

Use of the LIGA process for the production of pyramid wavefront sensors for adaptive optics in astronomy.

M. Ghigo¹, E. Diolaiti², F. Pérennès³, R. Ragazzoni⁴

- 1) INAF-Osservatorio Astronomico di Brera, via E. Bianchi 46, I-23807 Merate, Italy
- 2) Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
- 3) Sincrotrone Trieste, S.S. 14 Km 163,5 in Area Science Park, 34012 Basovizza - Trieste, Italy
- 4) INAF-Osservatorio Astronomico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

ABSTRACT

Nowadays many groups in the world are developing adaptive optics (AO) systems for the real time correction of the aberrations introduced by the turbulence of the atmosphere in the field of view of the astronomical telescopes. The Shack-Hartmann wavefront sensor has been often used for the detection of the optical aberrations but over the past few years an alternative wavefront sensor with pyramidal shape has been developed. The properties of this sensor have been extensively investigated both theoretically and experimentally (for example in the AO module of the Italian "Telescopio Nazionale Galileo"). Important features of this pyramidal sensor are that it offers the advantage of either variable gain against the wavefront deformation and tunable sampling of the telescope pupil. These features translate into a considerable gain in the limiting magnitude of the reference star when compared to the classical Shack-Hartmann sensor. The manufacturing of single pyramid prototypes has been initially accomplished using the classical figuring and polishing technique, a time consuming procedure. Since the multi-conjugated adaptive optics (MCAO) that are under study, foresee the use of a large number of identical pyramids, it has been investigated and developed an alternative method for the mass production of this optical component. Using a lithography-dedicated beamline already operating at the ELETTRA Synchrotron in Trieste, a manufacturing technique has been implemented that uses a process named LIGA (Lithography, electroplating (German: Galvanik) and molding (German: Abformung)). With this method it is possible to create a master pyramid made of a polymeric material and having the characteristics requested. The master is then used to create a metallic mold by means of electroforming. In the end the mold is used for the molding of a number of identical pyramids made in a suitable amorphous optical polymer, using the technique of the hot embossing. This technique produces identical copies of the master pyramid, a desirable feature for the MCAO systems, and once the mold has been manufactured, permits a very fast production of large numbers of identical pyramids. In this paper we present the results obtained with this manufacturing process.

Keywords: Adaptive Optics, DXRL, LIGA, Pyramid Wavefront Sensor

1. INTRODUCTION

The pyramidal wavefront sensor (PWFS) is a refractive optical component that in the last few years has been largely investigated for its application in the present and future Adaptive Optics (AO) for Astronomy. The working principle and its characteristics have been extensively described elsewhere^{1,2,3}. This pyramidal optical component is used in an AO as an image splitter that executes a knife-edge optical test along the x and y axis at once. A suitable reference star (i.e.: a natural star or a laser guide star) is focused on its tip and its light is split into four images of the entrance pupil of the telescope that are imaged onto a fast CCD using relay lenses. These dynamic images contain information about the optical aberrations introduced by the atmosphere in the field of view of the telescope and can be used to drive an adaptive or deformable mirror to compensate the errors and correct the incoming wavefront permitting the telescope to reach higher resolutions not limited from the seeing. It is well known that the corrected field of view for a "classical" adaptive optic is quite small (isoplanatic angle) and amounting to few tenths of arcsec. To overcome this limitation recently Multi-Conjugate Adaptive Optics (MCAO) systems have been proposed that are able to correct a larger field of view to image large celestial objects and to use telescope time more efficiently. They can also achieve a more uniform

