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Design and performance evaluation of a compact, large-area PET detector module based on silicon photomultipliers

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ABSTRACT

A PET module that comprises a pair of compact, high-resolution and large-area detectors based on silicon photomultipliers (SiPM) was developed and evaluated. The detector's effective area was 24 mm × 24 mm. LYSO crystals measuring 1.9 mm × 1.9 mm × 10 mm and charge division circuit were employed to obtain high spatial resolution with relatively concise Front-end electronics (FEE). Initial results showed the detector to be compatible with 1.5 T magnetic fields. The system's intrinsic FWHM spatial resolution is 1.50 mm. The average energy resolution is 18.5% and the coincidence timing resolution is 2.6 ns.

1. Introduction

Nuclear imaging technologies are playing an important role in medical diagnosis, space physics and public safety. Positron Emission Tomography (PET) is a functional nuclear imaging modality that provides information about physiological processes in vivo. In current PET detectors, photomultipliers (PMTs) are widely used for their fast time response, large area and high quantum efficiency. PMT achieves signal gain through electron multiplication over a dynode structure subject to a high voltage cascade. These are strongly affected by magnetic fields under which PMT performance deteriorates. The Silicon Photon Multiplier (SiPM) is an innovative photosensor composed of an array of avalanche photodiodes (APD) operating in Geiger Mode [1]. Like conventional APD, it is compact and insensitive to magnetic fields [2,3]. Moreover, the gain can rise up to 10^6 at a bias voltage as low as 15 V [4]. All these features make SiPM an optimum choice for PET under special circumstances, e.g. PET-MR where space is limited and the detector operates in a strong magnetic field.

Several studies have been reported based on Hamamatsu, FBK-irst, SensL and other products [5], showing the feasibility to attain sub-millimeter spatial resolution [6,7], DOI decoding ability [8], and further, to be used in PET/MR [2,3]. However, because of manufacturing and noise considerations, either large size SiPM pixel or large size Monolithic SiPM arrays are not commercially available [9]. When building a detector based on single SiPM arrays, the detecting area became the main limitation [10]. Additionally, there remain issues relating to detector performance, compactness and cost. In this paper we discuss a PET detector module with readout based on 2 × 2 SiPM arrays of 4 × 4 pixels each. The 64-channel signals were converted to 4 outputs by a charge division circuit [11] without using signal amplifiers in the detector, which simplified the electronics and gave a possible way to build large size detectors with single SiPMs. The measurements of energy resolution, timing resolution and intrinsic spatial resolution of this detector were performed. Tests under 1.5 T magnetic fields were also conducted.

2. Detector module description

The detector module consists of 2 × 2 SiPM matrix assembled on a non-magnetic package, a pixelated scintillator block, a light guide and readout electronics. These elements are described in the following.

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2.1. Photosensor

In this study, the SensL ArraySL-4-30035-CER (Fig. 1) was selected to be the photosensor for our system. It is a position sensitive SiPM with 4×4 sensitive pixels attached to a thin ceramic package. Each pixel chip area is 3.15 mm × 3.15 mm, with a sensitive area of 2.85 mm × 2.85 mm. The spacing between two neighboring pixels is 0.2 mm. Each pixel has 3640 microcells, which results in a large dynamic range [9]. The summed signal of the fired microcells in each pixel is read out via copper pins. Each 4-pixel column is biased separately through an independent pin. So there are a total of 16 signal and 4 bias pins at the bottom of the ArraySL-4–30035-CER package. The SiPM response spectrum ranges from 400 to 1100 and peaks at 480 nm [12]. To obtain large detecting area we arranged four units of the SensL detector into a 2×2 array as shown in Fig. 2. The dead space between neighboring detectors is 2.8 mm. The 8 pre-selected SiPMs used in this system have the same breakdown voltage of 26.8 V, according to the data sheet.

2.2. Scintillator block and coupling method

PET suitable scintillators are expected to have high light yield, fast decay time and strong stopping power. Moreover, considering cost and packing techniques, LYSO is the optimum crystal currently available [13] and was chosen for this study. The detector block used in our prototype PET was a 12×12 LYSO crystal matrix. Each crystal measures 1.9 mm × 1.9 mm × 10 mm with all sides polished. Approximately 0.1 mm thick Teflon was used to separate each crystal from its neighbors. The dimension of the entire block was 24 mm × 24 mm × 10 mm. A piece of transparent adhesive tape was attached to the face of the crystal matrix to be coupled to the SiPM. The other sides of the block were wrapped with 3 layers of Teflon tape serving as light reflector.

