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Performance characteristics of a silicon photomultiplier based compact radiation detector for Homeland Security applications

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ABSTRACT

A next-generation compact radiation detector was studied for more accurate measurement of radiation and for improvement of detector reliability for the purpose of developing radiation protection technology and military applications. The previously used radiation detector had some limitations due to its bulky size, limited range and its environment for radiation measurement. On the other hand, the compact radiation detector examined in this study utilizes a silicon photomultiplier which appears to be more suitable for this application because of its physical superiority characterized by its small size, high sensitivity, and durability. Accordingly, a SiPM based scintillation detector has been developed as part of this basic study of military radiation detectors. The detector has been tested for its ability to obtain the operating characteristics of a sensor and analyzed with variations of parameter values and for efficiency of detection in accordance with its ability to measure radiation in the environment. Two SiPM based Scintillation detectors with LYSO, BGO and CsI:Tl scintillators were developed and the detectors were analyzed by a number of operating characteristics such as reverse bias, operating temperature and high magnetic field, that depend on environmental changes in radiation measurement. The Photon count rate and spectra were compared for these three scintillators. We found that there were variations in the radiation detection which were characterized by reverse bias, temperature and high magnetic field. It was also found that there was an 11.9% energy resolution for the LYSO, 15.5% for BGO and 13.5% for CsI:Tl using Array SiPM, and 18% for CsI:Tl energy resolution using single SiPM when we measured energy resolution of 511 keV for ^{22}Na. These results demonstrate the potential widespread use of SiPM based compact radiation detectors for Homeland Security applications.

1. Introduction

The compact radiation detector is a device intended for Homeland Security applications. The design goals for this device are to establish a sensitive, durable and lightweight radiation monitor for more accurate measurement of radiation and to improve the reliability of the detector for the purpose of developing radiation protection technology and military applications. Traditionally, the readout of scintillation light from the crystal is performed by PMT, Avalanche photodiode (APD) and PIN silicon photodiodes for Homeland Security applications. However, the radiation detectors which were previously used have some limitations. PMT use requires high voltage supply and leads to bulky and sensitive magnetic fields. APD use also requires high voltage supply and stable temperatures in order to ensure the constancy of energy measurement. The use of PIN silicon photodiodes allows one to build compact probes without high-voltage supply. Sensitivity to magnetic fields is low and signal amplitude is weakly dependent on temperature changes. However, PIN silicon photodiodes do not have internal gain as APD and PMT. A special attention must be paid in order to minimize electronic noise, which is higher than statistical noise at low energies [1].

On the other hand, the silicon photomultiplier seems to be suitable for this application because of its physical superiority due to its small size, high sensitivity, low voltage supply, and insensitive magnetic field (Table 1). As a result of these properties, the silicon photomultiplier (SiPM) was introduced in the field of radiation detection mainly for radiation applications [2].

This study has the potential to impact a number of fields and have a significant influence on the operating characteristics of detectors and how they measure radiation in the environment. We have generated a SiPM based scintillation detector and performed tests on the environment of radiation measurement. In this study, we present a compact radiation detector for Homeland Security applications based on environmental changes of radiation measurement.

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Table 1
Commercial sensors under study.

Sensor	SiPM	PMT	APD	PIN
Voltage supply	Low	High	Medium	Low
Size	Small	Big	Small	Small
Gain	High	High	Low	Low
Sensitivity to microphonics	No	No	Medium	Yes
Magnetic field	No	Yes	No	No

Table 2
Specifications of the SiPM used in this study.

Series	Active area (mm^2)	Number of microcells	Pixel size (μm)	Fill factor	P.D.E (%)
Micro SL-10035	1 × 1	576	35	64	14
Micro SL-30035	3 × 3	4774	35	65	14
4 × 4 Array SL-30035	3 × 3	4774	35	65	14

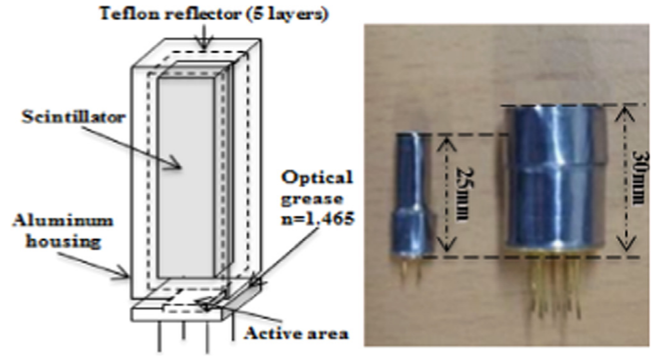

Fig. 1. Structures and picture of 1 × 1 mm^2, 3 × 3 mm^2 SiPM.