correction over the field of view, improving data quality and increasing the sky coverage. Such a correction systems requires the production of several identical PWFS. The classical manufacturing method used for the production of the pyramids is the polishing and figuring of a suitable glass sample⁴, for example BK7. This technique so far has been unable to provide a repeatable and time efficient mean of fabrication of the identical pyramids that are necessary for the MCAO systems. A new method⁵ based on the Deep X-ray Lithography (DXRL) was shown to allow optical surfaces of good quality and very precise and repeatable control of the pyramid angles. The method has been recently extended to a full LIGA⁶ process to permit the production of several identical PWFS. The LIGA process is a microfabrication procedure that use the collimated X-rays emitted from a synchrotron to irradiate through a mask a polymer, typically PMMA (Plexiglass). The irradiated polymer change its molecular weight in the areas not protected by the mask and became dissolvable in a suitable developer. In this way it is possible to create a master having a very precise shape. The master is then used to create a metal mold that is used during the replica process of the component to be produced. In this way many identical components can be produced starting from the master. The materials that can be used for the production of the finished components in the present application are optical plastics that can be molded using the injection molding or hot embossing⁷. In this article we describe the status of development of this technique and its application for the fabrication of 4 pyramids for the Italian telescope (Telescopio Nazionale Galileo). Under development are also 8 pyramids for the Multiconiugate Adaptive-optics Demonstrator (MAD) for the Very Large Telescope (VLT) of the European Southern Observatory.

2. FABRICATION PROCESS (PART 1)

The first step of the pyramids fabrication process use a lithographic technique named Deep X-Ray Lithography (DXRL) to produce a master pyramid and it is schematically described in Fig. 1. In Fig. 2 is visible a close-up of the special support that has been realized to implement the concept.

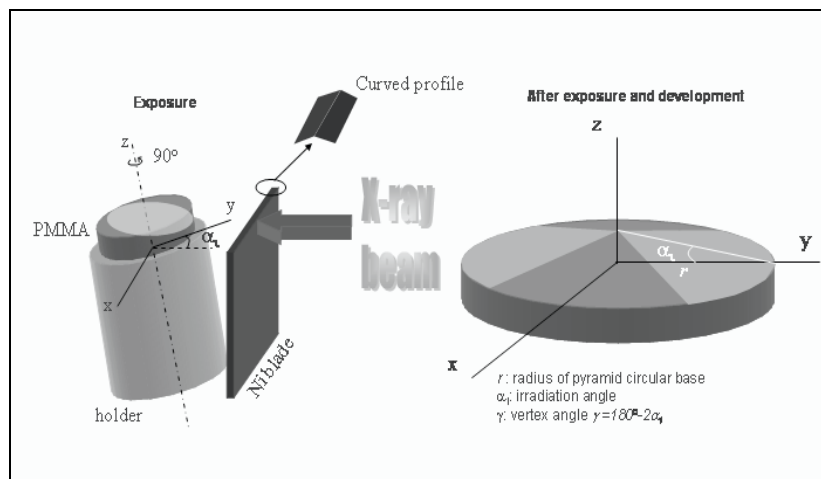


Fig. 1 - Production of the master pyramid

The support is attached to the scanning frame of the synchrotron beamline and includes two motor driven rotating tables that are used respectively to give the desired inclination α_i of the PMMA cylinder versus the beam propagation direction, and to perform the 90° rotation around the z axis after each pyramid face exposure. A pre-cut PMMA cylinder having diameter equal to the pyramid to be produced is placed onto an holder. A vacuum system is used to block the PMMA cylinder in flat contact with its base during the whole exposition. The starting reference horizontal position of the holder (corresponding to $\alpha_i=0$) is found using a precise bubble leveler. The desired irradiation angle is then set using the vertical rotating table. With the PMMA cylinder placed on the holder, a nickel blade with a superpolished edge is positioned as close as possible and slightly under the top surface of the PMMA. Then the whole assembly is scanned vertically up and down into the X-ray beam. The nickel blade will shield the lower part of the PMMA from the X-rays. Instead the unprotected upper part will receive the radiation. When the required dose is deposited at a depth equal to the cylinder radius r the first pyramid face is created in the material due to the changes in molecular weight of the PMMA

