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The measurement and evaluation of the SiPM PDE for the LACT camera

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The Large Array of Imaging Atmospheric Cherenkov Telescopes (LACT) project plans to deploy 32 imaging atmospheric Cherenkov telescopes with 6-meter apertures at the LHAASO site. This initiative aims to precisely resolve the ultra-high-energy gamma-ray sources previously identified by the LHAASO experiment. The SiPM camera is located at the focal plane of the telescope. It will measure the shape and the intensity of the weak atmospheric Cherenkov light cone under the night sky background (NSB) light. The SiPMs' photon detection efficiencies at different wavelengths affect the detection signal-to-noise ratio for the atmospheric Cherenkov light under the NSB light. This paper reports a pulsed-light measurement method for the SiPMs' photon detection efficiency(PDE), covering the wavelength range from 310 nm to 500 nm. The candidates from multiple manufacturers are tested through this method.

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1. Introduction

The Large Array of Imaging Atmospheric Cherenkov Telescopes (LACT) project will construct 32 six-meter aperture imaging atmospheric Cherenkov telescopes at the LHAASO (Large High Altitude Air Shower Observatory) site located at Haizi Mountain, Daocheng, Sichuan province, China[1]. Its primary scientific objective is to achieve high-precision morphological studies of ultra-high-energy gamma-ray sources through joint observations with LHAASO's Muon Detector (MD) array, leveraging the MD array's exceptional cosmic-ray suppression capability to enhance background rejection. LACT comprises 32 imaging atmospheric Cherenkov telescopes, each equipped with a 6-meter-diameter Davies-Cotton optical system and a silicon photomultiplier (SiPM) camera system composed of 16×16 pixels (0.2°/pixel field of view)[2].

The SiPM camera is mounted at the focal plane of the telescope. It will measure the shape and intensity of the Cherenkov light cone when the Cherenkov light is reflected and focused by the mirror disc onto the camera's surface. To improve the detection signal-to-noise ratio for the weak and flashing Cherenkov light under the night sky background, the photon detection efficiency (PDE) of SiPMs in the short wavelength band will play an important role.

The conventional DC-based optical calibration approach for SiPM performance characterization exhibits three major drawbacks: firstly, it imposes stringent requirements on the spatial uniformity and temporal stability of the light source, thereby increasing experimental complexity and cost[3]; secondly, its inherent measurement mode results in slow data acquisition rates, severely limiting throughput and rendering it inadequate for large-scale applications; thirdly, the testing conditions deviate significantly from actual SiPM operational environments. To overcome these constraints, this study introduces a pulsed-light calibration strategy. This approach not only relaxes dependence on source uniformity but, more significantly, better emulates the actual operational conditions of SiPMs when detecting transient Cherenkov light signals, thereby furnishing more robust and representative data essential for optimizing the performance of the LACT detector.

2. Experimental Design

2.1 Measurement Principle of SiPM PDE

In the paper, a SiPM independently measured by the National Institute of Metrology of China was employed as the reference standard device. Its calibration results were consistent with the manufacturer's specifications, with deviations less than 1%. Both the device under test (DUT) and the reference SiPM were sequentially illuminated under identical geometric conditions by a multi-wavelength LED light source operating in pulsed mode, covering a wavelength range from 310 nm to 500 nm.

The PDE measurement was based on a comparative method. First, under single-photon conditions, the absolute gain G_{refer} of the reference SiPM was measured using Equation (1)[4]. Subsequently, under identical pulsed photon flux conditions, the relative PDE of the device under test (DUT) was determined by comparing its output signal amplitude with that of the reference SiPM. In data analysis, the influence of optical crosstalk was subtracted using a standard methodology. However, contributions from afterpulsing were not corrected in the final results due to the difficulty in accurately quantifying afterpulse probability under the current experimental configuration.

$$y(x) = \text{Const} \times \sum_{n=0}^{\infty} \left(\frac{\mu^n}{n!} e^{-\mu} \times \frac{1}{\sqrt{2\pi}\sigma n} e^{-\frac{(x-n\cdot G)^2}{2\sigma_n^2}} \right) \quad (1)$$

- μ: The average number of photoelectrons per LED light pulse.
- G: The probe gain in units of ADC count/p.e. (measured as 5.717 ± 0.003 mV/p.e.).
- $\sigma_n = \sqrt{\sigma_{ele}^2 + n\sigma_{cell}^2}$
- σ_{ele}: Electronic noise
- σ_{cell}: Uncertainty of the avalanche gain for a single Si-APD cell.
- Const: The normalization constant Const represents the total event count, determined by the integral of the fitted curve and the total data.

