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Physics Procedia 37 (2012) 709 – 714

Physics Procedia

TIPP 2011 – Technology and Instrumentation in Particle Physics 2011

Light concentrators for Silicon Photomultipliers

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Abstract

Photosensitive devices represent a key solution for several current and future categories of experiments in which photon detection is the crucial point for the observation of physical phenomena.
Astro particle experiments for instance, one of the most promising observation channels for High Energy Physics, typically study energetic phenomena in which charged particles originating from the interactions or decays of primary particles radiate Cherenkov or fluorescence light, which is then detected by photosensitive devices.
In these fields of applications, the Silicon Photomultipliers (SiPM) devices based on the limited Geiger-mode avalanche (generally G-APD, Geiger Avalanche Photons Detectors), are extensively under study.
Unfortunately, applications of SiPMs are very limited by their small sensitive surfaces. In order to overcome the limits of the small dimensions of the sensitive area of SiPM devices, different solutions are reported. In particular it is discussed the use of Optical Concentrators with the correct refraction index, characteristic and geometry for the improvement of the sensitive surface dimensions of a SiPM device.

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KEYWORDS: Silicon photomultipliers; Geiger mode APD; Astro-particles; Photon detection; Photomultipliers; Light Concentrators; Scintillators; Cherenkov effect; MPPC;

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1. Introduction

Photosensitive devices represent a key solution for several current and future categories of experiments in which light detection can be considered the main observation channel for physical phenomena. Silicon Photomultipliers (SiPM) based on the limited Geiger-mode avalanche (generally G-APD, Geiger Avalanche Photons Detectors) are extensively studied in view of their future applications. Nevertheless they suffer of a generally limited sensitive surface, currently between 1 and 9 mm^2. Intrinsic noise depends linearly on the surface, thus limiting device with larger sensitive area. A solution to increase SiPM optical performances should be the use of Optical Concentrators with the correct refraction index, characteristic and geometry, in order to improve the SiPM's "field of view". We carried out several Monte Carlo simulations in order to estimate the collection efficiency of the light concentrator and to study its dependence on the length of the funnels and on the photons incidence angle. Various types of paraboloids and pyramidal light concentrators were examined by simulations and measurements.

2. Compound Parabolic Concentrators

Compound Parabolic Concentrators (CPC) [1], are light-collection devices intended to concentrate light on a smaller area. Characteristic parameters for CPCs are: dimensional geometry, compression, acceptance angle and collection efficiency.

A three-dimensional CPC is designed by rotating a parabola around the optical axis. The analytical description of the CPC profile is given by the following equation [1]:

$$\begin{aligned}&(r\cos\theta_{max} + z\, sin\theta_{max})^2 + \\ &+2a'(1+sin\theta_{max})^2 r - 2a' cos\theta_{max}(2+sin\theta_{max})^2 z + \\ &-a'^2(1+sin\theta_{max})(3+sin\theta_{max}) = 0\end{aligned} \quad (1)$$

in which θ_{max} is the acceptance angle and *a'* is the exit aperture radius. *r* e *z* are, instead, the reference axes as shown in Figure 1.

A useful ratio for describing the characteristics of a concentrator is the geometrical concentration ratio or compression [1] defined as:

$$C = \text{entrance surface / exit surface} \quad (2)$$

The theoretical maximum concentration ratio for a three-dimensional design is thus given by:

$$C_{max} = \frac{a^2}{a'^2} = \frac{1}{sin^2\theta_{max}} \quad (3)$$

Thus, defining the transmission efficiency ε_{trans} as:

$$\varepsilon_{trans} = n_d / N_{phot} \quad (4)$$

where n_d is the number of photons reaching the exit aperture and N_{phot} is the total number of photons penetrating the entrance aperture, the collection efficiency (ε_{coll}) can be written as:

$$\varepsilon_{coll} = \varepsilon_{trans} \cdot C_{max} \quad (5)$$

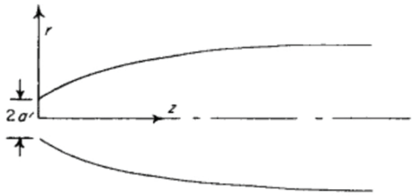

Fig. 1. CPC profile.

