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An all-refractive optics for tilt sensing

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Abstract

An all-refractive wavefront tip-tilt sensor, made with off-the-shelf components is described, such a device offers a number of advantages over other proposed techniques and would be particularly suitable for use in an adaptive optics system. A first prototype has been built and partially tested. Some details concerning its construction as well as recommendations for optimizing performance are provided.

1. Introduction

In an atmospherically aberrate optical system the single largest source of phase errors is wavefront global tip-tilt over the entrance pupil. This error results in image motion in the focal plane of the optical system. That motion, in turn, translates into image degradation when the exposure time becomes longer than the characteristic time for the fluctuations. It is obvious, therefore, that the removal of the tip-tilt errors is essential. Due to the large amplitude of the tip-tilt phase excursions it is desirable to have a separate tip-tilt sensor and corrector which functions independently from an adaptive optics system designed to correct higher order modes. The corrector is to conserve dynamic range of the high order corrective element. From the sensor point of view a difference must be made between natural star and laser guide star. In this latter case the separate tip-tilt sensor is required. In the first case the separate sensor is mostly to be used when the higher order correcting system is not in use. Since adaptive optics system performance is typically dominated by the accuracy of the global tip-tilt removal [1], there has been a corresponding effort in the development of high quantum efficiency photon counting devices for tip-tilt detection. Avalanche photodiodes (APDs) are amongst the most efficient detectors [2]. These detectors are only produced as single pixel devices and even the quadrant versions under development will still have a significant blind area between the adjacent elements. An optical system able to relay the focal plane light into four different detectors dissecting the light in a quadrant manner is required. Furthermore, tip-tilt stabilization of imaging systems is a fundamental requirement in a wider range of imaging applications, even when some post-processing is applied [3].

2. Our approach

In order to maximize the photon efficiency of single detectors, a configuration with the minimum amount of reflections and air–glass interfaces is desirable. A transmission of virtually 100% can be achieved with total internal reflection, compared to the 98.5% attainable with a fresh enhanced silver coating and narrow spectral band filter. In order to achieve higher SNR these tilt sensors are used in a wide band mode which further reduces the efficiency of reflective coatings. The adoption of UV-curing and matching refractive index glue yields an optically compact design, as presented in this paper. Such compact assemblies of prisms have already been proposed [4] as an elegant and compact solution for interferometric and curvature wavefront sensing devices. The simple solution of a specular pyramid requires an additional achromat lens for

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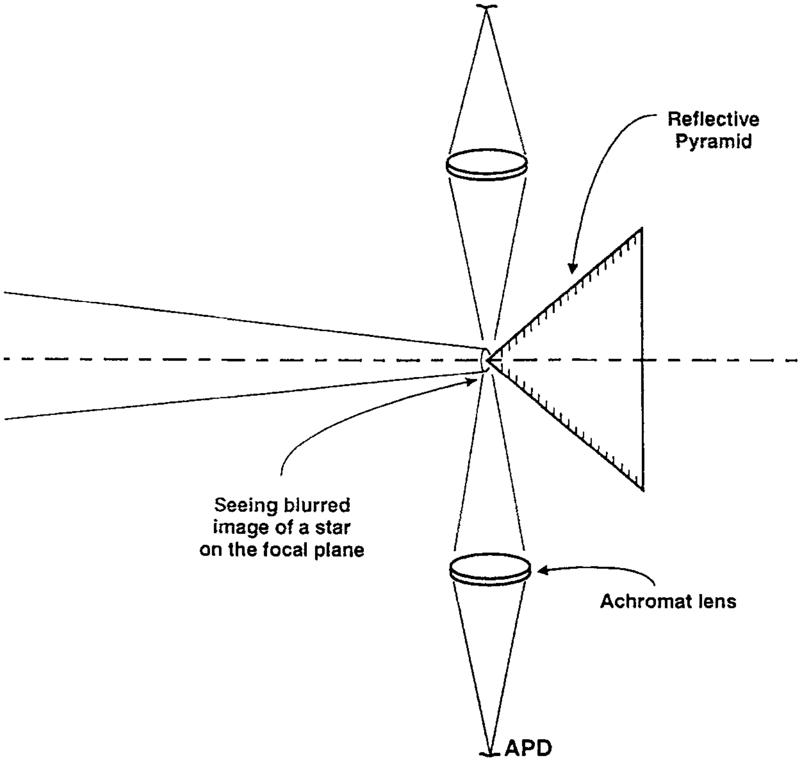

Fig. 1. A cross-section of the reflective pyramid solution.

