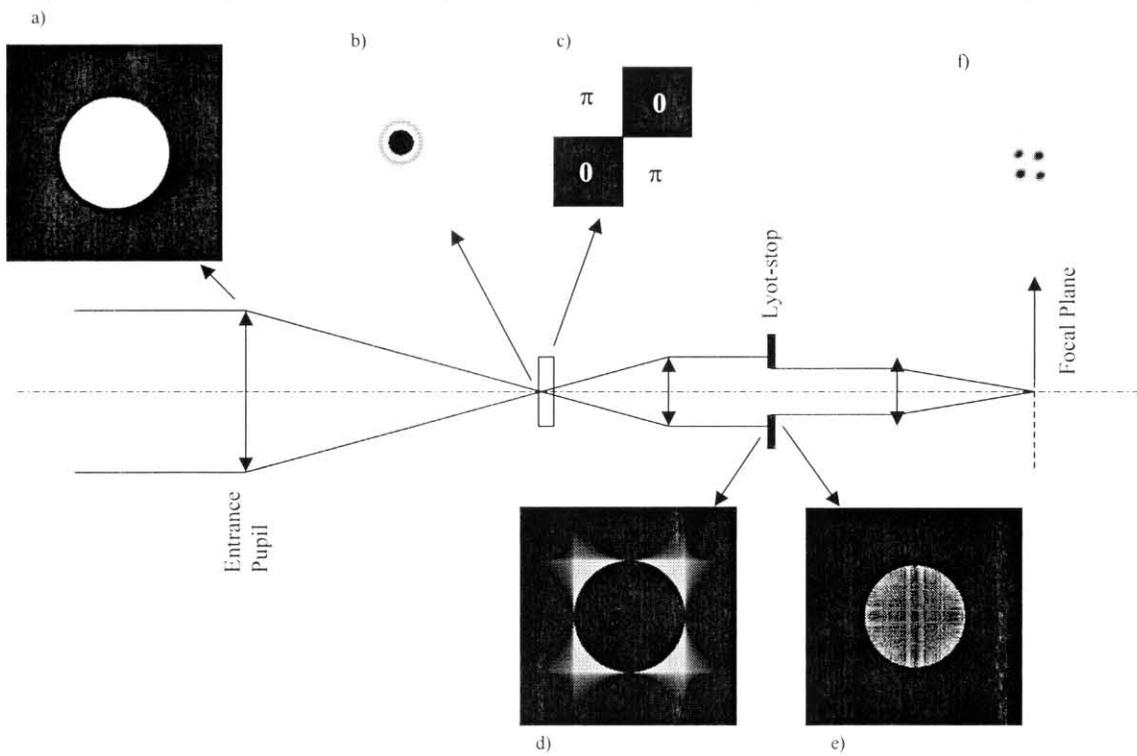


Figure 1. Principle of coronagraphy with a Four Quadrant Phase Mask.

3. Mask design

Four Quadrant Phase Mask technique has been tested by Riaud et al., but this promising solution for coronagraphy still needs technological development and manufacturing and experimental testing of these devices bring very useful informations and experience. When starting designing our devices some questions arise first:

- Should the design be first adapted to monochromatic or broadband operation?
- What precision do we need on the design?
- Accordingly what manufacturing technology is the most appropriate?

The choices that have been made, and are described in the following, result from our answer to these questions and our desire to get a rapid first experience in operating this type of devices.

As we wanted to use as much as possible existing facilities for on-sky demonstration of the FQPM, the Palomar 200 inches telescope has been chosen to take advantage of the already working adaptive optics system (this choice is described later, see 5.1), leading thus to near-IR and especially the K atmospheric band for the operating wavelength. For broadband operation, we need the phase shift to be exactly π for all the used wavelength at the same time. Such masks can be obtained by multilayer coatings (Riaud et al II) or newly proposed Zero Order Gratings (Mawet et al).

Both of these techniques require quite sophisticated designs and fabrication process. Trying these solutions first implied heavy work on the mask itself, which might not be compatible with a fast on-sky test and validation of the method. A single-layer deposition, i.e. “monochromatic”, is a much easier process as it relies on existing lithography and layer deposition processes. The theoretical performance of such a mask (see Riaud et al. III) is a rejection factor of 45000:1 for a 1% bandwidth (Brackett gamma filter) and of 240:1 for a 15% bandwidth (K or K short filters). As other factors, such as residual tip-tilt after the AO system, might be limiting the performances on ground telescopes to lower rejections, we made the choice of the more straightforward solution of depositing a single layer of dielectric on a glass substrate to create the phase shift.