CPCs can be used to extend the detection surface of SiPM in low photon detection. In this case, also the impact point on entrance surface has to be taken into account since this leads to a non-homogeneous efficiency. As we will show, bests results are obtained with acceptance angles lower than 5°.

3. Simulations

In order to estimate the collection efficiency of the light concentrator and to study its dependence on the length of the funnels and on the angle of incidence of the photons we carried out several Monte Carlo simulations. Photons with a given direction were simulated at the entrance aperture and their path was followed until the funnel walls absorbed them or they left the funnel through one of the apertures. Various types of paraboloids and pyramidal light concentrators have been simulated.

In particular, for a CPC having a 0° acceptance angle[†] and with entrance and exit apertures of 28 mm and 5.5 mm radius, respectively, corresponding to a geometrical concentration ratio of 25.9, the transmission and the collection efficiencies are shown in Figure 2 as a function of photon incident angles (with a uniform distribution of photon impact point).

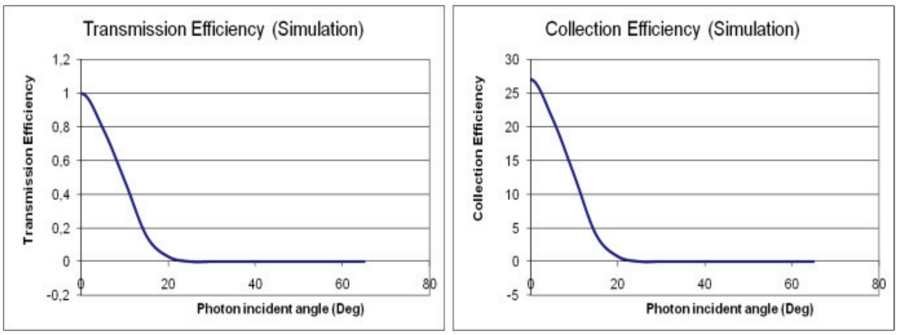

Fig. 2. Simulated transmission (left) and collection efficiency (right) as a function of incident photon angle.

As shown in Figure 2, the transmission efficiency is strongly suppressed for non-perpendicular photon incident angles in the case of devices designed with a 0° acceptance angle. However, the efficiency is about 50% for 10° incident angles.

[†] A CPC profile with 0° acceptance angle is given by equation (1) when $\theta_{max} = 0°$. Obviously, the effective acceptance angle depends on the CPC length. In this case, due to the finite length, we can see that the CPC has an effective acceptance angle of about 10°.

Concerning the collection efficiency, which takes into account also the compression ratio, simulation shows that, at about 20° photon incidence angle, the collection efficiency is equal to 1: the density of photons on the entrance surface is the same of that on the exit surface and the concentrator is useless.
In many experimental cases a wide acceptance angle is required, it makes sense to use a CPC to increase the detection surface of a silicon device only if the concentrator has a large acceptance angle.
To explore this option, a detailed simulation of a CPC with 25° acceptance angle ($CPC_{25°}$) has been performed. The simulated $CPC_{25°}$ is an optical B270 glass cone with 9.01 mm entrance diameter, 2.50 mm exit diameter and 19.25 mm length, which is commercially available by Edmund Optics [2]. Simulation studies show that the cone is able to transmit photons with incident angle up to about 25° with good collection efficiency, ranging between 0.5 and 0.8 depending on the incident angle, even if transmission efficiency for 0° incident photons is lower with respect to the case of a cone designed with a 0° acceptance angle.

4. Measurements

In order to experimentally check for simulation accuracy of the light concentrators we used two different settings. The first set up is shown in Figure 3.

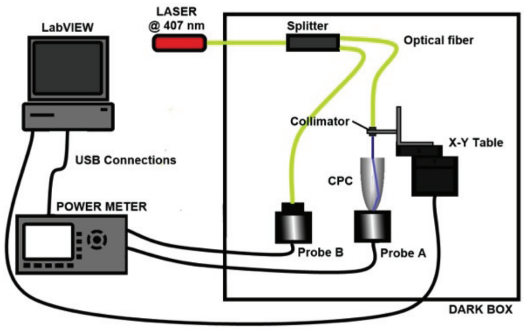

Fig. 3. The first experimental setup.