each arm (see Fig. 1) due to the usual small size of the APD sensing area. Defocussing the beam on the vertex of the pyramid, can improve the throughput by removing the need for lenses. However, in this case the enlarged defocussed spot on the pyramid vertex leads to a much lower sensitivity of the tip-tilt sensor. The efficiency of such a system can be given by $RI_{ag}^2 I_{gg}$ where R is the reflection efficiency, I_{ag} is the air to glass transmission efficiency and I_{gg} is the transmission efficiency for the light passing through the interface between two different glasses. Typical values are $R \approx 0.985$, $I_{ag} \approx 0.995$ with a near-IR dielectric multi-layer coating. Total internal reflection efficiency and the transmission through interfaces between two identical glasses, glued together with the proper index

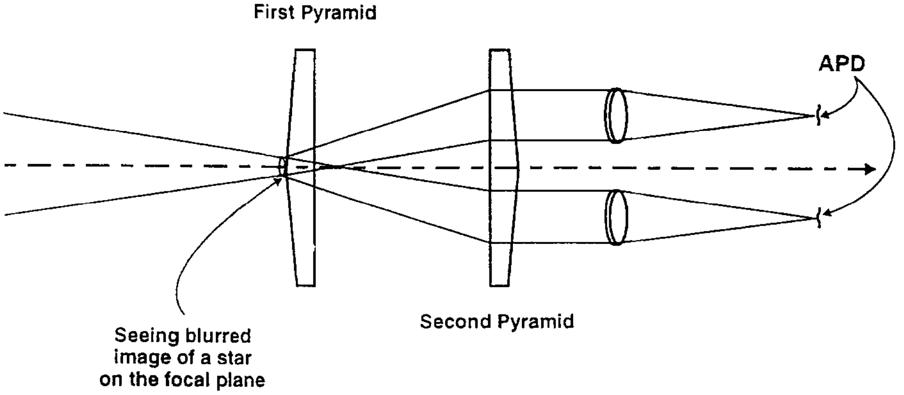

Fig. 2. A cross-section of the two pyramids refractive solution. The second pyramid is required to correct the chromatic aberration of the four beams.

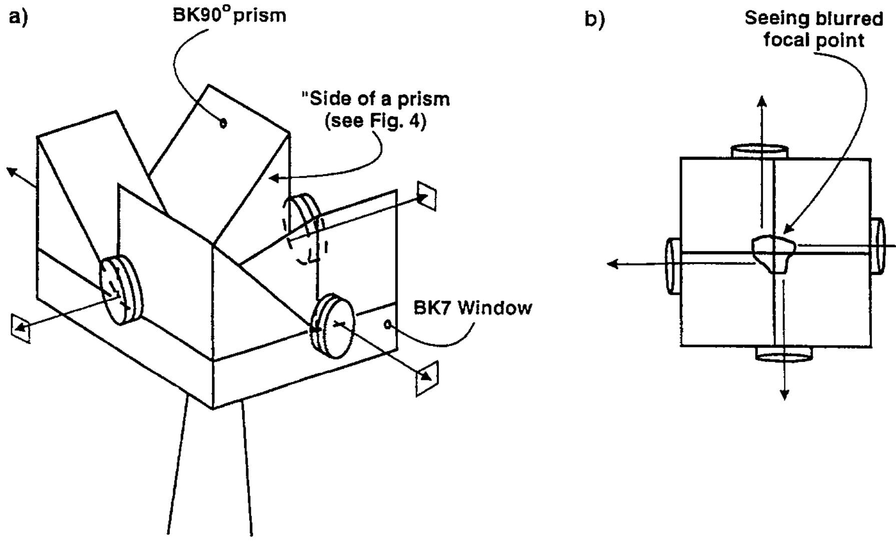

Fig. 3. (a) A three-dimensional view of the proposed prism assembly. (b) A bottom view of the prism assembly showing the directions of the four beams.

matching apoxy, were taken to be 100%. Hereafter we neglect I_{gg} since an achromat relay lens is required in all the configurations shown. Depending upon the focal ratio of the incoming beam to the beam dissector and to the size of the APDs sensitive area, achromats may not be required. Ray-tracing using an extended source of a size comparable to the seeing-blurred star is sufficient to determine which solution is to be adopted. With these figures an efficiency of $0.975 I_{gg}$ is obtained.

Because $R < I_{ag}$, a refractive pyramid solution is preferred. However, such a solution leads to chromatic dispersion because the single elements of the refractive pyramid act as a dispersing prism. This results in a broadening of the split beams to a size usually larger than the APD, even allowing for an appropriate reimaging lens. This can be avoided in an elegant way by doubling the refractive pyramids and assembling them as shown in Fig. 2. In this way the chromatic effect will cancel out (except for a tiny elongation of the exit pupil) and an all-refractive tip-tilt sensor is obtained. The efficiency is given by $I_{ag}^{6} I_{gg} \approx 0.970 I_{gg}$ unfortunately the pyramid described, having a vertex angle of few degrees, is not an off-the-shelf component.

