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A High Resolution, Monolithic Crystal, PET/MRI Detector with DOI Positioning Capability

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Abstract

We report on a high resolution, monolithic crystal PET detector design that provides depth of interaction (DOI) positioning within the crystal and is compatible for operation in a MRI scanner to support multimodal anatomic and functional imaging. Our design utilizes a novel sensor on the entrance surface (SES) design combined with a maximum likelihood positioning algorithm. The sensor will be a two-dimensional array of micro-pixel avalanche photodiodes (MAPD). MAPDs are a new type of solid-state photodetector with Geiger mode operation that can provide signal gain similar to a photomultiplier tube (PMT). In addition, they can be operated in high magnetic fields to support PET/MR imaging. Utilizing a multi-step simulation process, we determined the intrinsic spatial resolution characteristics of a detector using the proposed design. For a 48.8 mm by 48.8 mm by 15 mm LSO crystal detector readout by an 8 by 8 array of 5.8 mm by 5.8 mm MAPD elements the intrinsic spatial resolution is 0.83 mm FWHM in X, 0.92 mm FWHM in Y and 1.83 mm FWHM in Z (i.e., DOI) for normally incident photons. Comparing the results versus using a conventional design with the photosensors on the backside of the crystal, an average improvement of 25% in X, 23% in Y, and 20% in Z is achieved.

I. Introduction

Discrete crystal detector modules have traditionally been used to achieve high spatial resolution for small animal positron emission tomography (PET) scanners [1–5]. However, cost goes up quickly as crystal cross-section gets smaller. We have previously investigated a continuous miniature crystal element (cMiCE) detector as a lower cost alternative to high-resolution discrete crystal designs. This detector consists of a 50 mm by 50 mm by 8 mm slab of LYSO coupled to a 52 mm square, 64-channel flat panel photomultiplier tube [6]. A statistics based positioning (SBP) algorithm is used to improve the positioning characteristics of the detector compared to standard or modified Anger positioning schemes [7]. To improve the decoding performance a maximum-likelihood (ML) clustering method is used to extract depth of interaction (DOI) information from the detector [8].

For a traditional PET detector, the photosensors are positioned opposite the entrance surface of the crystal or distal to the object being imaged. Using that design, the best DOI estimation for a monolithic crystal detector occurs in the back section of the crystal, while most interactions occur in the front section of the crystal. One way to overcome this is to place the photosensors on the entrance surface of the crystal, which brings up the novel SES design.

As an enabling technology of the SES design, MAPDs are a new type of photodiode with Geiger mode operation [9,10,15]. They provide very high proportional signal gain ($\sim 10^5$), have potentially very fast timing (< 100 ps), and can be fabricated in user specified geometries. In our application, we are taking advantage of the fact that MAPDs are very thin and can be placed on the entrance surface of the crystal without having a significant attenuation effect. In addition, the MAPDs can be operated in high magnetic fields, which enables PET/MR multimodal imaging.

II. Detector design and methods

A. Sensor on entrance surface (SES) design

The following figures help to describe the SES concept. Fig. 1 shows a conventional design with the photosensors opposite the entrance surface of the crystal and what the light distribution probability density function (PDF) looks like for the photosensor directly under the photon flux. The cumulative PDF represents the amount of light collected by the selected photosensor for interactions occurring at different depths within the crystal. The linear attenuation coefficient of LSO was used to determine the number of gamma interactions at each depth. Along with the cumulative PDF, the plot is further separated into four depth regions using the known DOI information. As can be seen, for the traditional configuration, the PDF varies more significantly for events interacting at depths between 8–15 mm than for events interacting within 0–8 mm. Since our DOI estimation is more accurate for regions where the PDF is varying more rapidly with depth, ideally we would like most of the interactions to take place within depths 8–15 mm. However, because of the exponential interaction probability, a significant majority of the interactions occur within the first 8 mm of the crystal (over 50% of the interactions occur in the first 5.5 mm) where DOI discrimination is the poorest.

The fact that the majority of events were occurring within the opposite end of the crystal led to the SES design, as shown in Fig. 2. For the SES design the PDF varies more rapidly within the 0–5.5 mm region, where most interactions occur. Therefore, the novel SES design has the potential to provide better DOI positioning.