The extra deposited layer is on only two quadrants of the mask to have them π -phase-shifted compared to the two other ones. The thickness of the extra layer is given by $\Delta e = (\lambda/2)/(n-1)$, with λ the operating wavelength and n the refractive index of the deposited material. For typical material used in deposition processes, this leads to Δe of the order of λ . The size of the quadrants has to be many radius of the diffraction limit of the focusing optics to avoid side effects. For typical telescope parameters, the quadrants size has to be a few millimeters. We also wanted the edges of the quadrants to be sharp to some fraction of the Airy spot. The output of the Palomar Adaptive Optics System (PALAO) is a $f/16$ beam, so at $\lambda = 2.2\mu\text{m}$, the spot radius is about $35\mu\text{m}$. With all the preceding taken into account, the following technological choice have been made:

- Use standard photolithography which has a resolution of $1\text{-}2\mu\text{m}$ on the fabrication,
- Thermal deposition of SiO which is easy to deposit and has an index of about 1.84 at $2.2\mu\text{m}$ (higher index means thinner layer to deposit),
- Choice of a high index glass to try to match as much as possible the SiO index and limit internal reflections inside the mask.

The mask fabrication design is presented on Figure 2 (left). Our masks have been realized at the Micro-Devices Laboratory (MDL) at JPL. On a 2mm thick glass substrate, a SiO base layer is deposited over the entire bare substrate. This first layer allows keep balanced reflection coefficients between all the quadrants. An extra layer of SiO is then deposited on two of the quadrants using standard UV photolithographic masking techniques.

Figure 2 right shows an example of a mask realized by this process. On the top picture, one can see our coin size masks where the extra layer quadrants are visible (squares with a different color). Actually this device offers four vertexes, i.e. four FQPM, where we can measure the extinction allowing thus testing the homogeneity of the deposition process. The second picture is a microscope image showing the crosshair between the quadrants. Microscope inspection of the mask allows checking the quality of the fabrication. The obtained film quality is high despite the fact that the deposited layer is rather thick, and the edges are straight. A vertex gap of about $1\text{-}2\mu\text{m}$ can be seen and the edges are out of place by about $1\mu\text{m}$, but modeling predicts that this is still compatible with our 1000:1 extinction goal. Electron-beam lithography, also available at MDL facility, can deliver resolution in defined features that is several orders of magnitude finer than that achieved with optical photolithography, giving us a possibility of correcting the vertex gap and edges shift in the future if needed.

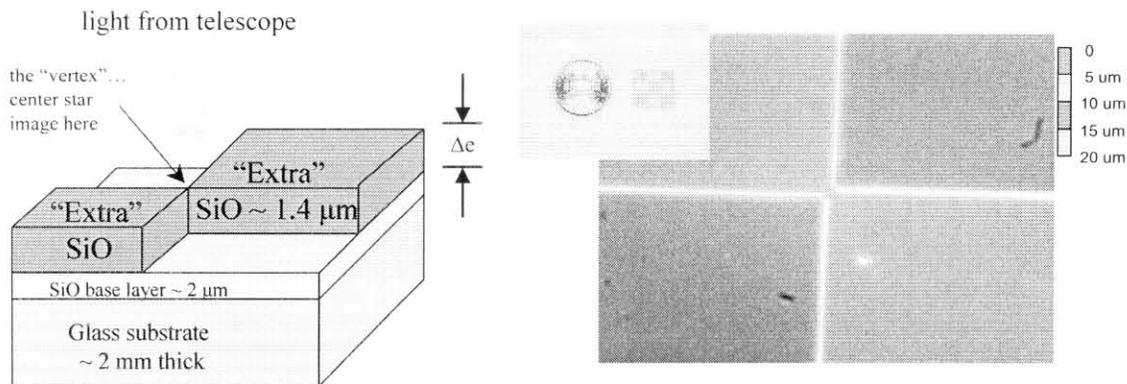


Figure 2. Realization of the FQPM: scheme of the deposited layers (left), and images of a fabricated FQPM (right).

