Performance comparison of two compact multiplexed readouts with SensL's SPMArray4 for high-resolution detector module

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***Abstract*–The purpose of this study was to investigate a compact readout for silicon photomultiplier (SiPM) array in the development of high-resolution imaging detector to reduce the readout channels while maximizing the detectors performance. The detector module was composed of a LYSO scintillation crystal array and a SensL's SPMArray4. The crystal array was coupled to the SiPM array with a 2mm-thick silicone pad to improve the light sharing among the SiPM array elements. Three LYSO crystal arrays of 4x4, 8x8 and 12x12 crystal elements with pixel sizes of 3.2, 1.6 and 1.0 mm were investigated in this study. Two compact multiplexed readouts based on the light sharing principle have been developed to reduce the detectors readout channels from 16 to 4 outputs while achieving a maximized performance in its spatial resolution. One is based on a conventional charge division method which was utilized with a discretized positioning circuit (DPC). The other is based on a novel two-stage charge division which was utilized with a symmetric charge division circuit to divide the charges from 16 SiPM elements into a 4-row and 4-column resistive network and then used a subtractive readout circuit to further reduce the readout channels from 8 to 4 outputs. The performance of the detector module with two compact multiplexed readouts was evaluated with LYSO arrays with different crystal sizes using a ^{137}Cs point source. The preliminary results show that both compact multiplexed readouts can provide very good spatial resolution with good uniformity and resolve up to 1mm pixel elements of LYSO arrays. The compact readout based on the two-stage charge division with subtractive resistive-readout shows a slightly better improvement in the crystal identification while reducing the non-linearity of the flood image as compared to the DPC readout. In conclusion, both compact multiplexed readouts are effective approaches for the development of high-resolution detector module for compact micro-PET.**

I. INTRODUCTION

In recent years Silicon Photomultipliers (SiPM) has been aroused considerable attention and interest for applications in nuclear molecular imaging [1], because of its appealing properties of great compactness with high gain (~10^6), fast response, low current consumption and insensitive to the magnetic field. The feasibility of the SiPM used for the development of high-resolution compact PET and SPECT has been studying by many research groups.

However, the design and development of high-resolution detector modules based on the SiPMs into a practical imaging system are still of great challenges. Optimizing the combination between scintillation crystals and SiPMs, light sharing among SiPM array, and multiplexed readout schemes are very crucial for the detector module to achieve a maximized performance.

Recent advances of silicon photomultiplier (SiPM) detector technology, such as the scalable 4x4 array modules of the SensL ArraySL-4 and the Hamamatsu MPPC-S11064, provide a unique opportunity to implement a new generation of high-performance compact detectors for the MR-compatible PET and SPECT. However, high granularity of SiPMs imposes a challenge of the complexity and cost of the readout for the individual detector modules and for the whole system. Compact multiplexed readout techniques to reduce the readout channels are desired for the system development. The design and implementation of compact readout electronics for these compact detector modules are very essential for them to achieve a maximized performance.

In this work we used a LYSO scintillation crystal array coupled to a SensL's SPMArray4 for the development of a high-resolution detector module. Two compact multiplexed readout circuits have been developed for the detector module to reduce the 16 readout channels to 4 outputs while achieving a maximized performance in its intrinsic spatial resolution. The performance of the detector module with two compact multiplexed readouts was evaluated with LYSO arrays with different crystal sizes using a ^{137}Cs point source.

II. MATERIALS AND METHODS

A. Detector Module

The detector module composed of a LYSO crystal array and a SensL's 4x4 SiPM array (SPMArray4), shown in Fig.1. The LYSO crystal arrays were purchased from the Shanghai SICCAS High Technology Corporation, China. Three LYSO crystal arrays of 4x4, 8x8 and 12x12 crystal elements with pixel sizes of 3.2, 1.6 and 1.0 mm were tested with the SensL's SPMArray4. The crystal elements have a polish treatment on all sides. All other faces except for the light-out side are covered with a highly reflective PTFE-based material. The SPMArray4is a 4×4 array of SPM pixels. Each pixel has an active area of 2.85 mm×2.85 mm, made up of 3640 Geiger-mode avalanche photodiodes (microcells). The SPM array has

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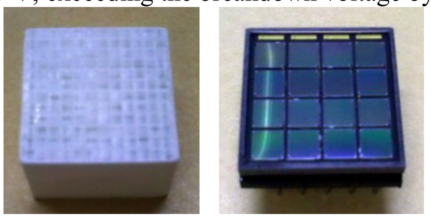
a typical gain of ~10^6 at the manufacture-specified bias voltage of 29.5 V, exceeding the breakdown voltage by 2.0 V.



(a) (b)

Fig.1 Photos of the components of the detector module. (a) a 12x12 LYSO crystal array; (b): a SensL's 4x4 SiPM array (SPMArray4).