When joining 4 SiPM arrays together a cross shaped dead area with more than 2 mm width is created (Fig. 2). As a consequence, the scintillating light from the LYSO crystals that were directly coupled above the cross will be lost. Therefore, a 26 mm × 26 mm × 1.3 mm quartz glass was placed between the scintillator block and the SiPMs, which serves to distribute the scintillating light and to increase light gathering efficiency. Optical grease was used on both sides of the quartz glass. Due to availability we only tested 0.7 mm and 1.3 mm thick quartz glass and chose the one with which we obtained better flood histogram (Fig. 3). The scintillating light does not redistribute enough in the 0.7 mm thick light guide, so the crystals that located right above the dead area almost cannot be seen in the flood histogram. Further work is required to optimize the light guide design.

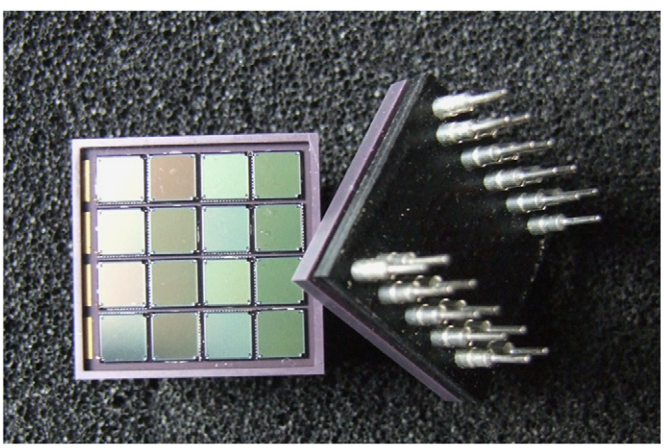

Fig. 1. SensL ArraySL-4-30035-CER, photosensor of the detector.

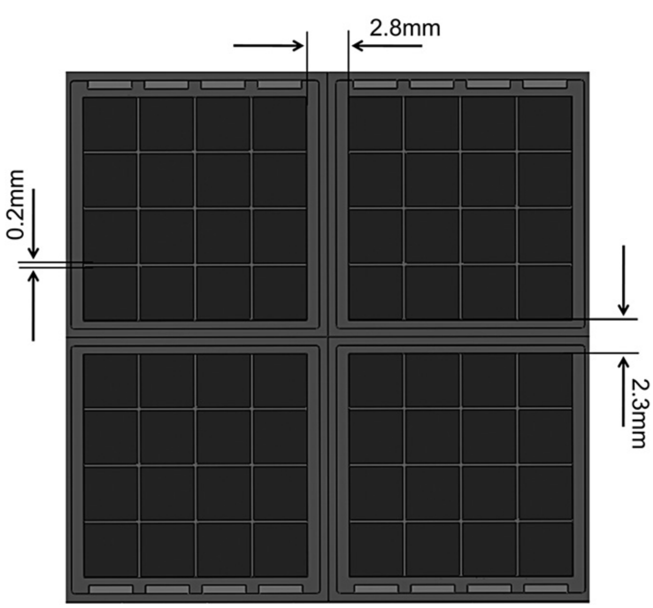

Fig. 2. SiPM array arrangement. When joining 4 SiPM arrays together a cross shaped dead area with more than 2 mm width is created.

2.3. Readout electronics

The 2×2 matrix of SiPM arrays was mounted on a printed circuit board (PCB). Every pixel of the SiPMs is read out using the

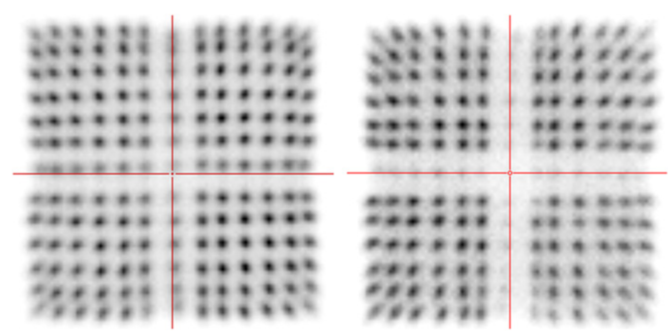

Fig. 3. Flood histogram obtained with the 1.3 mm thick quartz glass (left) and 0.7 mm thick quartz glass (right). The crystals that located right above the dead area almost cannot be seen when using the thinner quartz glass.

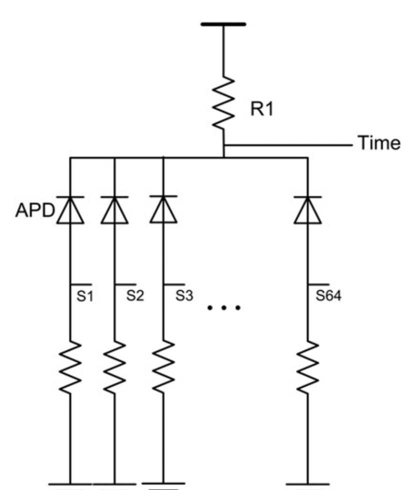

Fig. 4. Bias and passive quenching circuit. The timing signal was extracted from this circuit.