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Novel silicon photomultipliers suitable for dual-mirror small-sized telescopes of the Cherenkov telescope array

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ABSTRACT

Many of the characteristics of Silicon Photomultipliers (SiPMs), such as high Photon Detection Efficiency (PDE), are well matched to the requirements of the cameras of the Small-Sized Telescopes (SSTs) proposed for the Cherenkov Telescope Array. In fact, compared to a single mirror, the double mirror Schwarzschild–Couder configuration provides a much better Point Spread Function over a large field of view. It allows better correction of aberrations at large off-axis angles and facilitates the construction of compact telescopes. Moreover, the small plate scale of the dual-mirror SSTs allows the use of SiPM detectors despite their small pixel sizes. These sensors have two further advantages compared to the Photo Multipliers Tubes: the low cost and the possibility to observe in very high Night Sky Background (NSB) light level without any damage. However, one area in which SiPM performance has required improvement is Optical Cross-Talk (OCT), where multiple avalanches are induced by a single impinging photon. OCT, coupled with the typical NSB rate of 25 MCnts/s per pixel during Cherenkov observations, can place severe constraints on the triggering capability of the cameras. This paper describes the performance of novel Low Voltage Reverse (LVR) 2nd and 3rd generation Multi-Pixel Photon Counters manufactured by Hamamatsu Photonics. These are designed to have both enhanced PDE and reduced OCT. Two 7×7 mm^2 S14520 LVR2 MPPCs with 75 μm micro-cells are tested and compared with detectors of the same pixel size with 50 μm micro-cells. A comparative analysis of a 3×3 mm^2 S14520 LVR2 device and an S14520 LVR3 device is also carried out, demonstrating that the LVR3 gives better photon detection in the 240 – 380 nm wave-length range. Finally, the effect of an infrared filter on the OCT is analysed.

Contents

1. Introduction

The Cherenkov Telescope Array (CTA) [1] is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. It will be based on more than one hundred telescopes, located in two sites (in the northern and southern hemispheres). CTA will build on the strengths of current Imaging Atmospheric Cherenkov Telescopes (IACT), employing three telescope designs combined in the Large-Sized Telescope, Medium-Sized Telescope, and Small-Sized Telescope (SST) array to enhance the sensitivity by up to an order of magnitude

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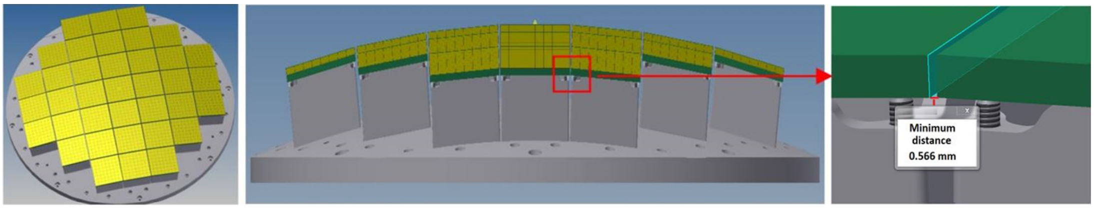

Fig. 1. ASTRI camera focal plane assembly. The telescope curved focal plane imposes the arrangement of detection modules and the maximum allowable dimensions of the tiles.

compared with current facilities [1,2] in the 100 GeV to 10 TeV range and extend the accessible energy range from 20 GeV to 300 TeV. The SST array sensitivity and coverage are optimized from a few TeV to 300 TeV. About 70 SST telescopes are planned to be placed in the CTA southern site to cover several square kilometres in order to achieve the necessary sensitivity. Because of the large number of telescopes required, cost reduction is critical for the SST. However, the camera cost cannot be reduced by simply decreasing its size, due to the minimum number of pixels required (>1000) and the relatively high unit cost of traditional photon sensing photomultiplier tubes (PMTs). In order to mitigate this problem, the SST utilizes silicon photomultipliers (SiPMs) as the baseline photon sensor technology [3]. Currently, SiPM detectors with large size (i.e. 20×20 mm^2) surely suffer from high dark count rates and very high recovery time. One solution is to make use of dual-mirror optics which have a relatively small plate scale and whose focal plane can be covered with SiPMs with sizes ranging from 6×6 mm^2 to 7×7 mm^2 [4].