4. Laboratory experiment and results

4.1. Laboratory experiment setup

In order to first demonstrate the capabilities of the four-quadrant phase mask coronagraph for star light extinction, we have developed a laboratory breadboard. The goal was to be able to test the devices with a setup close to the one envisioned for the on-sky experiment to be conducted on Palomar. The relatively short wavelength range chosen here has allowed the rapid development of a breadboard based on optics used in transmission.

An IR single-mode fiber combined to a lens allows simulating the star. A diaphragm is then used as the entrance pupil, and the collimated beam is focused on the crosshair of the FQPM. The ratio of the focal length used for focusing on the FQPM to the beam size is the same than for the on-sky experiment. However, the beam size being set by a diaphragm, its size can be varied if one wants to test the influence of this parameter. In the same way, the Lyot stop, used to block the light that is diffracted outside the pupil by the FQPM, has a variable size to find the optimal solution: blocking the maximal amount of the on-axis star light without reducing too much the pupil size to keep a good signal to noise ratio for the companion. The entrance pupil and the Lyot stop are conjugated planes through our optical setup. Different filters can be inserted on the optical beam, allowing testing the performances with varying central wavelength and wavelength range.

The FQPM holder allows fine translations to adjust it perfectly at the focal point of the optics. A rotation stage has also been implemented for fine-tuning of the phase-shift to the used wavelength range, by increasing this way the thickness of SiO through which the beam travels.

A LN₂ cooled IR camera combined with an adjustable imaging system allows acquiring both focal plane and pupil plane images. The pupil-imaging mode also allows to image at the same time the pupil and the Lyot stop to check their precise relative centering.

4.2. Laboratory results

First devices have been tested on the breadboard. The goal was there to obtain first results of nulling, to test the coronagraph concept, and to get information for accurate tuning of the manufacturing process to the chosen wavelength range.

Extinction ratios with our devices are presented on Figure 3. The SiO layer on this device has a thickness of about 1385nm, corresponding to a first attempt to get the desired π -phase shift, based on refractive index assumption from values for SiO bulk material. First measurements with the FQPM placed perpendicular to the beam (normal use of the device) have led to the extinction of the flux by a factor of 20 on the central pixel of the image. Measuring the nulling ratio for three filters with different central wavelength has led to increasing results for the shortest wavelength, clearly indicating then that the thickness of the layer was too small. In order to determine the correction factor to apply for the next device, and thus to get an idea of the refractive index difference between bulk material and deposited layer, a rotation stage was added to the FQPM holder. Indeed, tilting the device allowed increasing the width of SiO the light goes through. The rotation angle leading to the best results gave the amount by which the thickness has to be increased. An extinction ratio of **2260:1** (Figure 3 left) has thus been obtained for an increase of the thickness by 14%. The tilt angle has been optimized for the target wavelength of 2.168 μm . Using at that point a filter with a shorter central wavelength did not lead anymore to better nulling results showing that the thickness has been tuned.

Tilting the device has proven to be a good method for fine-tuning of the FQPM to the wavelength range and to determine the correction to apply to the manufacturing process. New devices have therefore been manufactured, using the new thickness goal derived from the tuning method. Figure 3 right presents the extinction ratio versus tilting angle for one of our most recent mask. The correct thickness value has been almost obtained at that time, the remaining uncertainty resulting from the thickness measurement during deposition process. The lower maximum value for the best tuning obtained here is due to a small gap that appeared at the junction between the quadrants, leaving some light going through the mask without any phase shift effect, and therefore without being canceled. But this effect can be easily corrected for future masks.

Figure 4 top shows images obtained on the camera with the FQPM on and off in different configurations. Two different filters have been used here: a Brackett gamma one (left), $\lambda_0 = 2.168\mu\text{m}$ and $\Delta\lambda = 19 \text{ nm}$, and one with a wider range

(right), $\lambda_0 = 2.1\mu\text{m}$ and $\Delta\lambda = 50\text{ nm}$. On every image, three cases are presented: FQPM out of the beam (used for calibration), FQPM centered on the axis but without the Lyot stop in place, and FQPM with a Lyot stop equal to 90% of the pupil size. The extinction effect of the phase mask is clearly visible here, with almost no light left (at our detection level) in the best case (Brackett gamma with Lyot stop).