induced from the X-rays. The operation is repeated three more times rotating the PMMA block of 90° around the z-axis after each face exposure. After development in a suitable chemical bath, the irradiated zones of the PMMA cylinder above the 4 faces are etched (dissolved) away leaving a pyramid with a vertex angle of $\gamma=180^\circ-2\alpha_i$ and a tip at the center of the circular base. Typically we used the GG developer, a developing bath that is the most used for the PMMA. The microroughness of the pyramid faces is strictly dependant from the knife-edge surface roughness. Therefore a 1 mm thick nickel blade was hand-polished on its edge with extreme care until a microroughness of 2-3 nm rms was achieved. Moreover the nickel beam cutting-edge was given a curved profile to ease the alignment with the incoming X-rays.

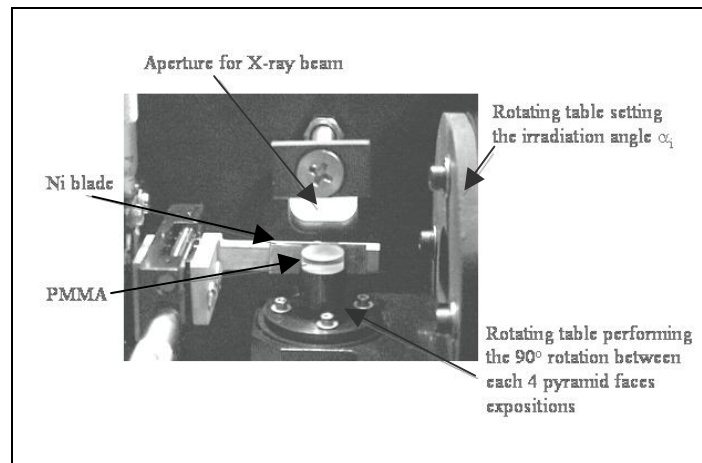


Fig. 2 - Support for the PMMA in the Beamline

At this point of the procedure a single pyramid is obtained and a measurement of its vertex angle is performed. If the measured angle is outside the tolerance requested, the value of the angle obtained can be used to fine tune its value changing the rotating table angle α_i of the corrective value and then exposing a new pyramid. The pyramid obtained with this procedure could be used as it is and inserted in the adaptive optical system. It make sense to manufacture the pyramids in this way only if the requested number of pyramids is limited and their size don't exceed few mm in diameter. This procedure has been followed for the MCAO breadboard prototype in test at the Telescopio Nazionale Galileo (TNG) that looks simultaneously at four references stars⁸. It require four PWFS of 6 mm of diameter with a vertex angle (angle between two opposite sides of the pyramid) of $\gamma=178.256^\circ (\pm 0.058^\circ)$ and a repeatability among them of 0.007° (25 arcsec). The turned edges among the faces were required in the range of 10 – 15 microns.

To deposit a dose of 1.2 kJ/cm^3 (necessary for the next chemical development) at a depth $r=3\text{mm}$ and with an average ring current of 105 mA, one hour exposure was necessary per pyramid face for a synchrotron electron energy of 2.4 GeV. After the exposure of the four faces, the cylinder was immersed for at least 24 hours in a slowly stirred GG developing bath at a temperature of 29°C . It was then rinsed with deionised water and blow-dried. In this way flat point-like pyramids were produced with a surface microroughness measured⁹ around 5 nm rms.

The irradiation angle α_i of the rotating table was set to 0.872° and frozen for the four pyramids fabrication. Therefore only hand positioning error of the PMMA cylinder on the holder could eventually affect the reproducibility of the vertex angle. Accurate optical measurements on the four pyramids gave a value of $\gamma=178.273^\circ$ (0.02° more than the requested 178.256°) with a repeatability among the pyramids of $\pm 0.007^\circ$ (25 arcsec). These errors are within the angle specification of the MCAO prototype and the 0.02° difference can be attributed to the difficulty in determining the reference horizontal position ($\alpha_i=0$). It could be possible to reduce this error furtherly calibrating a new α_i but it was decided that the error was small enough.