An even higher throughput can be achieved by adopting the configuration shown in Fig. 3a. In this case four 90° off-the-shelf prisms are glued onto an optical quality window made of the same glass as the prisms. The lenses, moreover, can be glued directly on the prism' ends. This last option cannot be achieved using the previous method because of a tilt of the last pyramid surface with respect to

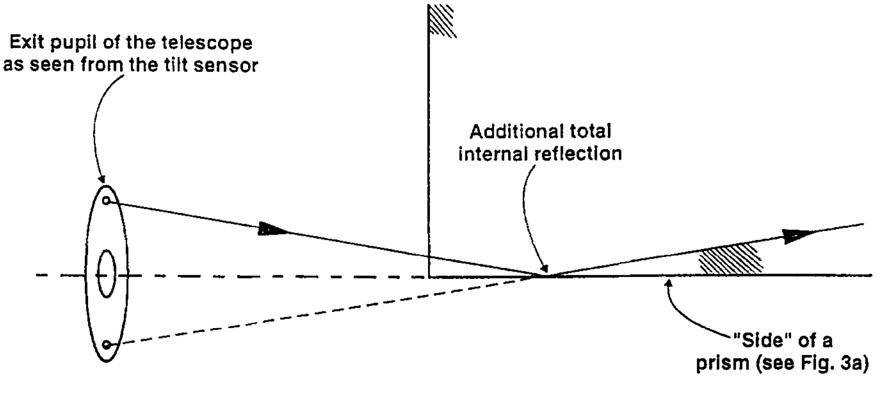

Fig. 4. Rays coming from the exit pupil can be further totally reflected by the side faces of the prisms. However, their virtual image is always located in the pupil.

the beam's optical axis. Care must be taken in attaching the lenses because the prism faces are not usually machined at the wanted accuracy. However, in the case of our prototype the off-the-shelf components used are accurate enough to achieve the wanted result. In principle, tiny departures from the required surface accuracy can be overcome by inserting matching index glue in the empty spaces.

In Fig. 3b the direction of the beams after their splitting is clarified. It should be pointed out that for some rays a further total internal reflection can occur. However, as it can be seen in Fig. 4, the virtual image formed falls onto the pupil, and a relay lens providing the re-imaging of the exit pupil onto the APD will collect the whole beam. The efficiency of such a solution is $I_{ag}^2 I_{gg} \approx 0.990 I_{gg}$. In these calculations we have not taken into account the internal transmittance of the glass. However this is usually a negligible value: for a 25 mm path, for example, BK7 has an efficiency better than 0.995 at wavelengths longer than 600 nm.

Even though the efficiency gain is not dramatic, the simple and cost effective solution provided by the compact all-refractive system is still more advantageous than the other solutions. Furthermore, the average lifetime of an antireflective coating is usually longer than a reflective one.

An additional loss can occur with the internal reflections at the larger faces of the single right angle prisms. In this case, dust and any other material that collect on these surfaces will lead to a lower reflective efficiency. This can be avoided by enclosing the beam dissector in a small box (with open holes for the beam input and the lenses) and, eventually, drawing the air inside. In some focal plane detectors such a source of depression can be refrigerated to avoid the condensation of the water in the detectors windows. As a radical alternative one might consider the alluminization of these surfaces. In this last case it is clear that the problem is completely solved, at the cost of a lower overall efficiency. Compactness and the absence of need for more than a single optical piece are thereby retained.

3. The prototype

Fig. 5 shows the assembly of the prototype illuminated with a focused laser beam and the four resulting beams.