The capability of imaging the pupil has also been implemented in order to be able to compare the experimental results to the simulations. Images have thus been acquired in different configurations: FQPM tilted or not, with and without the Lyot stop, and for different filters. The obtained images (see Figure 4) did present the same shape as the one predicted by the numerical simulations (see Figure 1).

The effect of a phase-shift of not exactly π is here to keep more light inside the pupil, as shown by the results with the FQPM perpendicular to the beam or with the FQPM tilted but used with a different central wavelength. With a short passband filter and the FQPM optimized to work at its center wavelength, almost all the light is sent outside of the pupil and a Lyot stop with a size equal to 90% of the pupil diameter allowed getting rid of this flux (bottom left case). At that level, the remaining flux inside the pupil is only hardly detectable, the number of photons being very small as confirmed by the 2000 level nulling measured on the focal plane images.

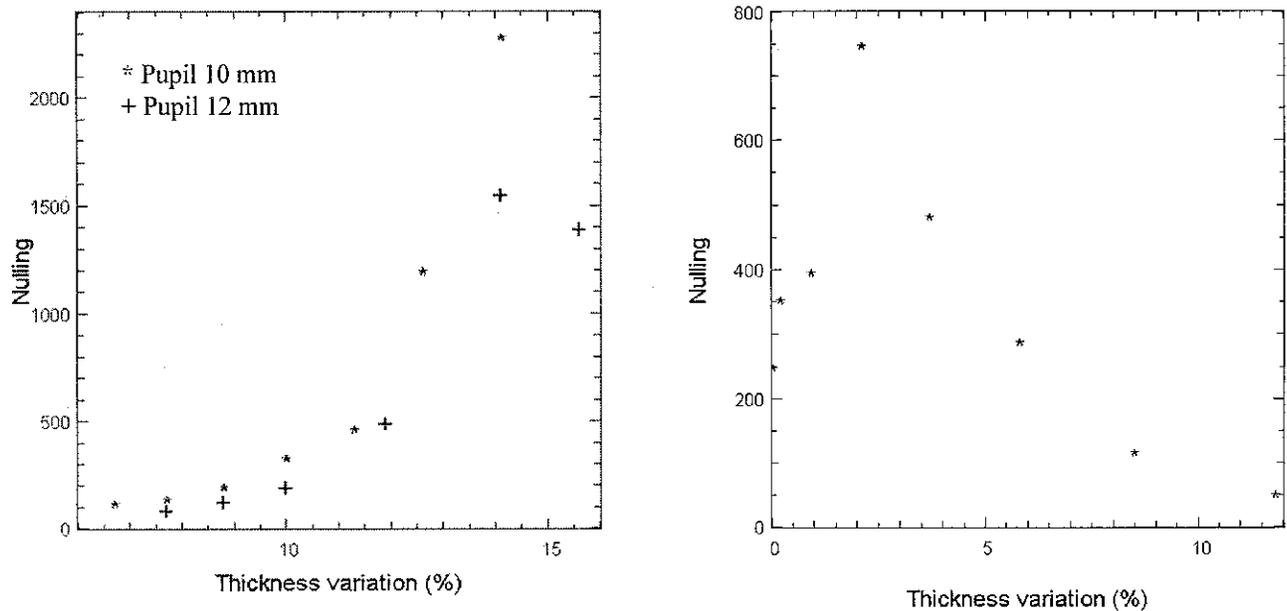


Figure 3. Extinction results with FQPM on the laboratory testbed. Thickness tuning by tilting the device is used to find the best extinction.