The turned edges obtained were of 30 microns, a value outside the goal of 10 microns. The larger value obtained depends from the large value of the vertex angle required for the pyramids and will be discussed later. In the case of these pyramids anyway also a value of 30 microns is a good compromise. In this respect much more important was the ability to manufacture with good repeatability identical pyramids.

3. FABRICATION PROCESS (PART 2)

The exposure time necessary for the irradiation of the four 6 mm diameter pyramids were of four hours each. This time is dictated from the necessity to deposit the correct radiation dose into the material for the next development. If the pyramids to be manufactured are more numerous and with a larger diameter, like for the case of the eight PWFS for the MAD module of the Very Large Telescope (VLT), the exposure times increase exponentially. These eight pyramids have a diameter of 12.7 mm diameter each. It is therefore necessary to deposit enough dose at a depth of 6.35 mm corresponding to the half of the pyramid diameter. To this purpose filters were inserted in the beam path to shift the spectrum of the radiation towards the higher energies. This step is necessary to avoid the deposition of a larger quantity of energy in the entrance surface of the PMMA with a consequent wrong energy distribution along the volume of the material. The harder X-rays are less absorbed and are hence deposited more uniformly along the thickness of the material. With a filter of 80 μm of Aluminum, 565 μm of carbon and 25 μm of kapton a dose contrast of 5.65 was achieved between front and back dose at a depth of $r = 6.35$ mm. A minimum dose deposition of 1.5 kJ/cm^3 at the bottom requires an average exposition time of 4 hours per pyramid face for an average ring current of 100 mA. It is clear that in this case the total irradiation time of 16 hours per pyramid renders the fabrication process using DXRL very inconvenient and demanding in beam time especially when 8 identical components have to be produced. A complete LIGA process has been hence developed to take care of this problem.

A pyramid in PMMA is fabricated with the DXRL procedure described above and is used as a master to fabricate a mold in nickel. The master pyramid is glued on a suitable holder in PMMA and a gold base plating is vacuum deposited on top of the assembly as shown in Fig. 3.