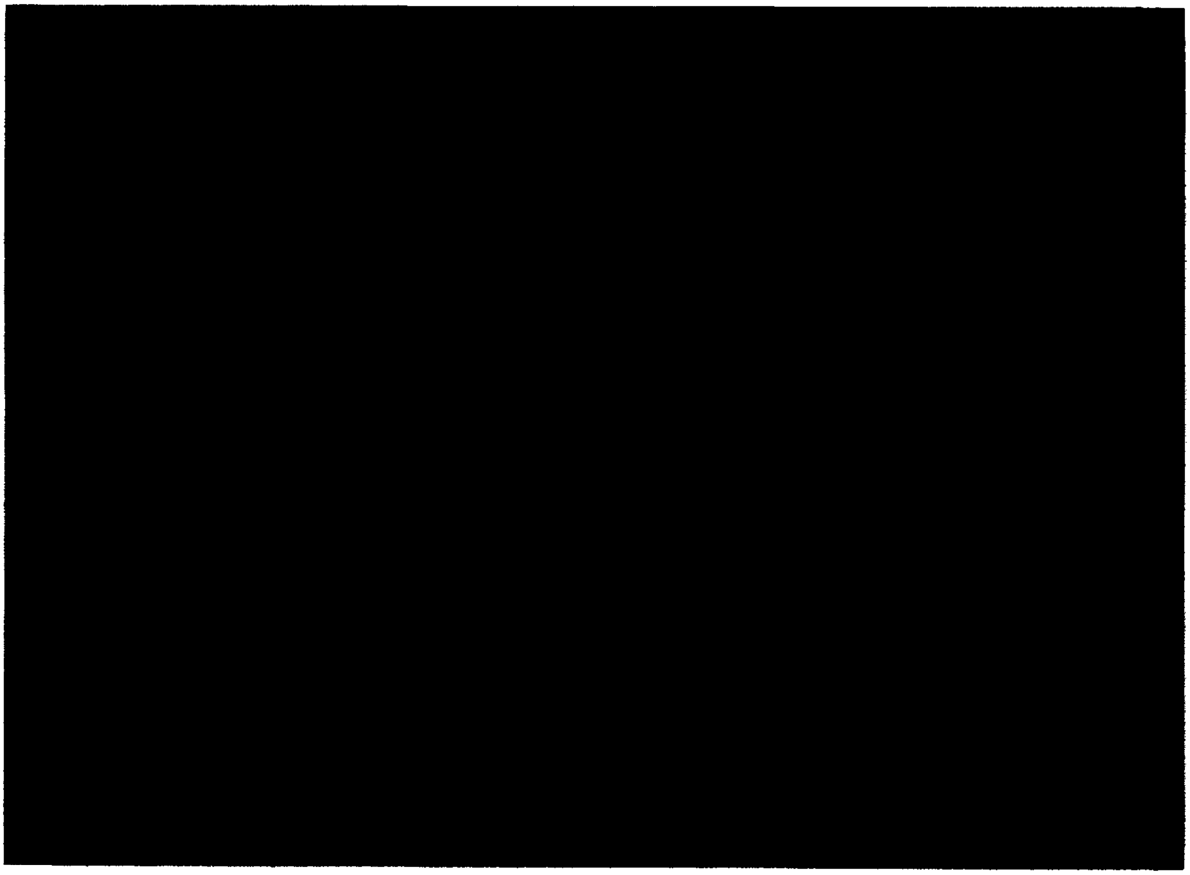

Fig. 5. The first beam-dissector prototype illuminated by laser light.

The overall throughput of the device is compatible with the losses due to the air–glass interface (in this first prototype such surfaces are not anti-reflection coated) and the total internal reflection turns out to be 99% ± 1%. An important point to raise is that since this arrangement is designed for measuring global tilt only the remapping of the pupil is not an important issue. The four beams resulting from the splitting if put recombined and reimaged in the pupil plane will show some gaps. However, since we are interested in measuring only the global tilt this is not an important issue. This device is now under test on the 1.82 m telescope of the Padova Astronomical Observatory in Italy. Preliminary results of the performance of the system are sufficiently encouraging to warrant consideration as tip-tilt sensor. Three other beam dissectors of this type are now under construction.

Some useful hints can be given on the question of implementing the tip-tilt sensor:

- We have procured prisms from different manufacturers. Some manufacturers do not provide the triangular lateral faces of the prisms polished in a way that reflection occurs. Such prisms should be avoided or a loss of some light will occur (however this loss can be very small if the beam wander is made to be significantly larger than its size on the entrance at the beam dissector).
- During gluing (some mechanical device, able to place the various components in position during this operation can be very useful) care has to be given that the glue does not spill from the central crossing between the four right-angle prisms. If some spill occurs a *hole* will be generated just at the center of the beam dissector. In order to avoid this occurrence we have used a needle linked to a vacuum cleaner to remove the spilled glue.
- It is interesting to consider producing the whole beam dissector with a relatively large ($n \approx 1.7$) refractive index. In this case, the final lens can be made with a shorter focal length, thus eliminating the need for an achromatic lens. However, usually such a material, being much harder, it is more brittle and fragile. For our prototype we used BK7 glass, so this last concern does not apply.
- As a final remark one should consider the option to have some custom components for the device described in this paper. In some case you can choose to have the parallel plate window custom manufactured with off-the-shelf prisms, or vice versa; in these cases it is not to be neglected the fact that right angle prisms are a standard production item. This is not the case of the refractive pyramids shown in Fig. 2 where the manufacturer needs to establish some dedicated hardware depending upon the vertex angle to be adopted, angle that will change depending upon the constraints of the other parts of the tip-tilt sensor.

4. Conclusions

We have presented an all refractive design for a beam dissector that can be used to obtain optimal tip-tilt measurements using high sensitivity, single cell detectors like APDs. The optical design is simple and can use off-the-shelf components. Although the preliminary results from a prototype are encouraging more study is needed in order to fully characterize the system.

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