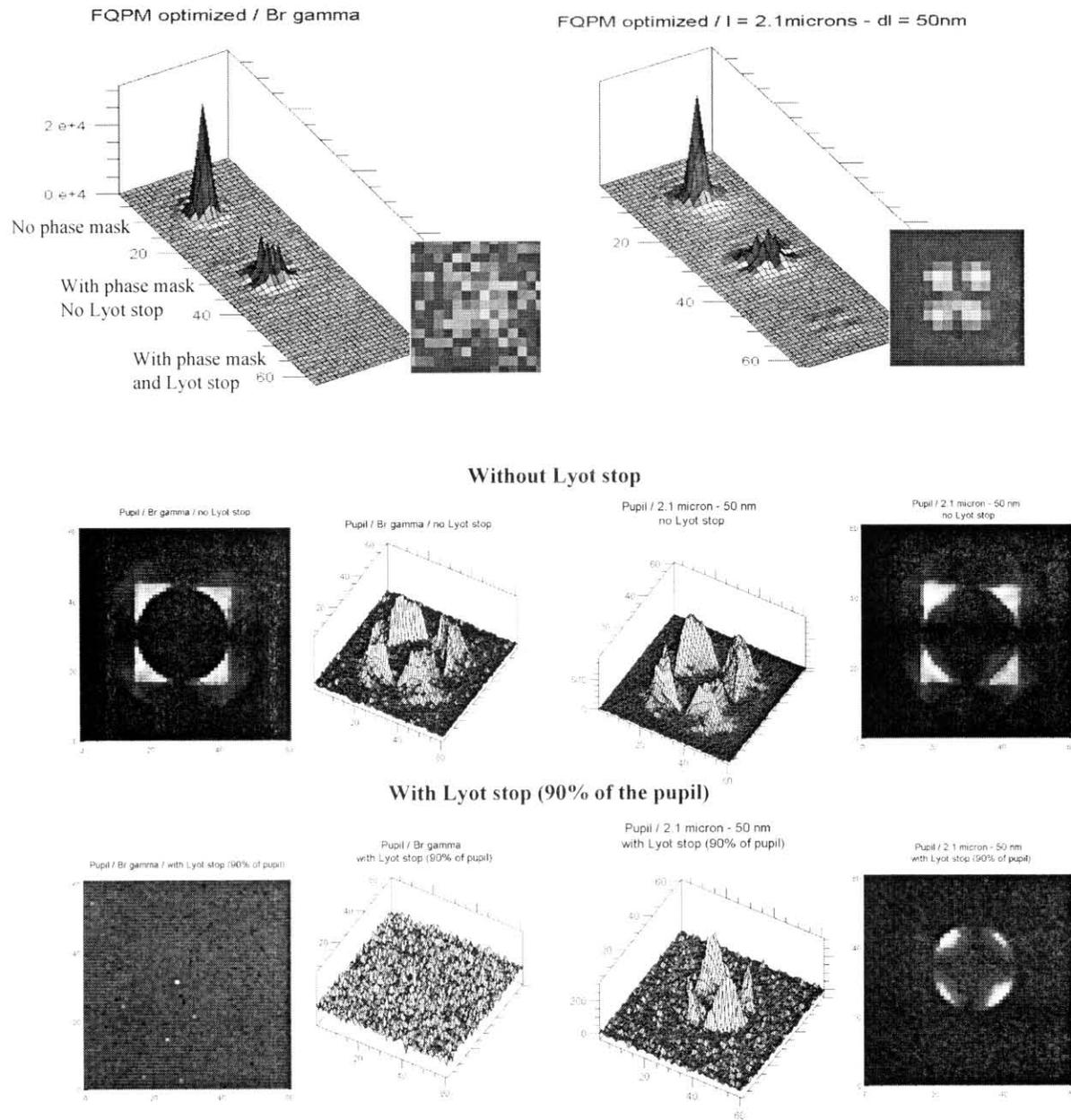


Figure 4. Focal plane (top) and Pupil plane (bottom) images obtained with a FQPM on the laboratory testbed.

5. On-sky instrument and measurements

5.1. On-sky instrument design

Four Quadrant Phase Masks can in principle achieve perfect extinction of an on-axis source for a perfectly circular aperture. In the real world, the performances can be highly degraded by beam obstruction like secondary mirror or spider legs. The perfect light cancellation will also occur if the incoming wavefront is perfectly plan. Any residual wavefront distortion, coming from both optical elements before the FQPM and atmospheric turbulence, will also lead to a decrease of the maximum achievable extinction.

We took these facts into account when designing our ground demonstrator instrument. First, an off-axis configuration of the telescope allows accessing a non-obscured circular pupil. Second, an adaptive optics system (AO) with a high level of correction is required to reduce as much as possible residual wavefront errors. These two points led to the choice of the 5.1m telescope of the Palomar Observatory. The large size of the primary mirror allows using an off-axis part of it with a diameter of still 1.5m, keeping therefore a good angular resolution. The already existing high performance AO on this telescope gives an answer to the second point. Figure 5 presents the setup of the on-sky instrument. Only a few optical elements have to be added to the already existing facilities. A subaperture reimager allows feeding the AO system with an unobscured pupil, the 1.5m part of the primary being scaled to the full aperture like dimension. One can thus benefit of an AO system designed for a 5.1m telescope on a 1.5m and expect a very high Strehl ratio. One FQPM has been added in a focal plane of the camera after the AO.