The crystal array was coupled to the SPMArray4 with a soft silicone pad with a thickness of 2 mm as a light guide to improve the light sharing among the SiPM array elements. All the 16 channels of the SiPM array were operated at the same bias voltage of 29.8V without tuning the individual bias for their gain variations.

B. Conventional multiplexed readout with the discretized positioning circuit (DPC)

The conventional multiplexed readout is based on a discretized positioning circuit (DPC) that was proposed by Dr. Siegel [2]. It consists in a 2D resistor-chain network to sum all the charges from the 16 SiPM pixels and divides them into 4 outputs, shown in Fig. 2. We have carefully tuned the resistor parameters to minimize the image shrinkage effect [3]. The four output signals were amplified and shaped by 4 low-noise charge sensitive preamplifiers and then output to the data acquisition system. A summed signal from the four position signals was used to provide the trigger for the DAQ system. Then the standard center-of-gravity (also be called Anger Logic) method was used to calculate the position of the incident gamma-ray.

$$X = \frac{(V_a + V_b) - (V_c + V_d)}{V_a + V_b + V_c + V_d}$$

$$Y = \frac{(V_a + V_d) - (V_b + V_c)}{V_a + V_d + V_b + V_c}$$

$$E = V_a + V_b + V_c + V_d$$

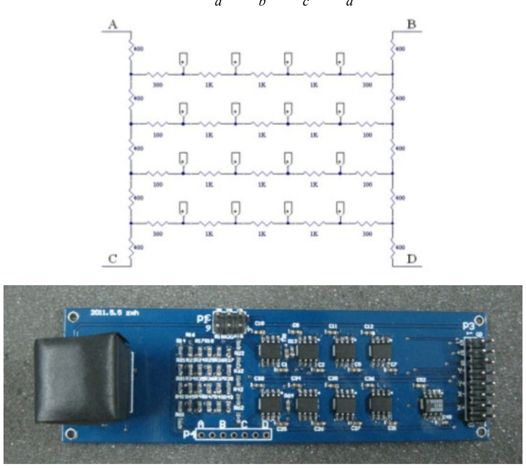


Fig.2 A compact readout with the discretized positioning circuit (DPC). Top: Schematic diagram of the DPC; Bottom: Photograph of the detector module implemented with the DPC readout board.

C. Compact multiplexed readout with the 2-stage charge division method

Another compact multiplexed readout is based on a novel two-stage charge division scheme. First, the incoming charges from the 4x4 SiPM array are equally split into X and Y directions using a symmetric 2D decoupling resistive matrix [4-5], which results in 16 readout channels reducing to 8 channels (4 rows and 4 columns), shown in Fig.3 (top-left). Secondly, the 8 readout channels are individually amplified and shaped. Then a subtractive resistive charge division [6-7] was developed for the second-stage signal processing, where a fractional subtraction circuit was used to cut off the long tail of charge distribution and remove the noise contributions far from the incident site of gamma-ray. The 8 readout channels are further reduced to 4 outputs (X^-, X^+, Y^-, Y^+) using a conventional resistive bridge circuit. The position of the incident gamma-ray is also computed by the Anger Logic.

$$X = \frac{X^+ - X^-}{X^+ + X^-}$$

$$Y = \frac{Y^+ - Y^-}{Y^+ + Y^-}$$

$$E = X^+ + X^- + Y^+ + Y^-$$

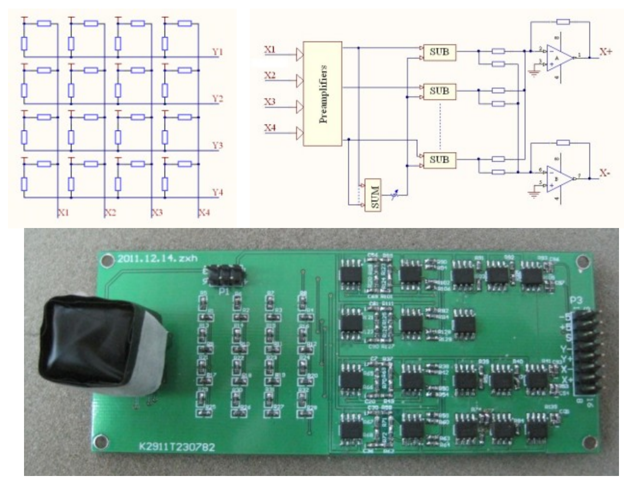


Fig. 3 Compact readout with novel two-stage charge divisions. Top: the first multiplexing with the symmetric charge division circuit (left) and the second multiplexing with subtractive charge division shown in the x-direction (right); Bottom: photograph of the detector module implemented with the two-stage charge division readout board.