B. Statistics-based positioning (SBP) algorithm with DOI information [7]

Suppose, the distributions of observing signal outputs $M = M_1, M_2, \dots, M_n$ for scintillation position x , are independent normal distributions with mean, $\mu(x)$, and standard deviation $\sigma(x)$.

The likelihood function for making any single observation m_i from distribution M_i given x is:

$$L[m_i|x] = \prod_{i=1}^n \frac{1}{\sigma_i(x) \sqrt{2\pi}} \exp\left(-\frac{(m_i - \mu_i(x))^2}{2\sigma_i^2(x)}\right) \quad (1)$$

The maximum likelihood estimator of the event position x is given by:

$$\hat{x} = \arg \min_x \left[\sum_i \frac{(m_i - \mu_i(x))^2}{2\sigma_i^2(x)} + \ln(\sigma_i(x)) \right] \quad (2)$$

The SBP method requires that the light response function versus interaction location be characterized for the detector. Two SBP look-up tables (LUTs) corresponding to the mean and variance of the light probability density function (PDF) versus (X,Y) position are created during the characterization process.

To extend our SBP method, we developed a maximum likelihood (ML) clustering method for extracting DOI information from a monolithic crystal [8]. The DOI separation technique divides the calibration data into different DOI regions. LUTs are then created for each DOI region. The full set of DOI LUTs allows 3D positioning within our detector module. Our ML clustering technique has been used to extract up to 7 DOI regions from our 15 mm thick cMiCE detector. Based on the 7-depth DOI LUT, a third-order polynomial fit is applied to the mean and variance respectively for each (X,Y) position. Then, a 15-depth DOI LUT is generated from the fit result.

The algorithm utilizes the fact that the light distribution pattern varies continuously and smoothly with DOI so scintillation events happening in similar DOI regions of the crystal will produce similar light distribution patterns. The 7-depth DOI LUT generation can be separated into five basic steps.

Step 1—For the training data at each position, the photosensor channel N receiving the maximum amount of light is located. The light histogram data for that channel is separated into seven initial groups according to their pulse height in photosensor channel N. Group 1 consists of events within the highest one-seventh of the PDF histogram, which correspond to interactions occurring closest to the photosensors in the crystal. Group n ($n=2 \dots 6$) consists of events with the nth one-seventh highest section of the histogram. Group 7 consists of events comprising the lowest one-seventh of the PDF histogram, which correspond to interactions occurring in the crystal furthest from the photosensors. While the initial separation is based upon the pulse height of the signal in photosensor channel N, each event consists of signals from all 64 channels. In doing our depth separation, we use all the channels.

Step 2—For each set of data (i.e., groups 1 through 7), the mean $\mu(j)_i$ and standard deviation $\sigma(j)_i$ are generated, where i is the number of the photosensor channel and j is the group number.

Step 3—For each event, the likelihood ratios (LR) between different groups are calculated. Separation in LR can be used to tune the number of events falling in each group. After all the data has been sorted, iterate by going back to Step 2.

Step 4—After a stable separation is reached, the final mean and standard deviation are generated where they represent the light response LUTs for DOI regions 1 through 7, respectively.

Step 5—For each (X,Y) position, a third-order polynomial fit is applied to the seven DOI means and standard deviations, respectively. A 15-depth DOI LUT is generated from the fitting results.

The idea behind the initial grouping in Step 1 is that the signal from channel N correlates with DOI. Based upon solid angle considerations, interactions near the photosensor window will have a larger amount of light collected by the photosensor channel directly under the interaction location than interactions further from the photosensor.

C. Simulation program for look up table (LUT) generation and testing

We utilize simulation tools that we have previously integrated to investigate different detector design alternatives. To summarize, DETECT2000 [11,12] is used to determine the probability

that a light photon generated at a specific (X, Y, Z) position in the crystal is detected by a specific photosensor. GEANT [13] is used to track the gamma interactions (both Compton and photoelectric) within the crystal. For each interaction, the number of light photons produced by the scintillator crystal is determined. That number is adjusted for the non-proportionality of LSO according to the tables reported by Rooney [14]. Poisson noise is then added to the number of light photons produced. Using the detection probabilities determined from the DETECT2000 simulations, the number of light photons striking each photosensor is determined. The number of light photons is then adjusted by the photon detection efficiency of the photosensor. Poisson noise is then added to the number of detected light photons. The number of light photons detected by each sensor for each interaction is summed for the final light distribution for a given event.