The optical crosstalk (CR) phenomenon, which occurs in silicon photomultipliers (SiPMs), is formally defined as: The conditional probability of a primary avalanche triggering one or more secondary avalanches through photon emission. This is quantified by the ratio:

$$CR = \frac{N_{\text{xtalk}}}{N_{\text{total}}} \quad (2)$$

where:

- N_{xtalk} denotes the count of cross-triggered avalanche events
- N_{total} represents the total trigger count, including both primary and secondary events

To measure the intrinsic CR probability CR_{refer} of the reference SiPM, its noise signals were first recorded in a dark environment without any light source. By analyzing the amplitude distribution of the noise (Fig. 1b), the mean (μ) and standard deviation (σ) were determined. Signal events with amplitudes exceeding $\mu + 2\sigma$ (corresponding to a confidence level greater than 97.7%) were identified as originating from CR. The ratio of the number of crosstalk-induced events to the total number of events yields CR_{refer}. This procedure enabled the determination of the intrinsic crosstalk probability CR_{refer} for the reference SiPM.

Subsequently, the intensity of the pulsed light source was adjusted to I_λ, and the average output signal amplitude $S_{\lambda\text{-refer}}$ of the reference SiPM sample under this illumination condition was measured.

The initial photoelectron number $N_{\text{pe-}\lambda\text{-raw-refer}}$ was calculated using Equation (3), and finally, the effective photoelectron number $N_{\text{pe-}\lambda\text{-refer}}$ was obtained by applying the CR correction formula (4).

$$N_{\text{pe-}\lambda\text{-raw--refer}} = \frac{S_{\lambda\text{-refer}}}{G_{\text{refer}}} \quad (3)$$

$$N_{\text{pe-}\lambda\text{-refer}} = \frac{N_{\text{pe-}\lambda\text{-raw--refer}}}{1 + \text{CR}_{\text{refer}}} \quad (4)$$

Under identical incident photon flux I_λ, the output signal amplitude $S_{\lambda\text{-test}}$ of the device under test (DUT) SiPM sample was measured. (Note: The intrinsic parameters of the DUT SiPM—specifically, its absolute gain G_{test} and CR probability CR_{test}—were independently determined through the same single-photoelectron calibration procedure and crosstalk analysis protocol as described previously.)

First, the uncorrected raw photoelectron number was calculated according to Equation (3). Subsequently, the true effective photoelectron number $N_{\text{pe-}\lambda\text{-test}}$ detected by the DUT SiPM was obtained by applying the crosstalk correction formula (4).

Finally, the photon detection efficiency (PDE) of the DUT SiPM at wavelength λ was determined via the comparative method. Under identical incident photon flux I_λ, the crosstalk-corrected photoelectron numbers for the reference and DUT SiPMs, denoted as $N_{\text{pe-}\lambda\text{-refer}}$ and $N_{\text{pe-}\lambda\text{-test}}$, were measured respectively. After accounting for differences in their active areas, the PDE of the DUT SiPM was calculated using Equation (5):

$$\text{PDE}_{\text{test-}\lambda} = \text{PDE}_{\text{refer-}\lambda} \times \frac{N_{\text{pe-}\lambda\text{-test}}}{N_{\text{pe-}\lambda\text{-refer}}} \times \frac{A_{\text{refer}}}{A_{\text{test}}} \tag{5}$$

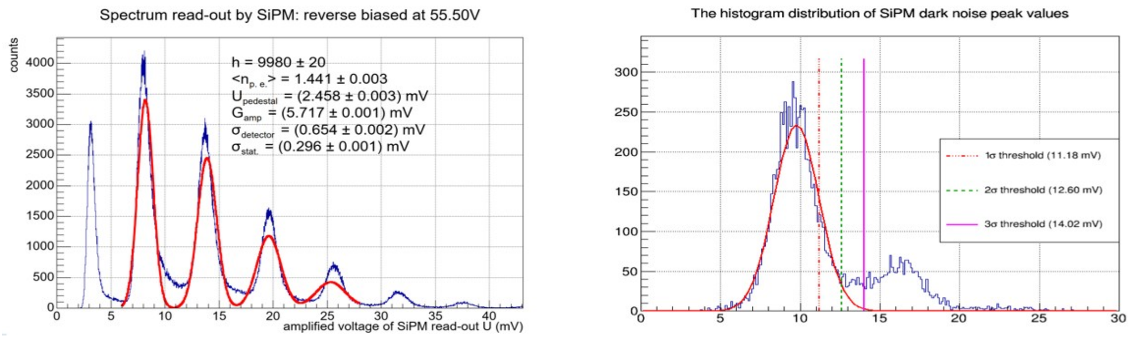
Among these:

