Solid light concentrators for small-sized photosensors used in Cherenkov telescopes

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Abstract: Multipixel Imaging Air Cherenkov Telescope cameras feature a pixel design that utilizes specific light concentrators to fill the dead space between photosensors and to considerably increase their photon collection area. These light concentrators additionally reduce the noise contribution from night sky background which arises from scattered photons that come from airglow, nearby cities, stars etc. A new design of solid light concentrators is presented here that interfaces a hexagonal entrance structure to small square-shaped Geiger-mode avalanche photodiodes (G-APDs). The price per unit sensitive area of G-APDs is still higher than for more conventional photosensors, such as photomultiplier tubes. Therefore, a higher area concentration ratio is desired than in previous experiments. The FACT (First Geiger-mode Avalanche Photodiode Cherenkov Telescope) camera will make use of G-APDs in combination with these light concentrators. Solid light concentrators, that are based on total internal reflection, intrinsically lead to an increased area concentration ratio compared to the non-solid version. As production method, injection moulding of polymethyl methacrylate (PMMA, Plexiglas) is investigated, which is ideal for larger scale production. Development, production and the measured characteristics of these devices are presented here and comparisons to predicted values based on ray-tracing simulations are shown. The results of this study will be relevant for future Cherenkov telescopes as the Cherenkov Telescope Array (CTA).

Keywords: Solid light concentrator, Imaging Atmospheric Cherenkov Telescope, FACT

1 Introduction

In current Imaging Air Cherenkov Telescopes (IACTs), as HESS, MAGIC or VERITAS, pixelized cameras feature a pixel design in which the photosensors are equipped with special light concentrators (see for instance [1]). The light concentrators increase the photosensitive area per pixel and thereby minimize dead spaces on the camera. Furthermore, they are designed to cut off environmental stray light from night sky background photons by only accepting light that is incident from the telescope's reflector. For axisymmetric light concentrators, the cutoff angle Θ is related to the size ratio of the light guide's input aperture A_{input} to its output aperture A_{output} by $(A_{input}/A_{output}) \propto (n/\sin\Theta)^2$ [2], where n is the refractive index of the material the light guide is filled with. It may be air (hollow light guide) or any dielectric (solid light guide). This area concentration allows the expensive photosensitive area to be enlarged and thereby to reduce the costs per mm^2.

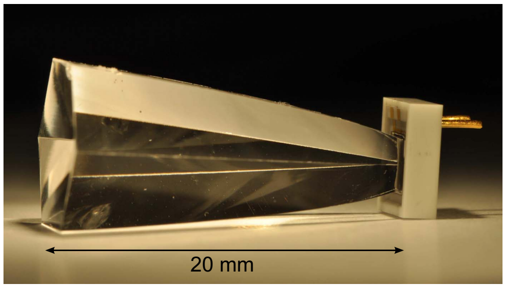

Figure 1: A solid light concentrator made of PMMA, optically glued to a G-APD.

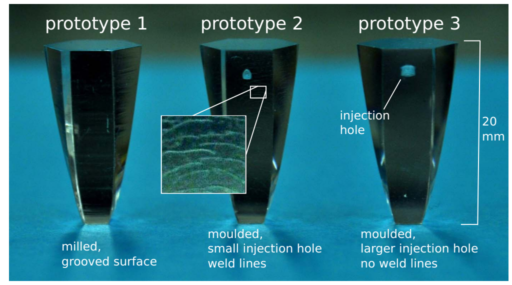

Figure 2: CNC-milled and injection-moulded prototypes.

2 Design criteria

For the First Geiger-mode Avalanche Photodiode Cherenkov Telescope (FACT) [3], specific light concentrators are designed. The telescope mount that is used for the FACT camera has a focal distance to diameter ratio f/D of 1.4. This implies a desired cutoff angle per pixel of approximately 20°. As photosensors, Geiger-mode avalanche photodiodes (G-APDs) are utilized, here Hamamatsu MPPC S10362-33-50C [4], with a square-shaped sensitive area of 3.0 x 3.0 mm^2. In order to tolerate alignment uncertainties, the output aperture of the light concentrator is fixed to 2.8 x 2.8 mm^2. A hexagonal input aperture ensures equal distances between directly neighbouring pixels and allows for nearly 100 % coverage of the camera with photosensitive area. Hexagonal pixels are commonly chosen in current IACTs. Light concentrators produced out of a solid material lead, due to Snell's law, to a larger area concentration at the same cutoff angle compared to hollow light guides. In case of a camera front window, solid light guides allow the losses due to Fresnel reflections that occur at transitions between materials of different refractive indices to be minimized. A refractive index of about 1.5 is pre-defined by the protective epoxy layer on top of the sensitive silicon area in the photosensor. Therefore, polymethyl methacrylate (PMMA, Plexiglas), a material with a similar refractive index, is selected for the light guides and the front window. UV-transparent PMMA is chosen in order to make the camera as sensitive as possible to wavelengths below 400 nm.

