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Improvement of crystal identification performance for a four-layer DOI detector composed of crystals segmented by laser processing

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A B S T R A C T

We have developed a four-layer depth of interaction (DOI) detector with single-side photon readout, in which segmented crystals with the patterned reflector insertion are separately identified by the Anger-type calculation. Optical conditions between segmented crystals, where there is no reflector, affect crystal identification ability. Our objective of this work was to improve crystal identification performance of the four-layer DOI detector that uses crystals segmented with a recently developed laser processing technique to include laser processed boundaries (LPBs). The detector consisted of $2 \times 2 \times 4$ mm^3 LYSO crystals and a 4×4 array multianode photomultiplier tube (PMT) with 4.5 mm anode pitch. The 2D position map of the detector was calculated by the Anger calculation method. At first, influence of optical condition on crystal identification was evaluated for a one-layer detector consisting of a 2×2 crystal array with three different optical conditions between the crystals: crystals stuck together using room temperature vulcanized (RTV) rubber, crystals with air coupling and segmented crystals with LPBs. The crystal array with LPBs gave the shortest distance between crystal responses in the 2D position map compared with the crystal array coupled with RTV rubber or air due to the great amount of cross-talk between segmented crystals with LPBs. These results were used to find optical conditions offering the optimum distance between crystal responses in the 2D position map for the four-layer DOI detector. Crystal identification performance for the four-layer DOI detector consisting of an 8×8 array of crystals segmented with LPBs was examined and it was not acceptable for the crystals in the first layer. The crystal identification was improved for the first layer by changing the optical conditions between all 2×2 crystal arrays of the first layer to RTV coupling. More improvement was observed by combining different optical conditions between all crystals of the first layer and some crystals of the second and the third layers of the segmented array.

1. Introduction

A depth of interaction (DOI) detector is needed for high resolution and high sensitivity PET systems with a uniform spatial resolution across the entire field-of-view (FOV). Numerous types of DOI detectors have been proposed using segmented scintillator arrays composed of small crystals [1–6] or monolithic scintillators for PET detectors [7], and some of them have been implemented into PET systems [8–10]. Using segmented scintillator arrays, our group developed a four-layer DOI detector based on the reflector control [3]. All crystals in the four layers were identified by a photo detector mounted on only one side of the crystal array. In our implementation, room temperature vulcanized (RTV) rubber was chosen for optical coupling in the gap between each pair of crystals in which no reflector was inserted [11–13].

Fabricating segmented crystal arrays involves complicated crystal cutting and assembly steps and that was accomplished efficiently and precisely using a subsurface laser engraving (SSLE) technique [14]. We have reported the performance of the four-layer DOI detector with segmented crystals having laser processed boundaries (LPBs) fabricated using the SSLE technique in 2×2 and 2×1 segmented arrays [15]. Although, the detector using segmented crystals with LPBs was not able to give good crystal identification performance, we thought its

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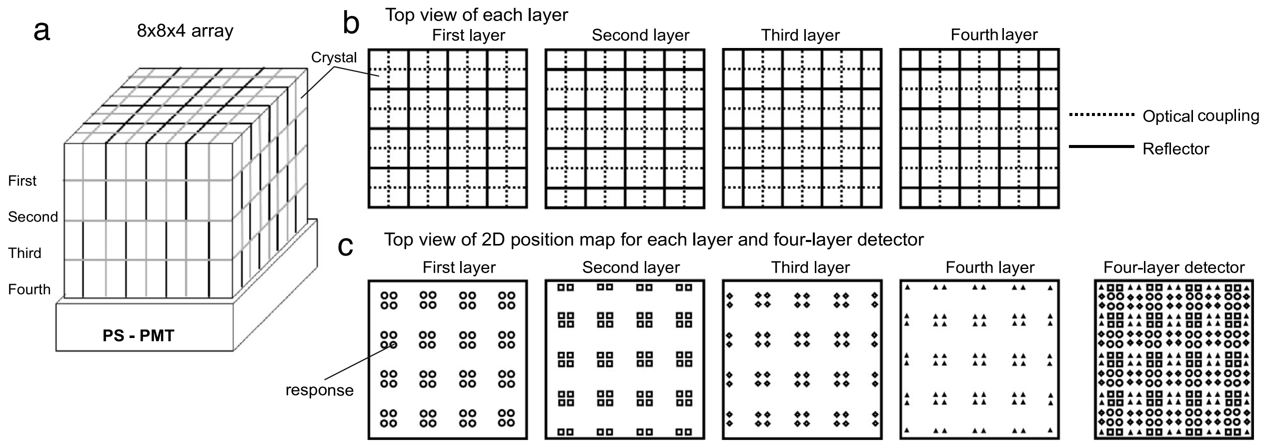

Fig. 1. Schematic drawings of the four-layer DOI detector (a), reflector arrangement in each layer (b) and expected 2D position map for each layer and the four-layer detector (c).