- $PDE_{\text{refer}-\lambda}$ denotes the PDE value of the reference SiPM at wavelength λ, which was pre-measured by the National Institute of Metrology of China and has undergone corrections for CR effects.
- A_{refer} and A_{test} represent the effective photosensitive areas of the reference and DUT SiPM samples, respectively.
- $N_{\text{pe}-\lambda-\text{refer}}$ and $N_{\text{pe}-\lambda-\text{test}}$ indicate the corrected photoelectron numbers detected by the reference and DUT samples under identical incident photon flux I_λ.

2.2 Schematic Configuration & Parameter Optimization

To measure the photon detection efficiency (PDE) of silicon photomultipliers (SiPMs), we constructed a dedicated test platform (Fig. 2) within a darkroom. The core of this system is a multi-wavelength pulsed LED light source, emitting across a spectral range of 310 nm to 500 nm. This wavelength band not only covers the high-responsivity region of SiPMs but also fully encompasses the primary energy distribution of their intended detection targets (e.g., atmospheric Cherenkov light), making it an ideal choice for performance calibration. The pulsed characteristics of the light source (full width at half maximum of 15 ns, repetition rate of 1 kHz) are controlled by a high-precision signal generator, which simultaneously provides trigger signals to the oscilloscope, ensuring strict synchronization of photoelectric signal acquisition.

Control of light intensity is critical for the experiment. To achieve this, we adjusted the driving voltage of the LED to produce different output photon fluxes: a low driving voltage of 3.8 V was used during the calibration of the SiPM single-photon spectrum and gain to obtain single-photon signals; during PDE measurements, a driving voltage of 8.0 V was employed to provide sufficient photon flux. The SiPM under test was biased by a low-noise DC power supply (typical value 55.5 V). The weak anode signals generated were first amplified by a low-noise amplifier with a gain of 41



(a) **(b)**

Figure 1: Single-photoelectron response characteristics and dark noise analysis of the SiPM under a reverse bias voltage of 55.50 V.
(a) Single-photoelectron spectrum measured under pulsed illumination (blue scatter points) showing resolved peaks corresponding to 0, 1, 2, and 3 photoelectron events, with a peak separation of approximately 5.717 mV. The distribution is fitted with a Poisson-Gaussian convolution model (red solid line) with $\mu = 1.441$.
(b) Dark noise peak amplitude histogram used for calculating the CR probability. The threshold $\mu + 2\sigma$ (12.60 mV, green dashed line) demarcates events attributable to CR, enabling quantitative determination of the CR probability.

and a bandwidth of 42.7 MHz, and then transmitted via a 50 Ω impedance-matched coaxial cable to a 1 GHz bandwidth, 10 GSa/s sampling rate oscilloscope for digitization.

The entire optical path system was enclosed within a light-tight darkroom to eliminate interference from ambient stray light. Ultimately, the raw waveform data acquired by the oscilloscope were transferred to a computer and processed using custom algorithms (e.g., peak extraction, charge integration, and statistical analysis) to derive core performance parameters of the SiPM, including photon detection efficiency, gain, and CR.

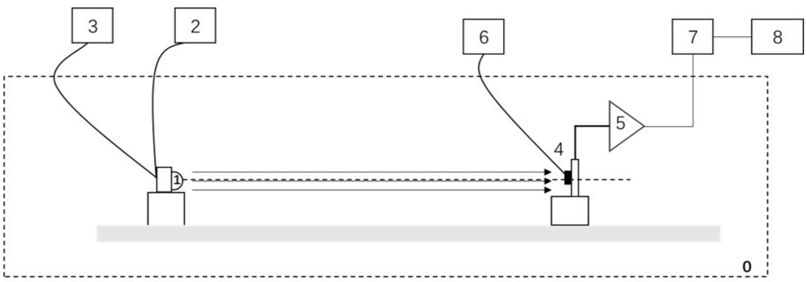


Figure 2: SiPM Photon Detection Efficiency Measurement Block Diagram, The numerical designations correspond to: 0 - Light-tight enclosure (dark chamber) 1 - LED light source 2 - DC linear power supply 3 - signal generator 4 - Silicon Photomultiplier (SiPM) 5 - Front-end signal amplification PCB 6 - SiPM bias voltage supply 7 - oscilloscope 8 - computer