3 A solid parabolic light concentrator

In comparison to hollow light guides whose inner surface is covered with a reflective foil, solid light guides make use of total internal reflection. The classical "Winston cone" that is described in detail in [2] is widely used in Cherenkov telescopes. Instead of using a "Winston cone" shape that is characterized by tilted parabolic side walls, we have developed a light concentrator with upright parabolic side walls. With this design, the complicated three-dimensional shape that interfaces a hexagonal input to a square-shaped output is much easier to produce. In contrast to the "Winston cone", the upright parabolic concentrator offers two more free parameters, the input area and the height of the light guide. While the output area is fixed by the photosensor size, the desired cutoff angle determines the input area but the exact size of the area needs to be found with the aid of ray-tracing simulations. Additionally, a fine-tuning of the height is used to sharpen the angular cutoff and thereby to increase the ratio of the acceptable light from the reflector (signal) to the stray light from the environment (background). An extensive ray-tracing study has been performed to determine these parameters, based on the software and experience from [5]. The study resulted in a 78.2 mm^2 area for the hexagonal input and in a height of 19.9 mm. The input area is adjusted to a cutoff angle slighty larger than 20° to be sure that no acceptable light from the reflector is rejected. The corresponding area concentration is in the order of 10. The solid light guides are finally produced by injection moulding of a PMMA granulate called Plexiglas® 7N OQ [6], a special selection of granulate to achieve a high optical quality. Figure 1 shows one of the injection-moulded light guides with a photosensor optically coupled to the output area. Figure 2 gives an overview on the iteration process during the prototyping phase. The first prototype is produced by CNC-milling out of a block of commercially available extruded PMMA. However, the milling process leads to a grooved surface. Therefore injection moulding is investigated as production method. Injection moulding guarantees a high surface quality which is necessary to ensure efficient internal total reflections. The second prototype is injection-moulded. Although a much smoother surface is achieved, weld lines are present, caused by a low flow rate of the fluid PMMA during the injection into the mould. In the third and final prototype, the weld lines are eliminated by enlarging the injection hole that is positioned at one of the side walls.

4 Spectral transmittance

Figure 3 shows the transmission spectrum averaged from the measurements of more than 1400 injection-moulded light concentrators. A Perkin Elmer Lambda 900 spectrometer is used for this purpose. Losses due to Fresnel reflections occur at the input and at the output area of the light guide. The light guide transmission spectrum affects

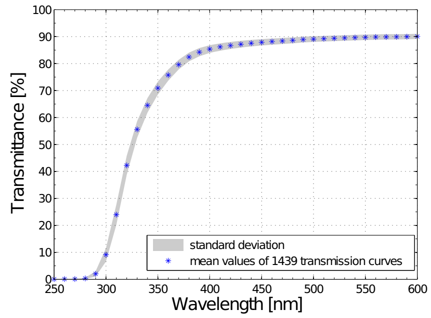

Figure 3: Transmission spectrum averaged from more than 1400 measurements. The spectra are not corrected for Fresnel losses.

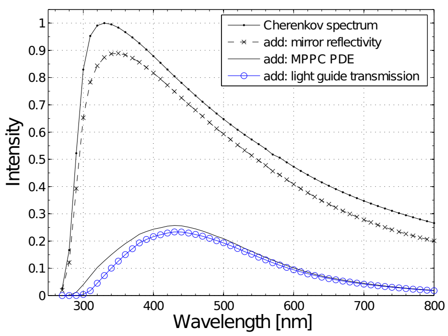

Figure 4: Measurable intensity of the Cherenkov spectrum versus wavelength. The simulated Cherenkov spectrum at 2200 m asl (maximum is normalized to 1) is folded iteratively with the mirror reflectivity, the photosensor PDE and the light guide transmission. Perfect optical coupling between light guide and photosensor is assumed.

the measureable intensity of the atmospheric Cherenkov spectrum. The measureable intensity is further restricted by the reflectivity of the mirrors utilized in the telescope and particularly by the photon detection efficiency (PDE) of the photosensor. This is illustrated in figure 4. A typical Cherenkov spectrum, simulated as it is expected at the FACT site (2200 m asl), is folded with the measured FACT mirror reflectivity, the measured PDE of the photosensors and finally with the averaged spectral transmission of the light guides (extrapolated to 800 nm).

5 Angular acceptance

The angular acceptance is probed with the aid of the goniometric setup that is schematically sketched in figure 5. The setup features a light source that emits parallel light with a wavelength of about 630 nm. This wavelength is chosen to be in the wavelength range of maximum light guide transmittance (see figure 3) to prevent the measurements from being severely affected by absorption losses. EPO-TEK 301 glue [7] is used for the optical coupling between

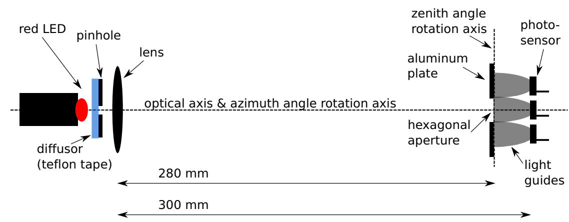

Figure 5: Goniometric test setup to probe the angular acceptance and the light throughput of the light concentrators. The light guide's orientation relative to the light beam can be varied within a wide azimuth and zenith range.