D. Intrinsic spatial resolution testing

For this initial work, the crystal was modeled as a 48.8 mm by 48.8 mm by 15 mm slab of LSO. An 8 by 8 array of 5.8 mm by 5.8 mm MAPD elements with 6.08 mm center-to-center spacing was placed on the entrance surface of the crystal for the SES design, while an 8 by 8 array of PMT elements with the same configuration was placed on the exit surface of the crystal for the conventional design. The 15-depth DOI LUTs were built from photon fluxes with a diameter of 0.6 mm FWHM perpendicular to the face of the detector. The spacing between photon fluxes was 1.52 mm in X and Y. Twenty thousand events were used for training (i.e., building the LUTs). Photon fluxes of normal incidence were used to test the X, Y and DOI positioning of the detector. The test events were simulated as being a point flux. Ten thousand events were used for testing. The effect of Compton scatter in the crystal was included for both training and test data.

III. Results

The two-dimensional contour plots illustrating the FWHM for normally incident photons are illustrated in Fig. 3. The spacing between photon fluxes is 1.52 mm. A 15-depth DOI LUT was used for positioning. The SES design (Fig. 3a) shows better performance when compared to the conventional design (Fig. 3b). Fig. 4 shows representative distributions of DOI positioning error. Doing a Gaussian fit, the FWHM is 1.62 mm for the SES design, (Fig. 4a) and 2.2 mm for the conventional design (Fig. 4b).

Table I summarizes the intrinsic spatial resolution performance for the SES design. Excluding the last row and column at the edge of the crystal, the spatial resolution is 0.83 mm FWHM in X and 0.92 mm FWHM in Y. The DOI positioning error is 1.83 mm FWHM. Table II summarizes the spatial resolution for the conventional design, the FWHM in X is 1.11 mm, the FWHM in Y is 1.19 mm, and the DOI positioning error is 2.28 mm. An improvement in spatial resolution of greater than 20% in each dimension is achieved using the SES design.

IV. Discussion and Conclusion

The SES design provides outstanding X, Y and DOI positioning resolution and allows the detector to provide nearly the same intrinsic spatial resolution for normally and non-normally incident photon fluxes. A key to the results is having a majority of the photon interactions occurring in a region of the crystal where the light distribution PDF is varying most rapidly (i.e., where the DOI positioning resolution is the most accurate).

The skewed DOI error distribution is caused by Compton scatter in the crystal. Events which are Compton scattered before being photo-electrically absorbed will have a broader light distribution and therefore will get positioned to deeper depths.

One of the keys to the design is the development of MAPDs. MAPDs are a new type of avalanche photodiodes with Geiger mode operation that can provide signal gain comparable to PMT. Their compact size enables the SES design. In addition, they can be operated in high magnetic fields to support PET/MR multimodal imaging.

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Fig. 1. Conventional design with the photosensors opposite the entrance surface of the crystal. The light PDF is a histogram, which shows the distribution of amount of light collected by a certain photosensor channel.

Fig. 2.
SES design with photosensors on the entrance surface of the crystal.

(a)

(b)

Fig. 3.
Contour plots of SBP positioning using 15-depth DOI LUT for: (a) SES design; (b) conventional design.

Fig. 4. DOI errors of SBP positioning using 15-depth DOI LUT for: (a) SES design; (b) conventional design.

TABLE I

Spatial resolution for SES design

Dimension	Bias (mm)	FWHM (mm)
X direction	0.00 $\pm$ 0.02	0.83 $\pm$ 0.10
Y direction	0.00 $\pm$ 0.04	0.92 $\pm$ 0.14
DOI error	0.16 $\pm$ 0.16	1.83 $\pm$ 0.24

TABLE II

Spatial resolution for conventional design

Dimension	Bias (mm)	FWHM (mm)
X direction	0.00±0.05	1.11 ±/− 0.16
Y direction	0.02 ±/− 0.04	1.19±/− 0.17
DOI error	−0.67 ±/− 0.10	2.28 ±/− 0.15