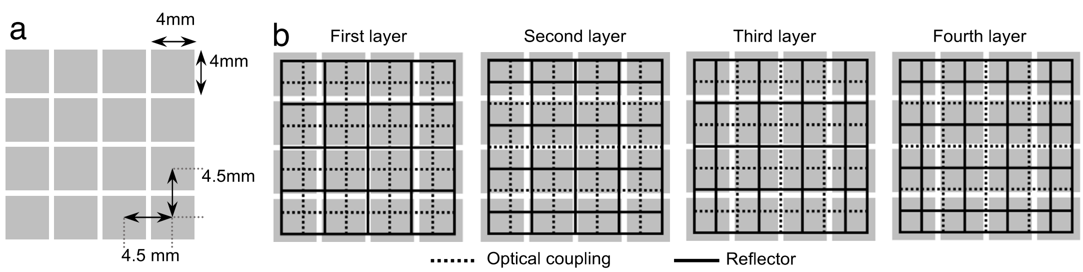

Fig. 2. Schematic drawings showing the anode of the multianode PMT (a) and relative position of the PMT anode and the crystal array for each layer of the four-layer DOI detector with an optical coupling condition (b).

performance could be improved by combining segmented crystals with different optical conditions.

In this study, therefore, we raised crystal identification performance of the four-layer DOI detector consisted of segmented crystals with LPBs using a combination of different optical conditions between the crystals. Three different optical conditions between the crystals were considered: segmented crystals with LPBs, crystals stuck together using RTV rubber and crystals with air coupling. The effects of these conditions were verified for a one-layer detector consisting of a 2×2 crystal array. For the four-layer DOI detector, the effects of various combinations of these optical conditions are investigated experimentally to get a better crystal identification.

2. Materials and methods

2.1. Concept of a four-layer DOI detector

The four-layer DOI detector is composed of a four-layer segmented crystal array and a position-sensitive photomultiplier tube (PS-PMT). Reflectors are inserted alternately between the crystals in each layer with different arrangements and small crystal arrays of 2×2 and 2×1 arrays between the reflectors are coupled with optical coupling material such as air or RTV rubber. The outermost surfaces of the crystal array, except the surface mounted on the PMT, are covered by reflectors to maximize the detection efficiency of the edge crystals for scintillation light. Schematic drawings of the detector composed of an 8×8 crystal array mounted on a PS-PMT and configuration of each layer are shown in Fig. 1(a) and (b). The reflector arrangement for each layer was intended to project a 3D interaction position of a gamma ray within each crystal onto a 2D position map. The electric signal outputs from the PS-PMT are recorded and the position of the gamma ray interaction in the crystal array is estimated by a conventional method, the Anger calculation. Basically, the gamma ray interaction (X and Y coordinates) for each event is determined by the mean of the readout signals. The expected 2D position map for each layer and the four-layer DOI detector are shown in Fig. 1(c).

A 2D position map including a 16×16 array of crystal responses are obtained for the detector of the 8×8 array; in another words, the crystal responses from two different layers are aligned in a row and each row included 16 responses in the position map. The optical coupling material with different refractive index affects distances between crystal responses in the 2D position map and a material with larger refractive index makes the responses closer than the one with smaller refractive index.

2.2. Detectors and experimental setup

2.2.1. One-layer and four-layer detectors

Scintillator crystals of Lutetium Yttrium Orthosilicate (LYSO; $Lu_{1.8}$ $Y_{0.2}$ SiO_5 (Ce)) with a size of 2 mm × 2 mm × 4 mm were used for both one-layer and four-layer detectors. Mirror reflectors (Sumitomo 3M, Ltd., Tokyo, Japan; 0.065 mm thickness) and RTV rubber (KE420, Shin-Etsu Chemical Co. Ltd., Tokyo, Japan; 1.45 refractive index) were used for both detectors. The PMT was a 4×4 multianode type with metal channel dynode (H6568, Hamamatsu Photonics K.K., Hamamatsu, Japan). The photocathode was made of Bialkali with an effective area of 18.1×18.1 mm^2. Each anode had the sensitive are of 4×4 mm^2 with an anode pitch distance of 4.5 mm, as shown in Fig. 2(a), and the high voltage was set at 800 V.

Interaction positions of the gamma ray for both one and four-layer detectors were estimated by the Anger calculation. When an interaction occurred in a crystal optical photons were generated, and some of these photons were detected by the sharp current signals generated at the anodes of the PMT. The position of interaction was estimated by Eq. (1), i.e., the Anger calculation formula.

$$r = \left[r_x, r_y\right], \qquad r = \frac{\sum_{i=1}^{n} s_i r_i}{\sum_{i=1}^{n} s_i}. \tag{1}$$