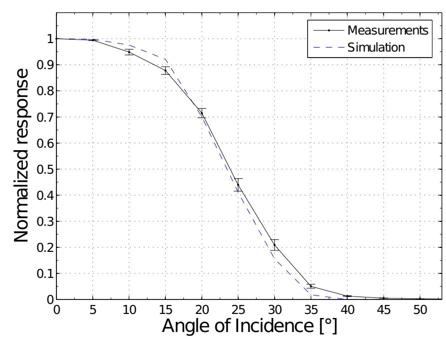

Figure 6: Measured and simulated photosensor response (normalized) versus the angle of light incidence.

photosensors and light guides. Light guide and photosensor are then mounted into a goniometric holder that allows the orientation relative to the light beam to be varied within a wide azimuth and zenith range. In figure 6, the response of the photosensor is plotted for a fixed azimuth angle versus the angle of light incidence (zenith angle). The curve is normalized to 1 at angle of incidence 0°. It is compared to a ray-tracing simulation using the same azimuth and zenith angle and the same light source configuration as in the measurement.

Separate measurements are performed to determine the light throughput through the light guide, defined as the ratio of the light flux measured at the output to the light flux incident on the input. The light guide's zenith angle orientation is fixed to 0° for this purpose. Well-coupled samples, that is samples with clear glue layers, achieve throughput efficiencies in the order of 90 %, measured with the 630 nm light source. Even a small number of small air inclusions in an elsewhere clear glue layer has no measurable effect on the throughput efficiency (see also [8]).

6 Collection efficiency

As mentioned in section 2, the light guides are designed for a cutoff angle of 20°. Light incident from angles [0°, 20°] is therefore treated as signal and light from angles]20°, 90°] as background. In the three-dimensional case, light incident from a certain zenith angle needs to be inte-

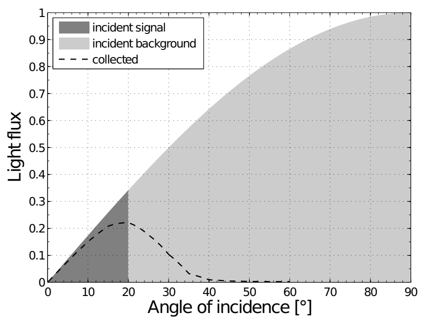

Figure 7: Simulated incident signal and background light flux in case of an isotropic incident flux distribution versus the angle of incidence. The dashed line corresponds to the flux that would be collected by the light guide.

grated over the total azimuth range. In figure 7, the light flux is plotted versus the angle of incidence, assuming an isotropic incident flux distribution. The dark grey and light grey filled curves correspond to the incident signal and incident background respectively, in the three-dimensional case. The flux value at angle of incidence 90° is normalized to 1. The dashed line in the same figure indicates the flux that is collected by the light guides taking the measured angular acceptance and 90 % throughput efficiency into account. This yields collected 80 % of the incident signal and collected 4 % of the incident background.

7 The FACT camera frontplane

1440 light concentrators form the FACT front plane. Prefabricated samples, that is light guides and coupled photosensors, are glued onto a circle-shaped PMMA front window (Plexiglas® GS 2458 [6]). A highly fluid glue called Acrifix® 1R 9019 Solar [9] is used. The glue layer between front window and light guide is achieved by capillary attraction. After intensive pre-treatment of the contact surfaces with 2-propanol, an optically clear glue layer is obtained. Figures 8 and 9 show two images of the front plane, viewed from a lateral point of view and from the front respectively. The front view makes the pixels appear dark. This is due to the fact that the sensitive area of the G-APD attached to the light guide's output appears enlarged at the hexagonal input.

8 Summary and conclusions

A new type of solid parabolic light concentrators for small-sized photosensors has been developed. It interfaces a hexagonal input to a square-shaped output aperture. Injection moulding of PMMA has been successfully tested as a production method, appropriate for large-scale production. These light guides have been utilized for the first time in the FACT camera front plane. For future projects, there is

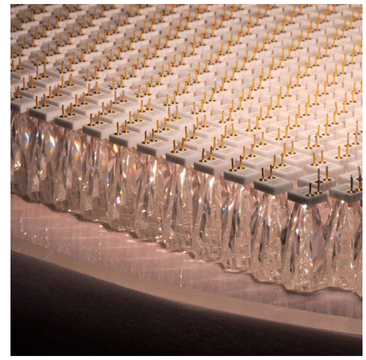

Figure 8: The FACT camera frontplane from a lateral point of view.

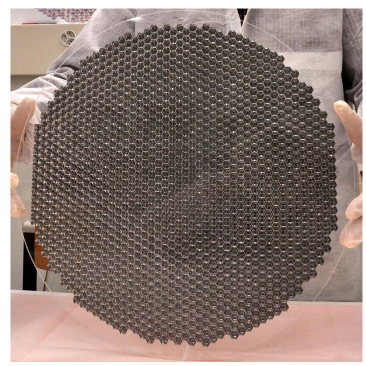

Figure 9: The FACT camera frontplane viewed from the front.

the option to substitute the manual placement of the light guides on the front window by a robotic assembly.

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