Performance evaluation of a four-layer LSO detector for a small animal DOI PET scanner: jPET-RD

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Abstract—Previously we proposed a new depth of interaction (DOI) encoding method and proved that it worked successfully with four-layered Gd$_2$SiO$_5$ crystals for a small animal positron emission tomography (PET) detector. We are now planning a small animal PET scanner, jPET-RD (for Rodents with DOI detectors), which has both high resolution and high sensitivity. Scintillator for the scanner will be Lu$_{2(1-x)}$Y$_{2x}$SiO$_5$ (LYSO).

In this work, we evaluated the DOI detector composed of four layers of 12 × 12 LYSO (Lu: 98 %, Y: 2 %) crystal array by irradiating 511 keV uniform gamma rays. For crystal identification, the new encoding method was used. The size of each crystal is 1.44 mm × 1.44 mm × 4.5 mm. The crystal block was coupled to a 256-channel flat panel position sensitive photomultiplier tube, which has 16 × 16 multi anodes at intervals of 3.04 mm. In this measurement, all crystals are expressed on a single two-dimensional position histogram without overlapping as we expected. Energy resolution of all events is 21.8 % and time resolution of all events is 0.69 ns in FWHM. The energy resolutions of the first, second, third, and fourth are 11.6 %, 12.3 %, 13.3 %, and 12.5 % and the time resolutions are 0.60 ns, 0.59 ns, 0.60 ns, and 0.66 ns, respectively.

Index Terms—positron emission tomography (PET), depth of interaction (DOI), small animal study, scintillation detector

I. INTRODUCTION

We are now planning to develop a small animal positron emission tomography (PET) scanner: jPET-RD (for Rodents with DOI detectors) [1], which meets the demand for high sensitivity as well as high resolution. The system consists of 12 scintillation detector modules arranged in a 2-ring configuration with a radius of 8.9 cm and an axial extent of 10.3 cm. In our previous report [2], we proposed a four-layer DOI encoding method in which all crystal elements are represented on a single two-dimensional (2D) position histogram without overlapping. Reliability of the method was proved experimentally with Gd$_2$SiO$_5$ scintillator. There are three advantages to this method. First, pulse shape discrimination is not required. Secondly, a photo detector is only on one side of the crystals. Finally, this method can also be applied to any scintillator and have been shown to work successfully with BGO scintillators [3]. Fig. 1 shows the conceptual structure of the four-layer DOI detector for jPET-RD. To achieve a high sensitive PET scanner, the scintillator used should have fast time response and it is also desirable for the scintillator to have large effective atomic number. Here we evaluated the performance of the detector using Lu$_{2(1-x)}$Y$_{2x}$SiO$_5$ (LYSO) scintillator, which satisfy the above requirements.

Fig.1 Conceptual structure of a four-layer DOI detector for the jPET-RD. The detector consists of four-layer scintillation crystal arrays and a 256ch FP-PMT. Each array is composed of 32 × 32 crystals and crystals of interaction are identified in the method.

II. MATERIALS AND METHODS

We measured the performance of four layers of 12 × 12 array LYSO crystals. The LYSO contains 98 % lutetium in atomic mass so that this scintillator should show characteristics similar to that of Lu$_2$SiO$_5$. We adopted the reflector arrangement in the four-layer crystal array as proposed in [2] for the DOI encoding method. The size of each crystal element is 1.44 mm × 1.44 mm × 4.5 mm and all surfaces of crystal elements are chemically etched by Hitachi Chemical Co., Ltd., Japan. The reflectors are multilayer polymer mirrors of 0.065 mm thickness and 98 % reflectivity. The material between adjacent layers is silicone oil of 1.45
refractive index. A photograph of the four-layer DOI detector is shown in Fig. 2. The crystal block is placed in two different positions; on the central and peripheral area of a 256-channel flat panel position sensitive photomultiplier tube (256ch FP-PMT: H9500, Hamamatsu Photonics K. K. Japan) [3, 4] as shown in Fig.3 and optically coupled to the 256ch FP-PMT with silicone oil. The opening area of the 256ch FP-PMT is 52.0 mm × 52.0 mm and the 256 anodes are arranged in 16 × 16 matrix at intervals of 3.04 mm.

The four-layer DOI detector is uniformly irradiated by gamma rays from a $^{22}$Na point source placed at a distance of 20 cm from the detector. To select the events detected by both the four-layer DOI and BaF$_2$ detectors, the outputs of coincidence module were provided to the analog to digital converter (ADC) gate and the time to digital converter (TDC) “start”. The area of the crystal block attached to the FP-PMT is 18 mm$^2$ so that signals of only 64 anodes are sent to four 16-channel 12-bit ADC modules in parallel while the other anodes are connected to ground. To determine the positions of the interaction crystals, we adopt an Anger-type calculation to the output values from individual anode after gain correction and acquire a 2D position histogram. The histogram of the difference between two TDC channels, each from the BaF$_2$ detector and the four-layer DOI detector, indicates the time resolution.

Fig.2 Setup of a crystal block made of four layers of a 12 × 12 LYSO crystal array. The crystal block is optically coupled to a 256ch FP-PMT by silicone oil.