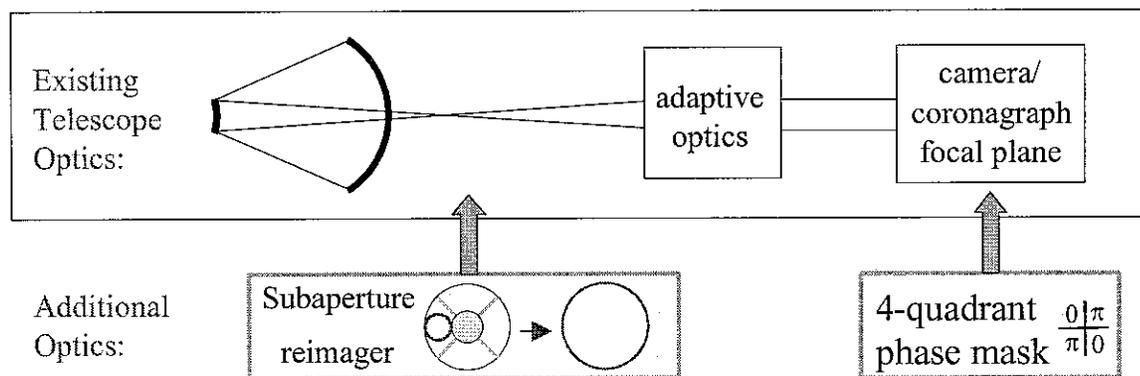


Figure 5. Schematic description of the instrument installed on the Palomar 200 inches telescope.

In order to check the improvement of this approach, we ran numerical simulations of the different cases that can be considered. Figure 6 shows the results of these simulations, with typical turbulence parameters at Mount Palomar and with the specifications of the PALAO system. For each angular position θ_i , we have plotted the ratio of the flux at that position in the Point Spread Function (PSF) of an on-axis star to the maximum of the PSF of a companion of the same magnitude with an angular separation from the star equal to θ_i . The following configurations have been tested: FQPM and classical Lyot coronagraph, for the full 5.1m aperture of the telescope with central obscuration and for a 1.5m unobscured off-axis subaperture. The size of the occulting disk for the Lyot cases has been chosen to be four times the diameter of the Airy disk. On the figure are also represented the diffraction limits of 1.5m and 5.1m telescopes, and the Lyot coronagraph blind zone corresponding to $4*\lambda/D$. Several results are clearly put into evidence by these curves:

1. On the full aperture with central obscuration, the FQPM does not give much better results than the Lyot coronagraph.
2. For an off-axis unobscured subaperture, the gain brought by the FQPM compared to the Lyot case is important and detection is possible with a very good contrast very close to the diffraction limit of the subaperture. Companion detection is even possible at angular separation lower than the diffraction limit, as the companion also suffers some extinction but at a lower level than the on-axis star.
3. The subaperture FQPM gives better results than any of the other cases, even the full aperture ones, up to about 1.6 arcsec. Better contrasts are obtained for the region of interest, i.e. in the close proximity of the parent star.