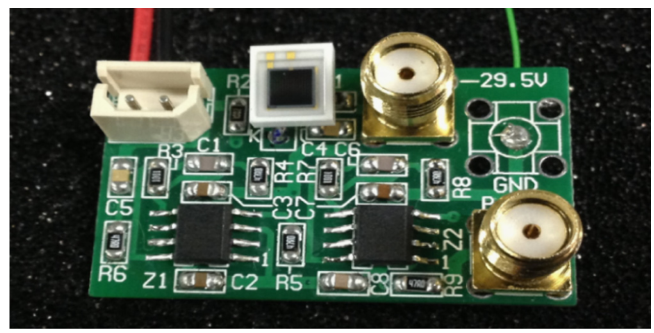

Fig. 2. Picture of readout electronics built for 1 × 1 mm^2, 3 × 3 mm^2 SiPM prototype: 40(W) × 20(L) mm.

2. Materials and methods

In this study we evaluated two types of SiPM with Micro SL (1 × 1 mm^2, 3 × 3 mm^2) and 4 × 4 Array SL (3 × 3 mm^2), both from SensL, for their use as compact radiation detectors (Table 2). These were coupled to LYSO, BGO and CsI:Tl (3 × 3 × 20 mm^3) crystals. In order to maximize the light output from the crystal and SiPM active area, the crystal geometry was optimized using a MCNPX (Monte Carlo n-particle extended) code. The source used for the evaluation was ^{22}Na which had an activity of 1 μCi. We have analyzed the variation in operating characteristics such as reverse bias, operating temperature and high magnetic field that depend on environmental changes of radiation measurement.

Data acquisition was performed using the oscilloscope and DAQ system. The width and height of output pulses for the analysis of pulse characteristics were measured using a Yokogawa: DL9140L digital oscilloscope (1 GHz). The oscilloscope was set to "Average mode" (higher), to provide a clear and stable pulse. The trigger level was set just above the dark current noise and was kept constant for each combination of SiPM and bias. The radioactive source was positioned 1 cm away from the front surface of the scintillator, to achieve uniform irradiation.

A DAQ system that consists of an Array 4-EVB (Preamplifier, SensL), NIM 575 (Amplifier, Ortec), and NIM 926 (Multi channel buffer, Ortec) was used for count rate and spectra measurements. The electronics board was designed to make output pulses suitable for the used single SiPMs. The MCB channel of photopeak centroid was recorded. Energy resolution was calculated from the FWHM of the photopeak, after applying a Gaussian fit.

2.1. Single SiPM detctor

Fig. 1 shows the detector head for 1 × 1 mm^2, 3 × 3 mm^2 SiPM. The detector head was coupled to a scintillator covered with five layers of white diffusive reflector (Teflon reflector) to achieve optimized scintillation light collection. The optical coupling was performed using optical grease (n=1.465) as the coupling medium. The coupled sensor was then covered and sealed using opaque masking tape and an aluminum case to prevent external light and electric noise from reaching the sensor [2]. For the experiments, we placed punctual sources 1 cm above the crystal, without collimation [1]. We have tested SiPM performances for three scintillators (LYSO, BGO and CsI:Tl).

Readout electronics, specifically tailored to this application was built in order to acquire the signals from the SiPM (1 × 1 mm^2, 3 × 3 mm^2). The readout had 3 stages: the first stage was the operating stage for the bias control of a SiPM, the second stage was the preamplifier to reduce the effects of noise and interference, and the third stage was the amplifier to increase the amplitude of the pulse [3]. This allowed for the handling of a very high count rate (Fig. 2). We have measured dependence of the characteristics of SiPMs with reverse bias, temperature and magnetic field using a ^{22}Na radioactive source. The energy resolution of the SiPM detector was also measured (3 × 3 mm^2).

2.2. Array SiPM detector

A 4 × 4 scintillator matrix was coupled to the 4 × 4 SiPM Array. Each crystal element, individually wrapped in Teflon reflector of five layers, has a size of 3 × 3 × 20 mm^3 (Fig. 3). The coupled sensor was then covered and sealed using opaque masking tape and an aluminum case [2].

For the readout electronics we used an Array SL module of SensL (Fig. 4), NIM 575A amplifier and an NIM 926 ADCAM MCB for the data acquisition. It independently measured preamplifier signals from each of the 16 pixels of the Array SL module giving a differential output for each channel. It also contained a regulator which was programmed to output the optimal bias voltage for the array and contained circuitry, such as analog-to-digital converters and digital signal processing [4]. The energy resolution and count rate were measured from 0 to 2 T [5]. A ^{22}Na radioactive source was used for these measurements.

3. Results and discussion

3.1. Single SiPM detector

Fig. 5 shows the amplitude of the output pulses obtained for the two SiPMs at different reverse biases and scintillators using a