Four-layer DOI-PET detector with a silicon photomultiplier array

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***Abstract*— Silicon photomultipliers are promising photo detectors for use in PET detectors due to their high internal gain, low power consumption and insensitivity to magnetic fields. We are developing a PET detector which consists of a scintillation crystal array and a silicon photomultiplier array. To achieve uniform spatial resolution, depth-of-interaction (DOI) detectors are required to reduce the parallax error. In this paper, we are studying the four-layer DOI PET detector with a silicon photomultiplier array.**

The prototype four-layer DOI detector consisted of a 6 × 6 × 4 LYSO crystal array and the SPMArray (SPMArray 3035G16, SensL, Ireland) which was an array of sixteen silicon photomultiplier detectors (each 3mm × 3mm). The size of each crystal element was 1.46 mm × 1.46 mm × 4.5 mm. The DOI encoding method we applied was a previously presented method which can identify crystals of four layers with only one photo detector and crystal array using an arrangement with the reflector inserted between crystals. We measured the performance of the four-layer DOI PET detector. Additionally, the related characteristics of the SPMArray when used in the four-layer DOI PET detector were measured.

We found that the crystal identification capability was similar to that of the detector which consisted of the same crystal array and another position sensitive photomultiplier tube we typically used. Energy resolution of 25.1% was obtained for 511keV gamma rays.

I. INTRODUCTION

Silicon photomultipliers (SiPM) are promising photo detectors for use in PET detectors due to their high internal gain, low power consumption and insensitivity to magnetic fields. Insensitivity to magnetic fields is indispensable for detectors used in MR-PET and better timing performance than that obtained by an avalanche photodiode (APD) is desirable for time-of-flight (TOF) PET. We have been studying a PET detector which consists of a scintillation crystal array and a silicon photomultiplier array.

For high performance PET, good capability for the depth-of-interaction (DOI) is required to reduce the parallax error which degrades the uniformity of spatial resolution. Many groups have been studying DOI detectors. However most of the DOI encoding methods developed can identify only two or three layers and stacking many detectors increases the number of readout channels and production costs. Previously, we proposed the four-layer DOI encoding detector (jPET detector) which consists of a four-layer crystal array and only one photo detector [1]. In most PET detectors using SiPMs and APDs, each scintillation crystal is typically coupled in one-to-one correspondence to a pixel of the photo detector. Almost all of the scintillation lights generated by interaction in a crystal are

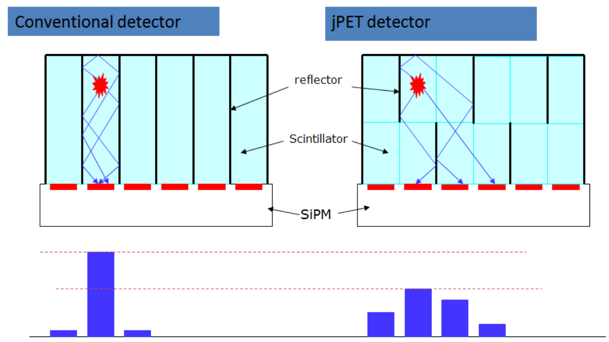

Fig.1 Scintillation lights spread and distribution of the photo

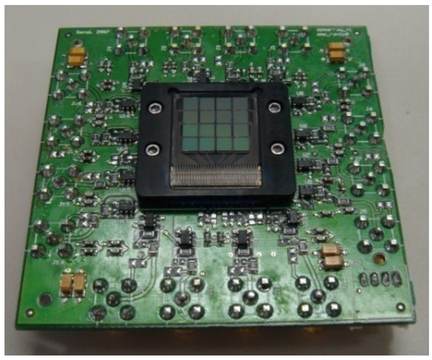

Fig.2 Photograph of the SPMArray and preamplifier board

detected by one SiPM element just under the interacting scintillator and it is possible for a "saturation effect" to occur especially using high light yield scintillators such as LSO, LYSO and $LaBr_3$. On the other hand, the jPET detector, scintillation lights are shared among many pixels. This can reduce the incident scintillation lights into one pixel and there is no saturation effect. We expect that the jPET detector using SiPMs can be normally operated with higher light yield scintillators.