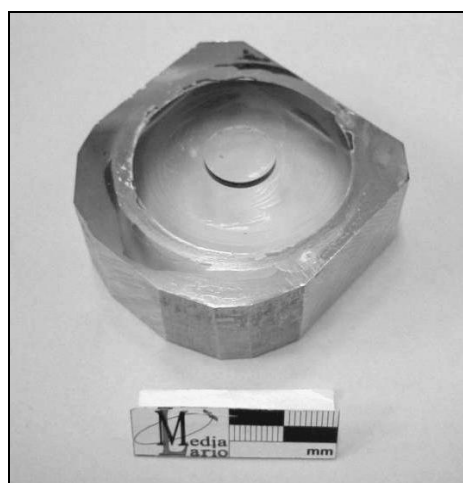


Fig. 3 - PMMA base for Nickel electroplating

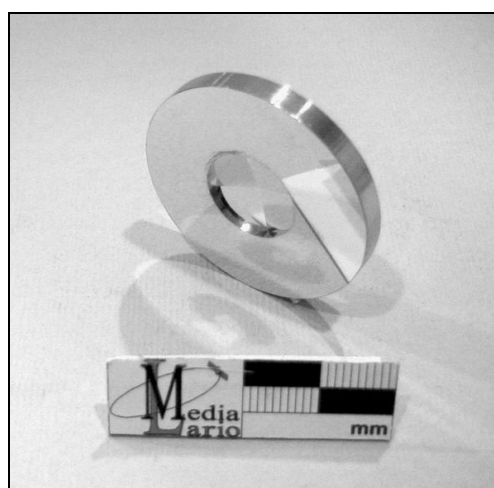


Fig. 4 - Nickel mold of the master pyramid

The nickel is then electroplated on the PMMA (Media Lario) until its total thickness reaches about 6 mm. After removal of the PMMA a cylindrical mold with the negative shape of the PWFS is obtained (Fig. 4). Note that the gold base plating remains attached to the nickel mold. The mold can then be used to produce several identical pieces of the same PWFS with any type of thermal polymer via the hot embossing process (Fig. 5). In the particular case of the MAD adaptive optics system, an optical polymer called Zeonex E48R was chosen for its high transparency and thermal properties. The mold insert is placed on the bottom plate of a press with the hollow face up and is filled with millimeter size cylindrical Zeonex pellets. An optical glass flat is used as a lid to cover the mold filled with the pellets. The top plate of the press is lowered down until touching the glass lid. Both hot plates are heated up to 195°C that is well high above the glass transition temperature of the Zeonex (138°C). When the material is in its semi-liquid state the top plate is lowered down in order to render the glass flat parallel to the plates and to leave a gap of approximately 0.5 mm between the mold and the lid. This state is maintained during 5 minutes to allow air bubbles escaping from the melted polymer. The temperature is slowly decreased and a pressure of 4 bars is applied on the assembly and maintained until

the temperature reaches 145 °C. Both the hot plates are then slowly cooled down to the room temperature, and finally the PWFS is mechanically released from the mold. The total fabrication process for one pyramid takes approximately 45 minutes. In principle it could be possible to produce more than one master and hence to manufacture a nickel mold with more than one cavity. In this way it could be possible to produce a large number of pyramids at once, optimizing the process.

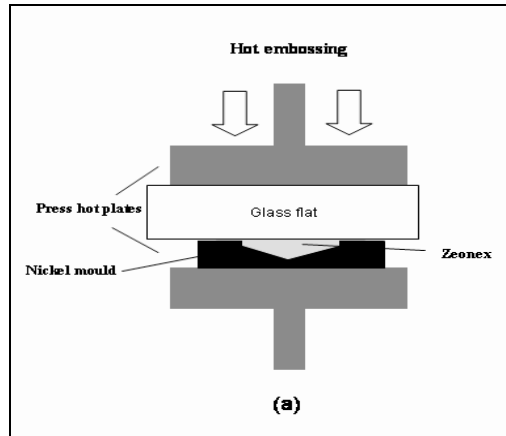


Fig. 5 – Hot embossing

4. TURNED EDGES

To investigate the limits of this manufacturing process from the point of view of the turned edges obtainable, we have made a large number of pyramids, with the DXRL technique, at different angles α_i . The turned edges are an important parameter of the pyramid sensor and must be kept as small as possible to avoid a too important loss of the starlight when the adaptive optics works near the telescope diffraction limit condition. The results obtained are summarized in Fig. 6. In this figure are indicated the turned edges obtainable in function of the irradiation angle α_i . The width of the turned edges for a certain angle α_i is not constant and can change from a lower value $W_{te}(c)$ to a higher value $W_{te}(a)$ depending from the position along the edge itself.

