Clarification

Dear Editor and Reviewers,

This paper partly overlap with another paper accessed from the website: 'https://pos.sissa.it/301/427/pdf'.

The latter one is my proceeding article at the International Cosmic Ray Conference hold at Busan, South Korea. The ICRC was hold about two months after TIPP and the paper is much longer than this one. So the proceeding paper of ICRC contains more details and more results.

Regards,

Baiyang

Silicon Photomultiplier Performance Study and Preamplifier Design for the Wide Field of View Cherenkov Telescope Array of LHAASO

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Abstract. The Wide Field of View Cherenkov Telescope Array (WFCTA), a main component of the LHAASO, requires a dynamic range between 10 and 32000 photoelectrons (pes) and stable gain of the photosensors. Silicon photomultipliers (SiPMs) are relatively new kind devices with respect to photomultipliers (PMT). Their performance are improving very rapidly since 1990s. SiPMs suffer for negligible ageing even under strong light exposure. SiPM-based cameras could operate under high moon conditions and their duty-cycle is larger than that of PMT-based camera. The design of preamplifier for the WFCTA camera is described this paper. Moreover properties of the SiPMs are studied, such as their linearity at high number of photoelectrons. An analytical function is derived to relate number of fired cells and the total number of cells in the SiPM. We also compare the performance of SiPMs and PMTs under long light pulses up to 3 μs. Furthermore, the additional non-linearity due to disuniformities in light distribution is also evaluated.

Keywords: SiPM; Dynamic Range; Long Duration Pulse; LHAASO; WFCTA.

1 Introduction

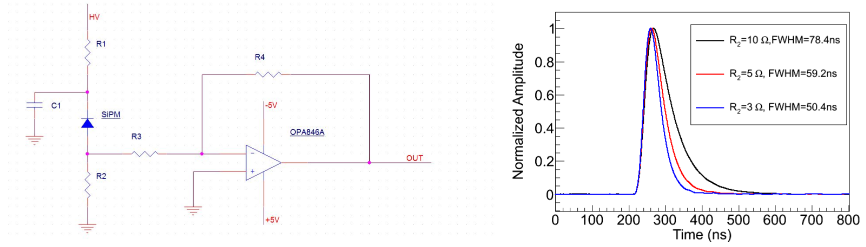
The Large High Altitude Air Shower Observatory (LHAASO) is a hybrid experiment designed for γ-ray astronomy and cosmic rays studies[1, 2]. The Wide Field of View Cherenkov Telescope Array (WFCTA), one of its three main component detectors, will be operated in two observation modes. The Cherenkov mode requires a photosensor dynamic range from 10 to 32,000 pes and the fluorescence mode requires that the gain of the sensor is stable for long duration light pulse up to 3 μs. The SiPM developed rapidly since 1990s, the gain of which is around 10^6 while the voltage is less than $100\ V$. The SiPM-based cameras can be operated with moonlight and achieves a larger duty cycle than PMT-based cameras. The First G-APD Cherenkov Telescope has been exploring the use of the SiPM technology [3] and CTA project will use the SiPM on single-mirror Small Size Telescopes (SST-1M) and dual mirror SSTs[4]. In this paper, the design of preamplifier is illustrated, the test results are shown, and additional non-linearities is simulated.

2 The SiPMs and Preamplifier

Fig. 1(a) illustrates the preamplifier for the SiPM. The resistor R_2 is to convert the output from current to voltage, which influences the output pulse shape(Fig. 1(b)). The pulse width is about $50ns$ when $R_2 = 3\Omega$. When the resistance value of R_2 increases to 10 Ω, the pulse width increases to about 78 ns. The pulse width of $50ns$ is suitable for the 50 MHz FADC in WFCTA electronics system. The preamplifier OPA846 has very high gain bandwidth and large signal performance with very low input voltage noise. The OPA846 can work in good performance at a high gain, e.g. +10. The capacitor C_1 is used to keep the operating voltage of the SiPM stable, especially during long light pulses. The parameters of SiPM samples from Hamamatsu, FBK and SensL are listed in Table 1. The avalanche photodiode microcell (APD) dimension of SiPM samples is $25\mu m$. The break down voltage of SiPMs is sensitive to the temperature. The break down voltage varies about $54mV/^{\circ}C$ for Hamamatsu's SiPM candidates, about $26mV/^{\circ}C$ for FBK's and about $21.5mV/^{\circ}C$ for SensL's. The fill factor of FBK's and SensL's candidates is higher than Hamamatsu's, so the photon detection efficiency (PDE) of FBK's and SensL's candidates is higher.

Table 1. Details information of the SiPMs we studied.

Models	PDE	Fill factor	Dark count rate	Cross talk	Gain (10^6)
S13361-5488 (Hamamatsu)	25%@400nm	47%	$45kHz/mm^2$	1%	0.70
FBK-25 (FBK)	38%@400nm	72%	$80kHz/mm^2$	15%	1.38
MicroJ-30020 (SensL)	33%@400nm	62%	$80kHz/mm^2$	5%	1.70



(a) (b)

Fig. 1. (a) The scheme of the preamplifier for the SiPM. (b) The pulses for different value of R_2 under a fixed intensity of light. The amplitudes are normalized to 1.