Many kinds of SiPMs have been developed and are commercially available. They are a single pixel device or a small array and then cannot be used in the jPET detector, except in the 4 × 4 array of SiPMs (SPMArray 3035G16,) produced by SensL (Ireland). So we constructed and evaluated a prototype four-layer DOI detector with an SPMArray. In addition, we studied charcteristics of the SPMArray used in DOI PET detectors. In addition,

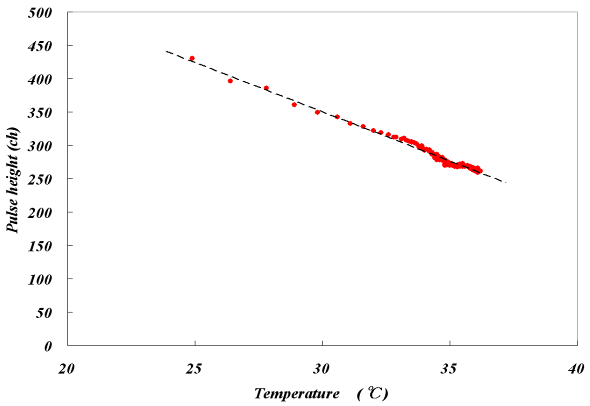

Fig.3 Temperature dependence of the internal gain of the SPMArray.

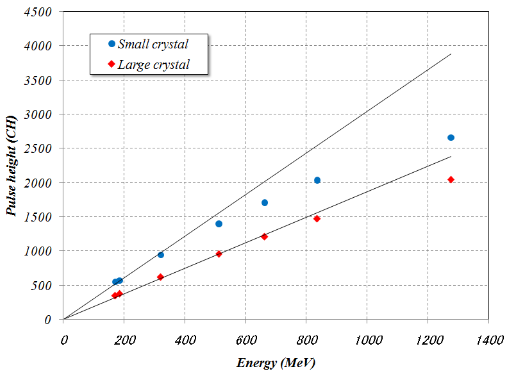

Fig.4 Linearity of the output signal of the SPMArray

II. Materials and Methods

The SPMArray (SPMArray 3035G16, SensL, Ireland) is an array of sixteen silicon photomultiplier detectors (each 3mm × 3mm). The active area of each pixel is 2.85mm × 2.85mm and each pixel has had 3,640 micro cells. Typical photon detection efficiency, internal gain and operating voltage are 13-30%, $>10^6$ and 29V, respectively. In the experiments, a preamplifier board (SPMArray A1) was used except in the experiment on the saturation effect. Figure 2 shows a photograph of the SPMArray.

First, we studied charcteristics of the SPMArray used as DOI PET detectors with a $Lu_{2(1-x)}Y_{2x}$ SiO_5 (LYSO) (Lu: 98 %, Y: 2 %) (Proteus Inc., U. S. A.) crystal array. In the experiment on temparature dependence of the SPMArray, we measured the energy spectrum for a single pixel of the SPMArray and a single LYSO crytal (size: 2.9mm × 2.9mm × 7.5mm). A thermometer was placed close to the SPMArray and measured temperatures were recorded. Linearity of the SPMArray response was measured with point-like sources of ^{22}Na (511keV and 1275keV), ^{54}Mn (835keV), ^{137}Cs (662keV) and ^{51}Cr (320keV). In this experiment, a large size single crystal (2.9 x 2.9 x 7.5mm^3) for whole body PET and small size crystal (1.46 x 1.46 x 4.5mm^3) for small animal PET were used. A shaping amplifier was used instead of the preamplifier board to prevent saturationin preamplifier board.

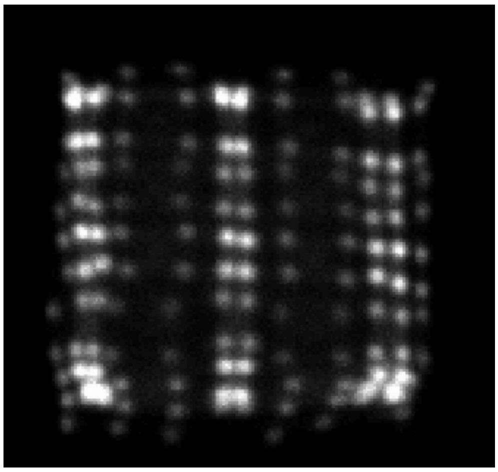

Fig.5 2-D position histogram for uniform irradiation of 511keV gamma rays.

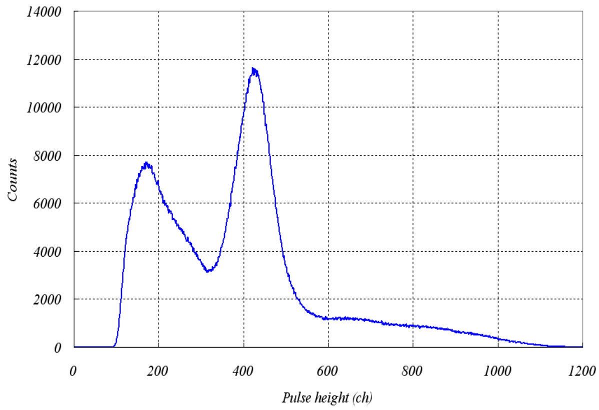

Fig.6 Energy spectrum of the four-layer DOI detector for the point-like ^{22}Na source.