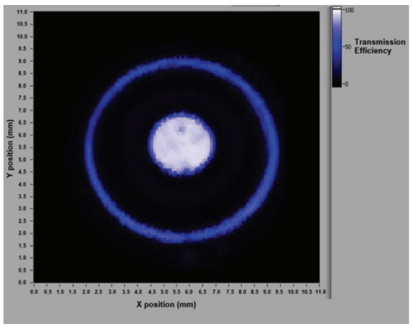

Fig. 4. Transmission efficiency on the entrance surface of the $CPC_{25°}$.

.The efficiency of a $CPC_{25°}$ has been measured as a function of the impact position on the cone entrance surface by employing a computer controlled x-y movement with a position precision of tens of microns. A λ=407 nm highly collimated pulsed laser beam (diameter spot = 0.9 mm) has been sent on the $CPC_{25°}$ and both beams at entrance and exit surfaces have been measured by a double channel Power Meter Newport mod. 2936-C. The measured intrinsic efficiency is strongly dependent on the impact point of the photon on the entrance surface, as shown in Figure 4.
The transmission efficiency measurements along the $CPC_{25°}$ diameter, superimposed to the simulation results, is shown in Figure 5 for impinging photons at 0° and at 20°: the simulation correctly reproduces the measurements and confirms the dependence of efficiency on the photon impact point on the entrance surface.
Discrepancy in the maximum collection efficiencies between data and simulation is mainly related to the optical coupling between the $CPC_{25°}$ and the Power Meter probe, but also to the photon absorption in the B270 glass, to the intrinsic Power Meter probe efficiency and its dependence on the photon incident angle.
The same measurement has been repeated for several photon incident angles.

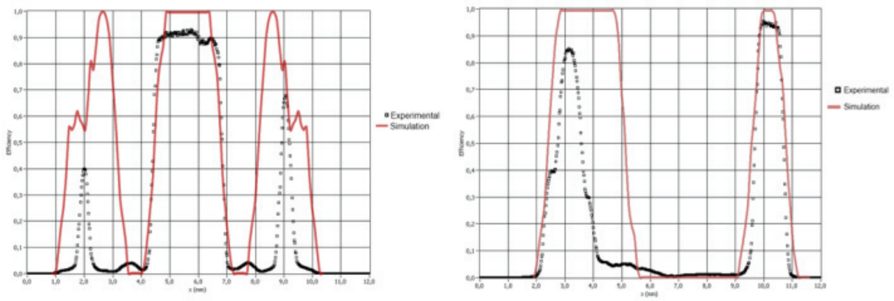

Fig. 5. Comparison between simulation and actual data on the CPC25° (CPC having an acceptance angle of 25°) for impinging photons at 0° (Left) and at 20° (Right).

This study shows as, in order to increase the detection surface of a SiPM by using parabolic concentrators, devices designed for small acceptance angles are preferred, with the better choice corresponding to 0°, but limiting in this way the field of view. Thus, the detection of radiation produced at fixed angles, as in experiments in which Cherenkov radiation has to be detected, can profit from the use of this solution.

In order to optimize the light concentration, a pyramidal device can be considered.

The pyramidal light concentrator used in this work is an optical glass N-BK7 device with 7.5 x 7.5 mm^2 entrance surface, 2.5 x 2.5 mm^2 exit surface and 50 mm length, commercially available by Edmund Optics [2]. Simulation studies have been carried out for this geometric structure.

Also for this light concentrator, the efficiency has been measured as a function of the impact position on the entrance surface by using the experimental set-up described in figure 3. The measured transmission efficiency is shown in figure 6 different incident angles.

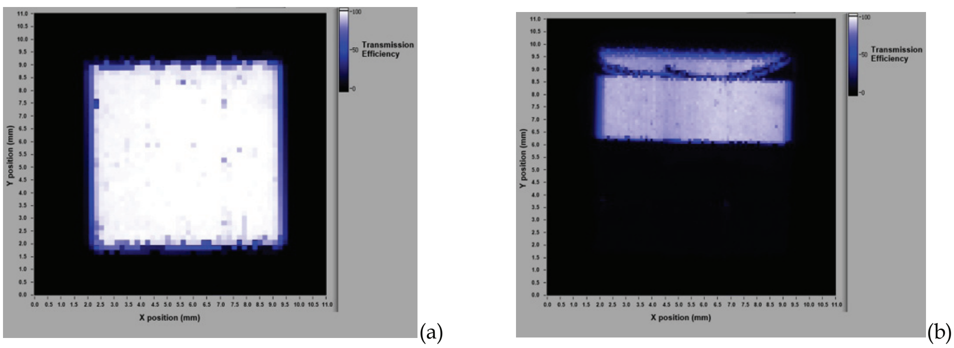

Fig. 6. Measurement of the transmission efficiency on the entrance surface of the pyramidal concentrator for 0° impinging photons (a) and 10° impinging photons (b).