3. Performance Characterization

To evaluate the performance of different silicon photomultiplier (SiPM) products, this study employed a certified S14466-type SiPM from the WFCTA project, measured by the National

Institute of Metrology of China, as the reference standard. Comparative tests were conducted on SiPM samples from multiple manufacturers, including Hamamatsu, Onsemi, NDL (Zhongjing Optoelectronics), and Broadcom. Key parameters of each tested device (such as active area, pixel size, and operating voltage) are detailed in Table 1.

Table 1: Key parameters of tested SiPM devices

Type	**Active Area (mm^2)**	**Cell Size** (µm)	$\mathbf{V_{br}}$ **(V)**	$\mathbf{V_{op}}$ **(V)**
HAMAMATSU-S14466	25.00	25	50.72	59.22
HAMAMATSU-S17351-SR	21.12	25	51.55	38.50
HAMAMATSU-S17351-HR	21.12	25	51.30	59.42
Broadcom-AFBR-S4N66P014M	36.00	40	32.34	59.71
onsemi-J-40035	15.4449	35	24.50	28.00
NDL-EQR20-11-6060D-S	38.9376	20	27.80	32.00

The CR probability was measured under the same bias conditions as the PDE tests (specific bias voltages are listed in Table 1), with the test environment maintained at 15±0.5°C. As shown in Fig. 1b, 10^5 dark noise events were collected under complete light shielding. Based on the single-photoelectron gain calibration result (5.717 mV/p.e., Fig. 1a), an amplitude threshold of $\mu + 2\sigma$ (12.60 mV) was applied to identify crosstalk events, corresponding physically to secondary avalanches triggered by a single thermally generated electron. The intrinsic crosstalk probability of each device (results summarized in Table 2) was obtained by calculating the ratio of events exceeding this threshold ($CR = N_{\text{xtalk}}/N_{\text{total}}$). Using the crosstalk correction relation in Equation (4) (where CR values are taken from Table 2), the apparent photoelectron number $N_{\text{pe-}\lambda\text{-raw-refer}}$ was converted to $N_{\text{pe-}\lambda\text{-refer}}$, reflecting the true photon events. This step eliminated a systematic bias of approximately $CR/(1+CR) \times 100\%$.

Table 2: CR probability measurements across tested SiPM models

Type	S14466 (Ref.)	J40035 -Onsemi	S17351 -HR	S17351 -SR	NDL -EQR20-11-6060D-S	Broadcom -AFBR-S4N66P014M
Crosstalk (%)	5	22	3	1	19	25

It is noteworthy that the subtle discrepancies between the measured data and the actual true values primarily stem from three factors:

1. Potential differences in the overvoltage settings between this study and the manufacturer's test conditions;

2. Nonlinear response effects of SiPMs under higher photon fluxes;

3. The influence of afterpulses has not been subtracted.

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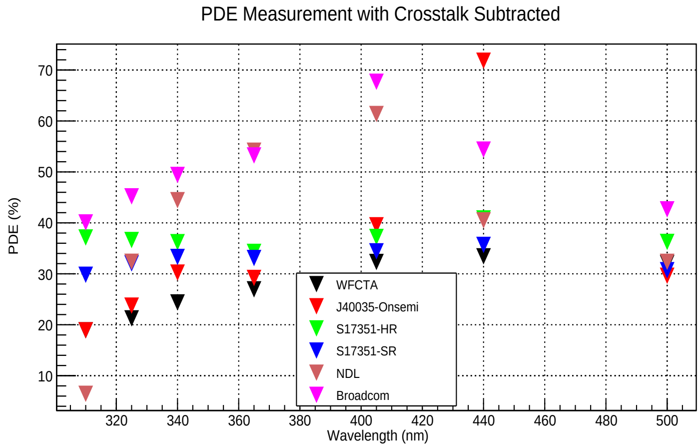

Figure 3: The measured PDE results after crosstalk correction (test temperature:15±0.5°C).

4. Summary

This paper reports a measurement method for photon detection efficiency of SiPMs based on the multi-wavelength pulsed-light source. The measurement results will better meet the detection requirements for flashing Cherenkov light, with a duration range from several nanoseconds to tens of nanoseconds. Additionally, this method did not account for the influence of the after-pulse on the PDE measurement. This should be clearly stated.

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