III. RESULTS

The initial performance tests of the detector module with the two multiplexed readout methods were made using a ^{137}Cs source. Three LYSO crystal arrays of 4x4, 8x8 and 12x12 crystal elements with pixel sizes of 3.2, 1.6 and 1.0 mm were tested with the SensL's SPMArray4. Fig. 4 shows the measured raw flood images of the detector module's responses with the two multiplexed readout methods using a ^{137}Cs source. The preliminary results show that both compact multiplexed readouts can provide good spatial resolution and well resolve up to 1mm pixel elements of LYSO arrays. However, the compact readout based on the two-stage charge division shows a slight better improvement in the crystal identification while reducing the non-linearity of the flood image as compared to the DPC based compact readout.

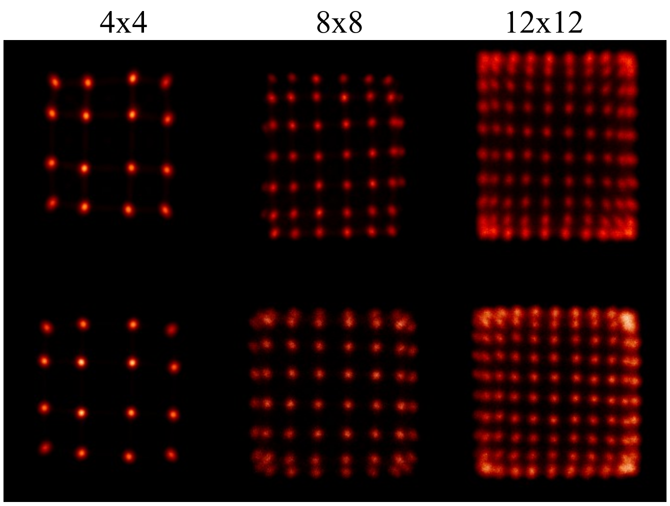


Fig.4 Measured raw flood images of the detector modules with 4x4, 8x8 and 12x12 LYSO arrays using with two multiplexed readout methods. Top-row: with the DPC multiplexed readout method; Bottom-row: with the novel two-stage charge division readout method. All the images are plotted in the same scale.

In the raw flood image of the 12x12 crystal array, we selected two small region-of-interests (ROIs) of A and B around individual crystal elements, where ROI-A is around a pixel in the edge of the detector while ROI-B is around a pixel in the central region of the detector. The measured energy spectra from the ROI-A and ROI-B are shown in Fig. 5. As expected, ROI-A in the edge of the detector and has a worse energy resolution while ROI-B in the central region of the detector has a good energy resolution of ~16.3%.

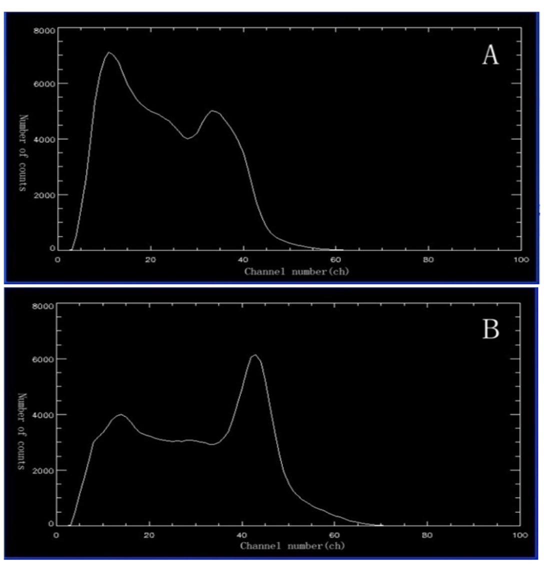


Fig.5 Measured energy spectra from two pixel regions in the raw flood image of the detector module with 12x12 crystal array. Top: energy spectrum from the ROI-A of a pixel in the edge of the detector; Bottom: energy spectrum from the ROI-B of a pixel in the central region of the detector.

From the measured flood image and the energy spectra, we can see that the detector's response in the central region has a better performance than that in the edges because the SPM array in the central region has a better collection and sampling of the scintillation light photons from the crystal array than those in the edges.

IV. CONCLUSION AND DISCUSSION

We have investigated two compact readout schemes for the development of high-resolution detector module with the SensL's 4x4 SiPM array (SPMArray4). One is based on a conventional charge division method which was utilized with a discretized positioning circuit (DPC). The other is based on a novel two-stage charge division method which was utilized with a symmetric charge division circuit and a subtractive resistive readout. Both compact readouts can effectively reduce the readout channels of SPMArray4 from 16 to 4 and provide a good spatial resolution to well resolve up to 1mm pixel elements of LYSO arrays. The results indicate that the conventional light sharing and charge multiplexed readout method is suitable for the high-performance imaging detector module.

In conclusion, both compact multiplexed readout schemes are effective approaches for the development of high-resolution detector module for compact micro-PET.

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