3 Performance of SiPMs

The response of the SiPM at the condition of uniform photons is expressed as Eq. (1). The APD works in Geiger mode which means the saturation happens when more than one photons hit on the same APD during the same readout window [5]. The expectation number of photon electrons (N_{pe}) can be exacted from the function of Eq. (1) and is expressed as Eq. (2).

$$N_{fired} = N_{cell}(1 - e^{-PDE \cdot N_{ph}/N_{cell}}) = N_{cell}(1 - e^{-N_{pe}/N_{cell}}) \tag{1}$$

$$N_{pe} = N_{cell} ln(\frac{1}{1 - N_{fired}/N_{cell}}) \tag{2}$$

where N_{fired} is the number of fired APDs and N_{cell} is the total number of APDs. N_{ph} is the number of photons hitting on the SiPM, and $PDE \cdot N_{ph}$ is equal to N_{pe}.

As shown in Fig. 2(a), the nonlinearities follow the expectation predicted by Eq. (1) very well. The dynamic range of SiPMs is proportional to the total number of APDs. After correction with Eq. (2), the dynamic range are extended to 32,000 pes for the Hamamatsu and FBK SiPM samples. Because N_{cell} is smaller, the dynamic range of SensL SiPM samples can reach to about 6,000 pes after correction. The resolutions of the SiPM are the same before and after correction, which is shown in Fig. 2(b).

To investigate the performance of SiPM under long duration pulse, we compared the response of the SiPM with that of the PMT which is satisfactory for our requirements[6]. According to the test result illustrated in Fig. 2(c), the value of C_1 influences the stability of the SiPM while the duration of light is getting longer. At the condition of $C_1 = 0.1\mu F$, the SiPM has a poor performance. At the condition of $C_1 = 1\mu F$, the deviation of the gain of the SiPM is less than 2% from 20 ns to 3 μs.

4 Additional Non-linearity due to Non-uniform Light Distribution

Eq. (2) is based on the assumption that the distribution of photons on the surface of the SiPM is uniform. However, photons are collected by sphere reflective mirrors and a light concentrator, which makes the distribution on the detector plane not uniform. There will be additional non-linearity due to the non-uniformities. We investigated this situation by Monte-Carlo methods. All the primary cosmic ray events are generated by the program CORSIKA-v7.4005[7], A simulation program has been developed for LHAASO-WFCTA, including ray-tracing of photons, response of SiPM, the electronics and the concentrator. Fig. 2(d) shows the results of the simulation. The total number of cells of the SiPM we simulated is 230,400. If the distribution of light on the surface is uniform, the output of the SiPM will be corrected perfectly with Eq. (2) (see open circle in the Fig. 2(d)). If the distribution of light on the surface is non-uniform, there are some deviation after correction (see black dot in the Fig. 2(d)). The additional deviation caused by the non-uniform photons distribution is less than 2% at 32,000 pes.

5 Discussion and Conclusion

We have developed a preamplifier for application of SiPM on LHAASO-WFCTA. The dynamic ranges of SiPM follow the theoretical line very well, and could be extended a lot after correction with Eq. (2). The additional deviation caused by the non-uniform photons distribution is less than 2% at 32,000 pes.

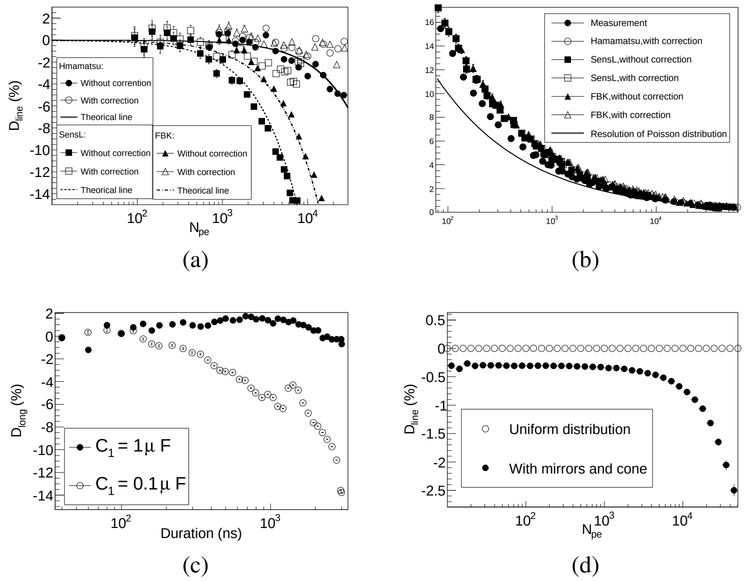


Fig. 2. (a) Results of Linearity of Hamamatsu(without correction: ●, with correction: ○, theoretical line: ———), SensL(without correction: ■, with correction: □, theoretical line: ··········) and FBK(without correction: ▲, with correction: △,theoretical line: —·—·-). (b) Resolution of Hamamatsu, SensL and FBK, the symbols are the same with those in (a), and the solid line is the resolution of Poisson distribution. (c) The stability of the Gain for $C_1 = 1\mu F(\bullet)$ and $C_1 = 0.1\mu F(\circ)$ (d) Simulation of additional non-linearity with Monte-Carlo program of WFCTA, including the mirrors and the concentrator.

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