Secondly, we measured the performance of a DOI-PET detector which consisted of a 6 × 6 × 4 array of LYSO crystals and the SPMArray. We adopted the reflector arrangement in the four-layer crystal block as proposed in [1] for DOI encoding. The size of each crystal element was 1.46 mm × 1.46 mm × 4.5 mm and all surfaces of crystal elements were chemically etched. The reflector was made up of multilayer polymer mirrors (Sumitomo 3M, Ltd., Japan) of 0.065 mm thickness and 98 % reflectivity. RTV rubber (KE420 Shin-Etsu Chemical Co., Ltd., Japan) was applied between crystals except for the space where the reflector was inserted. Temperature of the SPMArray was kept constant by blowing air over it for which temperature was controlled by a peltie unit. The output signals from all pixels were recorded independently with peak hold analog-to-digital converters (ADCs) after passing through the preamplifier board. Bias voltages of 30.5V were applied to all pixels.

III. Results and Discussion

Figure 3 shows the temperature dependence of the output

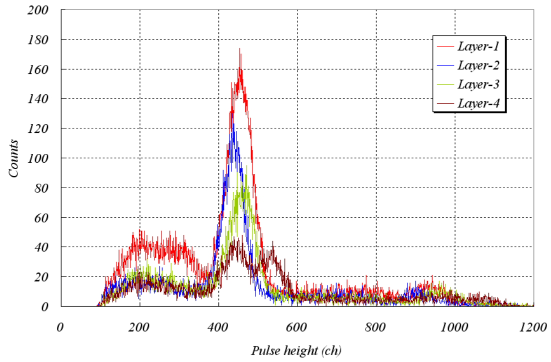

Fig.7 Energy spectra of each layer for the point-like ^{22}Na source.

signals of a pixel of the SPMArray. The pulse height of the output signals of the photopeaks corresponds to the internal gain of the pixel of the SPMArray. The temperature dependence is -14.8 ch/°C above room temperature (3.4 %/°C at 25°C). Typically, front-end circuits are placed close to PET detectors. Therefore, the gain of the SiPMs possibly decreases as its temperature increases. This result indicates that careful control of temperature is required for detectors of the SPMArray.

Figure 4 shows linearity of the pixel of the SPMArray to various gamma ray energies with a large size (2.9 x 2.9 x 7.5mm^3) crystal for whole body PET and the small size (1.46 x 1.46 x 4.5mm^3) crystal for small animal PET. The pulse height of the photopeaks of ^{22}Na (511keV and 1275keV), ^{54}Mn (835keV), ^{137}Cs (662keV) and ^{51}Cr (320keV) and the backscatter peaks of ^{22}Na and ^{137}Cs (170.3keV and 184.3keV) are plotted. Because the size of the larger crystal is the same as the pixel size of the SPMArray, part of the scintillation lights enter neighbor pixels. Therefore, the pulse heights of the large size crystal are lower than those of the small size crystal. The saturation effect can be seen clearly for the small size crystal. For only high energy gamma rays, the pulse height is slightly saturated for the large size crystal.

Figure 5 shows the 2-D position histogram for uniform irradiation of the point-like ^{22}Na source. The crystals responses of all layers are represented on the 2-D position histogram. The crystal identification capability of the DOI detector is similar to that of the detector which consisted of the same crystal array and the position sensitive photomultiplier we typically used [2].

Figure 6 shows the energy spectrum of the four-layer DOI detector for uniform irradiation of a ^{22}Na point-like source. The energy was defined by calculating the summation of all signal outputs. The energy resolution of 25.1% is obtained. The long tail in the high pulse height region is due to 1275 keV gamma rays from ^{22}Na. Figure 7 shows energy spectra for crystals in each layer. The energy resolutions of the first, second, third and fourth layers are 17.6%, 14.9%, 18.9% and 17.3%, respectively. Due to multiple interaction in crystals in different layers, there are two photo peaks for the spectrum of the fourth layer. The lower peak in the spectrum of the fourth layer is actually for the third layer.

IV. Conclusion

The four-layer DOI PET detector with the SPMArray which had 16 silicon photomultiplier detectors was constructed and tested. The crystal identification capability was similar to that of the detector which consisted of the same crystal array and the position sensitive photomultiplier tube we typically used. Energy resolution of 25.1% was obtained.

In this presentation, the part of the effective area was used in the experiment and timing performance was not evaluated. In the future, we will evaluate the timing performance of the DOI detector with the SPMArray.

Acknowledgment

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References

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