Measurement results show that transmission efficiency of such a pyramidal light concentrator has a slight dependence on the impact point except for the case of incident angles of 10°. In fact, as shown in Figure 6(b), in this case a large part of the entrance surface (about one half) results in a very low efficiency (about 10%). Actually, this partial inefficiency may be due to the very large angles of exiting photons (>60°), out of the angular acceptance of the Power Meter probe. The experimental set-up described in Figure 3 has been used to measure the efficiency of the pyramidal concentrator.

A second method adopted to evaluate the effect of light concentrators is based on the measurement of photons detected with a 3x3 mm^2 MPPC S10931-025P by Hamamatsu arranged at the exit surface of the light concentrator.
The average number of incident photons on the concentrator can be determined by measuring the laser power on one of the two outputs of a splitter. The MPPC signal, amplified by the National Semiconductor LMH6624 chip, has been measured and by evaluating the number of photons detected by the MPPC an estimation of the overall efficiency of the system (light concentrator + MPPC) has been done.
Laser power has been set to send 40 photons on the surface of the $CPC_{25°}$, with a frequency of 100 kHz and at an incidence angle of 0°. The maximum total efficiency was measured for several distances of the impact point from the center along one diameter (Figure 7). Results show that the maximum obtainable efficiency is 0.1, while observing the dynamic range it is possible to note that this light concentrator is not useful to increase the field of view of a MPPC.
Figure 8 shows the efficiency measurement for several distance of the impact point from the center (along one dimension) and for several incident photon angles in the case of a pyramidal concentrator. Again it can be observed that the maximum total efficiency is 0.1, but in this case the total surface is enhanced. Furthermore, the efficiency results to be very uniform for incident angles in the range 0°-10°.

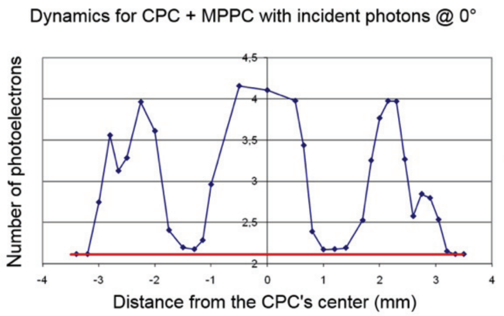

Figure 7. Number of photoelectrons as a function of the distance of impact point from the centre for the CPC.

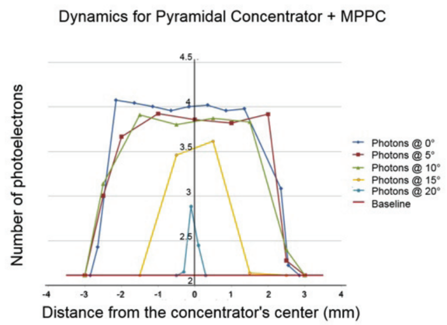

Fig. 8. Efficiency measurement for several distance of impact point from the center (along one dimension) and for several incident photon angles for the pyramidal.

5. Conclusions

The development of evoluted SiPM in which a front side illuminated detector structure with quenching resistor is integrated into the silicon bulk, would surely enhance the overall efficiency of the concentrator + MPPC system. In such a design the fill factor will only be limited by the gaps necessary for the suppression of the optical cross-talk and can reach theoretically 100% [3]. In fact several structures which contribute as optical obstacles (like metal lines or contacts) are here suppressed. Hence it will be possible to achieve very interesting global efficiencies of the order of 35-40%, which must be compared with the limit of 30% introduced by the fill factor only and that represents the main limit to the global efficiency. In this way the features of a SiPM + concentrator move in the direction of overcoming the properties of the classical PMT, with interesting possibilities of applications in Čerenkov and fluorescence light detectors.

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