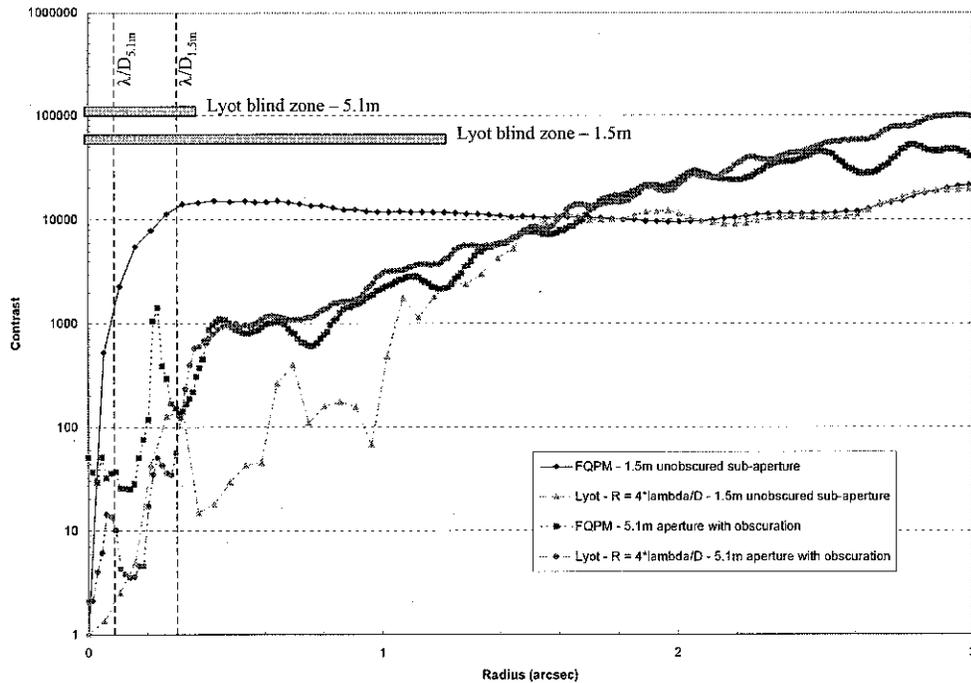


Figure 6. Simulation of performances of FQPM and Lyot coronagraph, in different configurations of the 200 inches Palomar telescope.

5.2. First tests with internal light source

Figure 7 presents the first images obtained with a FQPM installed in the PHARO camera, and using the PALAO system. This allowed us testing the capabilities of the system to work with the new mask. Mechanical arrangement of the camera only allows using the mask perpendicular to the beam (no tilt-tuning), so we are not here at the best working point of this mask. The left image has been obtained with the light focused on the crosshair of the FQPM. The right image, used for calibration of the extinction, was obtained with light going simply through one quadrant, i.e. without any differential phase shift effect. Each image is the mean of 50 consecutives images taken with the camera in a Brackett gamma filter ($\lambda_0 = 2168\text{nm}$, $\Delta\lambda = 30\text{nm}$). The center plot shows cuts along the line of the images. The extinction obtained on the central pixel of the image is 143:1. Extinction ratio of the order of 100:1 have also been obtained with a K filter ($\lambda_0 = 2196\text{nm}$, $\Delta\lambda = 336\text{nm}$), in the same conditions.

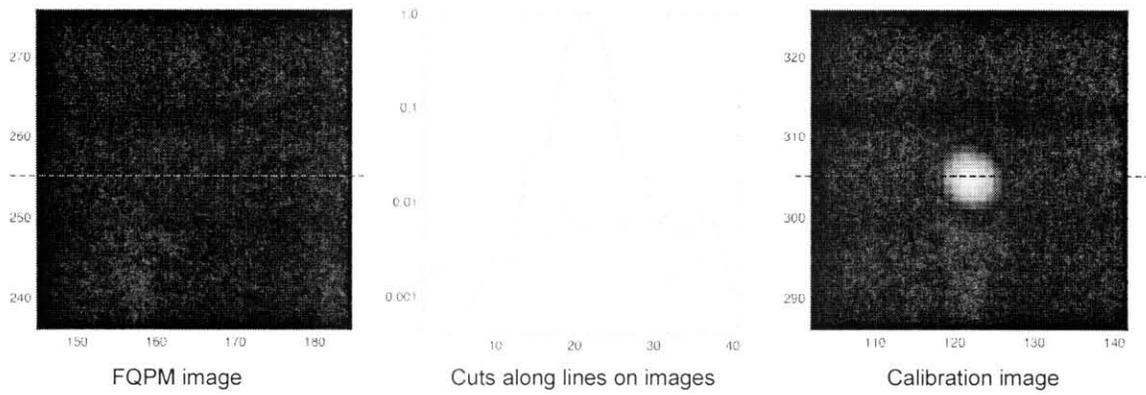


Figure 7. First images of the FQPM with the PALAO system, with an internal source. A Brackett gamma filter ($\lambda_0 = 2168\text{nm}$, $\Delta\lambda = 30\text{nm}$) has been used here. The extinction on the center of the Airy disk is 143:1.

5.3. On-sky results

(To be completed after measurements on telescope mid-June.)

6. Conclusions and perspectives

(To be completed after measurements on telescope mid-June.)