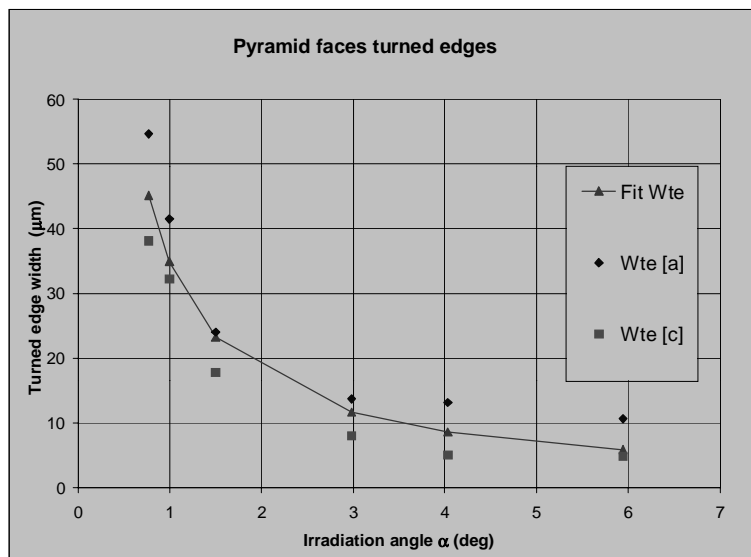


Fig. 6 – Turned edges vs. Irradiation angle

The fit of these values is also indicated. With an appropriate setup of the support that holds the PMMA during the exposure, it is possible to obtain the lower value near the tip of the pyramid (where it is desirable) and the larger value near the pyramid edge (where it is less critical). This behavior is due to the difference in dose that is deposited from the x-ray photons in the entrance side of the PMMA respect to the exit side. A way to reduce this effect is to shift the spectrum of the radiation towards higher energies with filters but of course the exposure time need to be incremented.

5. HYBRID PYRAMIDS

Given the refractive index of the Zeonex the initial design, performed with a ray-tracing program of the eight 12.7 mm diameter pyramids for MAD, gave a request on the vertex angle of $\gamma=178.857^\circ$ that translate in an irradiation angle of $\alpha_i=0.5715^\circ (\pm 0.013^\circ)$. However, for such a small α_i angle, we have seen that it is not possible to obtain turned-edges among the faces below $60 \mu\text{m}$. To overcome this limitation we are considering the possibility to manufacture a pyramid composed by two different optical polymers with refractive index $n_1 < n_2$ as depicted in Fig. 7.

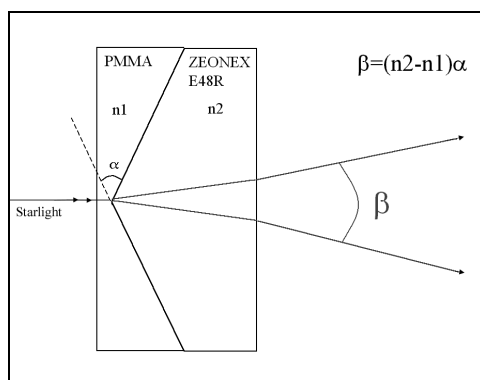


Fig. 7 – Hybrid pyramid ($n_1=1.4921 @633\text{nm}$; $n_2=1.528 @633 \text{nm}$)

The first component of this hybrid pyramid is molded in Zeonex. The second component is made in PMMA that has a refractive index lower than that of the Zeonex. Due to the fractional refractive index between the two surfaces, the vertex angle of the Zeonex pyramid can be much smaller than that of a classical pyramid. In fact, the angle of the Zeonex pyramid can be in this case of $\gamma=163.875^\circ$ that translate in an irradiation angle $\alpha_i=8.0625^\circ$. With this angle of irradiation it is possible to obtain turned edges better than 10 microns that is the requirement for MAD. The fractional refractive index between the surfaces of the two components is useful also to relax the tolerance on the vertex angle of the Zeonex pyramid that in this case is of $\pm 0.2^\circ$. After the molding of the Zeonex pyramids the manufacturing process foresees the deposition of liquid PMMA monomer on their top, in quantity sufficient to fully cover the pyramid tips, and its polymerization.

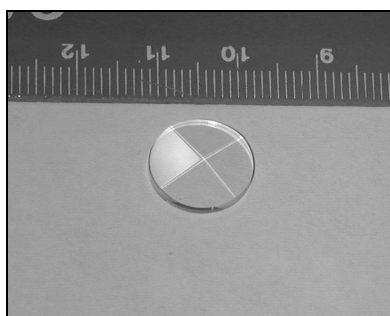


Fig. 8 - Close-up of a pyramid

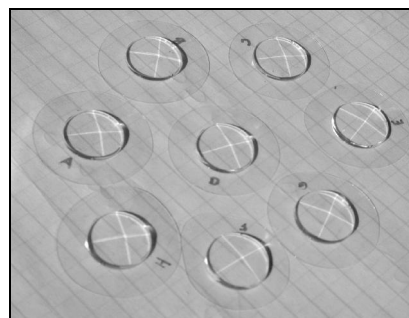


Fig. 9 – Eight pyramids made for the production of the hybrid pyramids

On top of the liquid monomer is placed a flat optical glass to create a flat PMMA surface. After the polymerization, the glass cover is separated and the hybrid pyramid is produced.