III. RESULTS

Figs.4 (a) and (b) show the 2D position histograms (512 × 512 pixel image) for events with full energy absorption. The darker the peak, the higher the crystal is located in the DOI block as the first layer crystals detect the most gamma rays irradiated from above. Here, the layers are numbered from the gamma ray source side. Figs. 5 (i) and (ii) show the profiles of Fig. 4 (a), along horizontal lines on the 13th and 14th row from the top and Figs. 5 (iii) and (iv) show the ones along vertical lines on the 13th and 14th row from the left, respectively. The mean of the peak to valley ratio in these profiles is 3.0: 1.

Figs. 6 and 7 show energy spectra of all events and timing spectra after energy discrimination. The energy resolutions are 21.8 % in FWHM at central area and 16.8 % at peripheral area. The time resolutions are 0.69 ns in FWHM and 1.32 ns in FWTM at central area and 0.73 ns in FWHM and 1.55 ns in FWTM at peripheral area. Figs. 8 and 9 show energy spectra and timing spectra of a central crystal element of each layer, respectively. Table I summarizes the average values of energy resolution, light output relative to that of the fourth layer, time resolution in FWHM and in FWTM, and transit time difference from the fourth layer, using four central crystal elements of each layer.

Fig.4 2D position histogram (512 × 512 pixel image) of the four-layer DOI detector. The 2D position histograms of (a) and (b) is corresponding to Fig. 3 (a) and (b), respectively.
Fig. 5 Profiles corresponding lines of Fig. 4.

Fig. 6 Energy histogram of all events.

Fig. 7 Timing spectrum of all events for the four-layer DOI detector with reference to a BaF$_2$ detector.

Fig. 8 Energy histogram of first to fourth layer events.

Fig. 9 Timing spectrum of first to fourth events.
TABLE I  
AVERAGED ENERGY RESOLUTION, LIGHT OUTPUT [A.U.], TIME RESOLUTION, AND TIME DIFFERENCE

<table>
<thead>
<tr>
<th></th>
<th>1st layer</th>
<th>2nd layer</th>
<th>3rd layer</th>
<th>4th layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resolution</td>
<td>11.6 %</td>
<td>12.3 %</td>
<td>13.3 %</td>
<td>12.5 %</td>
</tr>
<tr>
<td>Light output [a.u.]</td>
<td>0.91</td>
<td>0.90</td>
<td>0.93</td>
<td>1.00</td>
</tr>
<tr>
<td>Time resolution in FWHM</td>
<td>0.60 ns</td>
<td>0.59 ns</td>
<td>0.60 ns</td>
<td>0.66 ns</td>
</tr>
<tr>
<td>Time resolution in FWTM</td>
<td>1.27 ns</td>
<td>1.15 ns</td>
<td>1.17 ns</td>
<td>1.16 ns</td>
</tr>
<tr>
<td>Time difference</td>
<td>0.15 ns</td>
<td>0.14 ns</td>
<td>0.08 ns</td>
<td>0.00 ns</td>
</tr>
</tbody>
</table>

IV. DISCUSSION AND CONCLUSION

The four-layer DOI encoding method worked successfully with the use of LSO (actually LYSO) scintillator, whose fast time response and large effective atomic number will contribute to higher count rate of the PET system. In the 2D position histograms shown in Figs. 4 (a) and (b), the peak positions of each layer are clearly separated at even intervals in spite of rough assembly with only silicone oil. It is proved by the fact that even the minimum peak to valley ratio at the fourth layer is found to be 1.9:1. The peak positions are overlapping at the periphery of 256ch FP-PMT as shown in Fig. 4 (b) because photons cannot spread isotropically for crystal elements at the edge. So it might be difficult to utilize all the useful area (49 mm × 49 mm) of the 256ch FP-PMT, even though we would like to increase a packing fraction as high as possible.

The energy resolution at the peripheral area shown in Fig. 6 is better than the one obtained at the central area. It can be due to anode gain variation of the 256ch FP-PMT. Although the used 256ch FP-PMT has good cathode uniformity and these energy resolutions are made after correction of individual anode gains, some statistical effect caused by the anode variation might be remain. The average gain of 36 anodes at the center corresponding to the position under the crystal block is 81.2 % against the one at the periphery. Regarding outer anodes of the 256ch FP-PMT, approximately half of anodes are covered with packing material [4] and the averaged gain is calculated to be 70.7 % when the outer anodes are excluded. As indicated in Fig. 6 and Table I, the energy resolutions of each layer crystals are much better than the one for all events and the same can be said for the time resolution shown in Fig. 7 and Table I. This suggests that using the DOI information improves the performance of the detector. The full energy peaks of each layer appeared to be uniform as shown in Fig. 8. This makes the elimination of scattered events easy. The time resolution, even at peripheral area, is sufficient and is 0.73 ns in FWHM and 1.55 ns in FWTM. The layers closer to the PMT tend to show faster transit time as indicated in Fig. 7. The transit time differences between the first, second, and third layer and the fourth layer are 150 ps, 130 ps, and 80 ps, respectively.

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VI. REFERENCES