A new DOI detector design using discrete crystal array with depth-dependent reflector patterns and single-ended readout

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\textbf{A B S T R A C T}

We developed a depth of interaction (DOI) positron emission tomography (PET) detector using depth-dependent reflector patterns in a discrete crystal array. Due to the different reflector patterns at depth, light distribution was changed relative to depth. As a preliminary experiment, we measured DOI detector module crystal identification performance. The crystal consisted of a $9 \times 9$ array of $2 \text{mm} \times 2 \text{mm} \times 20 \text{mm}$ lutetium-yttrium oxyorthosilicate (LYSO) crystals. The crystal array was optically coupled to a 64-channel position-sensitive photomultiplier tube (PSPMT) and to evaluate its performance. Preclinical PET scanners based on this detector design offer the prospect of high and uniform spatial resolution.

\section{1. Introduction}

Preclinical studies using positron emission tomography (PET) are rapidly increasing in molecular imaging for demonstrating biomedical mechanisms in vivo [1,2]. Preclinical PET scanners generally have a small ring diameter and thin and long scintillation crystals to enhance sensitivity and spatial resolution [3]. Therefore, spatial resolution for sources distant from the center of the field of view (FOV) is degraded by parallax [4]. Depth of interaction (DOI) detection is an effective way to solve the parallax error and provide uniform spatial resolution. Various DOI detection methods have been developed [5–11]. One of the most promising methods is discrete DOI measurement using a multi-layer detector. This type of detector consists of multiple scintillation crystal array layers and distinguishes individual layers by crystal decay time or stacking geometry [12–17]. However, light loss occurs between layers, and the manufacturing cost increases by number of crystals in each layer [18]. In addition, the pulse shape discrimination method has a time performance problem due to different decay times [19].

To overcome the problems created by multi-layer detector use, we designed a new DOI detector with a discrete scintillator array using depth-dependent reflector patterns. This method is based on differential light dispersion along the crystal array depth by reflectors partially covering crystal surfaces. The aim of this study was to develop a prototype DOI detector using a lutetium-yttrium oxyorthosilicate (LYSO) crystal array coupled to a position-sensitive photomultiplier tube (PSPMT) and to evaluate its performance.

\section{2. Materials and methods}

\subsection{2.1. Light spreading method}

We arranged the reflectors between crystals as shown in Fig. 1, so that a significant amount of light is shared when a gamma interacts near the front face of a crystal. On the other hand, very little light is shared when an interaction occurs near the crystal back [4]. Thus, the 3D interactive gamma position in each crystal could be imaged and distinguished by a simple Anger algorithm.

To apply this principle to the crystal array, reflectors were designed as shown in Fig. 2(a). Light spreading was generated at each depth in different directions within the crystal array. Then, the gamma interactions at different depths in a single crystal were imaged separately, as shown in Fig. 2(b). Fig. 3 shows an experimental image obtained using two polished crystals with a diffuse reflector to verify this principle.

\subsection{2.2. Design of the DOI detector}

The detector consisted of LYSO crystals with a 420 nm peak wavelength [20]. The LYSO crystal array was composed of $9 \times 9$ crystals, each with dimensions of $2 \text{mm} \times 2 \text{mm} \times 20 \text{mm}$. All of the crystal surfaces were polished. The crystals were coated with a diffuse reflector...
(BC-620, Saint-Gobain Crystals) with a 98% reflective index [21]. The reflector covered either 14 mm or 6 mm of the crystal’s length for the 1st and 2nd layers, respectively. This was done so that each layer had approximately the same detection efficiency. Fig. 4 shows the DOI detector structure consisting of 9×9 crystals and reflector patterns for 2-layer measurement. Total size of the crystal block was 18.45 mm×18.45 mm×20 mm, and the thickness of the reflector was 0.056 mm.

The crystal array was placed in the center of an 8×8 anode array Hamamatsu H7546B PSPMT, whose anode size was 2 mm×2 mm with a 18.1 mm×18.1 mm effective area. The PSPMT spectral response was 300–650 nm, and the maximum quantum efficiency was 23% at 420 nm [22]. The crystal array was optically coupled to the PSPMT with optical grease with a 1.465 refractive index.

2.3. Experimental set-up

The data acquisition system used for the experiments is described in Fig. 5. The Na-22 point source, which emitted 511 keV gamma rays, was placed in front of the crystal array for uniform gamma ray
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