We have already produced a first mold with the requested angle and molded eight test pyramids (Fig. 8-9) manufactured with the same hot embossing process. As foreseen the turned edges angles are better than 10 microns. The measure of the vertex angle was made using a collimated laser beam pointed onto the pyramid tip. The distance between the four refracted beams was measured in a plane at a known distance from the pyramids. For the eight pyramids, the measured angle is $\gamma = 163.816^\circ (\pm 0.01^\circ)$ showing a repeatability amongst them better than the precision of our measurement setup. The microroughness, the turned-edge width, and the vertex angles are repeated with extreme precision using the hot embossing process.

The manufacturing of these pyramids is in progress and the first samples of hybrid pyramids should be tested in a short time. An unexpected problem arose due to the relatively poor adhesion of the polymerized PMMA onto the Zeonex polymer. Infact it is possible, applying a force, to separate the two components. An investigation has shown that it is possible to use an adhesion promoter on the Zeonex to obtain a full adhesion between the two surfaces and tests are under way.

6. CONCLUSIONS

Significant progress from the classical lapping/polishing technique has been achieved using DXRL for fabricating the pyramid wavefront sensors. The problem of reproducibility, manufacturing time and cost is resolved by extension to a full LIGA process. In that case only one master pyramid needs to be fabricated with the DXRL process. The mold obtained out of it can then be used to produce a large number of perfectly identical PWFS. Moreover the LIGA process allows the choice of a wide range of thermal polymers.

The capability of the LIGA process to mass-produce easily large number of pyramids and the good reproducibility of the molded pyramids are an advantage respect to the lapping/polishing technique. The main limitation of this technique is connected to the turned edge degradation for small irradiation angles as shown in Fig. 6. A possible solution to this problem is the use of a hybrid pyramid exploiting the fractional refractive index between two different polymers. A number of this hybrid pyramids are under manufacturing and will be tested in short time.

7. REFERENCES

1. Ragazzoni R, "Pupil plane wavefront sensing with an oscillating prism", J. of Mod. Opt., 43, pp.289-293 1996.
2. S. Esposito, O. Feeney, and A. Riccardi, "Laboratory test of a pyramid wavefront sensor," Proc. SPIE 4007, pp. 416-422, July 2000.
3. S. Esposito, A. Riccardi, and O. Feeney, "Closed-loop performance of pyramid wavefront sensor," Proc. SPIE 4034, pp. 184-189, July 2000.
4. M. Ghigo, G. Crimi, F. Perennes, "Construction of a pyramidal wavefront sensor for adaptive optics compensation" Proceeding of the Conference "Beyond Conventional Adaptive Optics", Venice 2001
5. Ghigo M, Pérennès F, and Ragazzoni R, "Manufacturing by deep x-ray lithography of pyramid wavefront sensors for astronomical adaptive optics", Proc. SPIE, Vol. 4839, p 259-265, 2002
6. H Guckel, "LIGA and LIGA-like processing with high energy photon", Microsystem Technologies, Vol. 2, Number 3/August 16, p.153 - 156, 1996. M. Hecke, W. Bacher, K.D. Muller, "Hot embossing - The molding technique for plastic microstructures", Microsystem Technologies 4 P.122-124 Springer-Verlag (1998)
8. Ghedina A, Ragazzoni R., Marchetti E, (1997), Optical design for the AdOpt@TNGmodule, Proc SPIE vol 2871, pp 927-936
9. Pérennès F, Ghigo M, Cabrini S, (2003), Characterisation of adaptive optic pyramid wavefront sensors fabricated by deep X-ray lithography, Microelect. Eng., vol 67-68, pp 566-573