SiPM detectors, thanks to their outstanding characteristics in terms of photon detection efficiency, photon number resolution, low operating voltage, fast dynamic response and insensitivity to magnetic fields, are suitable in the fields of high-energy astrophysics and IACT applications [5–13]. Considerable effort is presently being invested by the producers of SiPMs to further improve the performance achieved by this class of devices [14–16]; moreover, characterization studies and methodologies for evaluating the detector performance have been carried out [17–25]. Currently, we can safely assert that the SiPMs Photon Detection Efficiency (PDE) is greater than that of PMTs in the 300–700 nm spectral range, but another SiPM parameter has to be carefully considered: the optical cross-talk, a mechanism whereby a single optical photon can produce multiple avalanches in the SiPM. In CTA, the night sky background level of typically 25 MCnts/s/pixel places severe constraints on the trigger capability due to accidental coincidence of neighbouring pixels. In order to suppress such events, it is necessary to reduce optical cross-talk at very low level, while keeping good Photon Detection Efficiency. An OCT probability lower than 10% and a PDE higher than 25% meets the SST requirements.

This paper presents the characterization of a newly available large-area Low Voltage Reverse (LVR) 2nd and 3rd version Multi-Pixel Photon Counter (MPPC) detectors manufactured by Hamamatsu Photonics (HPK). These devices, can reach saturating PDE at lower over-voltage compared with Low Cross Talk (LCT), which means LVR devices can achieve higher PDE at lower OCT since OCT scales with over-voltage. Such detectors are suitable for the camera focal plane of the SST double mirror (Astrofisica con Specchi a Tecnologia Replicante Italiana) ASTRI telescopes [8] proposed for the CTA southern site. In order to show the perfect ASTRI camera fitting and the good geometrical fill factor achieved, a brief description of the relevant mechanical parameters is also provided.

Two 7×7 mm^2 S14520 LVR2 MPPCs with 75 μm micro-cells have been tested and a comparative analysis of the large pixel pitch (75 μm) detector versus the smaller pixel pitch (50 μm) device with the same active area is here described.

HPK selected the product code S14520 for the LVR devices (dedicated only to the CTA project). From now on we will cite the LVR series and leave out the product code.

We also carried out PDE measurements on a 3×3 mm^2 LVR3 SiPM detector and compared it with an LVR2 device. The results demonstrate that the LVR3 device gives better PDE in the 280–380 nm spectral range.

The effect of an optics (an infrared cut-off filter in the specific case of the ASTRI camera) placed in front of an SiPM on the OCT is described.

The measurements shown here are carried out at the Catania astrophysical Observatory Laboratory for Detectors (COLD) within INAF – Osservatorio Astrofisico di Catania.

2. ASTRI focal plane coverage and SiPM relevant mechanical parameters

The double-mirror optical configuration of the ASTRI telescopes permit us to design a compact and lightweight camera to be placed at the curved focal surface. The detection surface requires a spatial segmentation with an interspace of a few millimetres to be compliant with the imaging resolving angular size (0.19°). In order to match the angular resolution of the optical system, the design of the ASTRI camera has to comply with the dimensions of the single pixel and of the basic detection module (the tile). Since the convex shaped focal surface of the ASTRI camera has a curvature radius of about 1m, the curved surface of the camera has to fit with a certain number of square pixels without losing the required focusing capability of the optical system. This specification is physically accomplished by a pixel of about 7×7 mm^2 and a detection module of 57.6×57.6 mm^2.

Fig. 1 shows the focal plane assembly. A total of 37 detection modules (2368 pixels) form the camera at the focal plane; this structure is capable of achieving a full Field of View (FoV) of 10.5°.

The technical feasibility of this design has been demonstrated with the ASTRI optical validation [26].

Using 7×7 mm^2 SiPM detectors with a pitch-size of 75 μm, 93 micro-cells fill completely a pixel sensitive area, giving a total of 8649 micro-cells. This ensures a sufficiently high dynamic range as required by the CTA project. An 8×8 tile will cover a total area of 57.6×57.6 mm^2 meaning 3317.76 mm^2, 6.975×6.975 mm^2 being the active area of each pixel, 0.2 mm the interspace between pixels and 0.2 mm the tile edge spacing. The total active area is 3091.36 mm^2 and thus a tile geometrical filling factor of 93.18% is achieved. Fig. 2 shows the tile schematics, a single 7×7 mm^2 pixel and the edge detail.

3. Large-area low voltage reverse 2nd and 3rd version SiPM detectors

The optical trench improvement, started with the LCT series and characterized by new types of trenches that enabled cross-talk reduction, has been continued in the new denominated Low Voltage Reverse family. On the other hand, the fill-factor improvement of the new LVR series is achieved by maximizing the active area.

The characterized large-area SiPM described in this paper belongs to the latest device series manufactured by Hamamatsu Photonics, denominated LVR family and reported as the MPPC LVR2 CS (Ceramic package Silicone coating) and CN (Ceramic package No coating) and LVR3 CS and CN series. These are prototype devices provided by the vendor to the COLD laboratory for testing and evaluation purposes. Fig. 3 shows the three characterized devices while Table 1 reports the main features of the characterized detectors.