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Simulation study of PET detector configuration with thick light guide and GAPD array having large-area microcells for high effective quantum efficiency

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ABSTRACT

Background and Objectives: Light sharing PET detector configuration coupled with thick light guide and Geiger-mode avalanche photodiode (GAPD) with large-area microcells was proposed to overcome the energy non-linearity problem and to obtain high light collection efficiency (LCE).

Methods: A Monte-Carlo simulation was conducted for the three types of LSO block, 4×4 array of $3 \times 3 \times 20$ mm^3 discrete crystals, 6×6 array of $2 \times 2 \times 20$ mm^3 discrete crystals, and 12×12 array of $1 \times 1 \times 20$ mm^3 discrete crystals, to investigate the scintillation light distribution after conversion of the γ-rays in LSO. The incident photons were read out by three types of 4×4 array photosensors, which were PSPMT of 25% quantum efficiency (QE), GAPD1 with 50×50 μm^2 microcells of 30% photon detection efficiency (PDE) and GAPD2 with 100×100 μm^2 of 45% PDE. The number of counted photons in each photosensor was analytically calculated. The LCE, linearity and flood histogram were examined for each PET detector module having 99 different configurations as a function of light guide thickness ranging from 0 to 10 mm.

Results: The performance of PET detector modules based on GAPDs was considerably improved by using the thick light guide. The LCE was increased from 24 to 30% and from 14 to 41%, and the linearity was also improved from 0.97 to 0.99 and from 0.75 to 0.99, for GAPD1 and GAPD2, respectively. As expected, the performance of PSPMT based detector did not change. The flood histogram of 12×12 array PET detector modules using 3 mm light guide coupled with GAPDs was obtained by simulation, and all crystals of $1 \times 1 \times 20$ mm^3 size were clearly identified. PET detector module coupled with thick light guide and GAPD array with large-area microcells was proposed to obtain high QE and high spatial resolution, and its feasibility was verified.

Conclusions: This study demonstrated that the overall PET performance of the proposed design was considerably improved, and this approach will provide opportunities to develop GAPD based PET detector with a high LCE.

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1. Introduction

Positron emission tomography (PET) allows the visualization of in vivo radiotracer distribution with high sensitivity and acceptable spatial resolution for molecular imaging study. Since there has been growing interest in small animal imaging and organ specific imaging applications, it is important to develop a PET detector module that can provide high energy-, time- and spatial-resolution. One possible method is to use high light output scintillators like LSO, LaBr3, LFS and LuI to overcome scarce photon statistics [1–4]. Another method is to utilize the photosensor with higher quantum efficiencies (HQE) [5–8]. More than 80 years after its development, the photomultiplier tube (PMT) is regarded as one of the most useful photosensors in various radiation detection applications. This is due to its outstanding features of very high gain ($>10^6$), low noise and fast response relative to other photosensors. Also, it can provide energy linearity with a wide dynamic range such that the amount of photoelectrons is proportional to the number of incident photons striking the photocathode for the high flux regime. Recently, a promising Photomultiplier tubes (PMTs) employing super bialkali (SBA) and ultra bialkali (UBA) photocathodes have been introduced for superior quantum efficiency. It has been reported that the respective quantum efficiency (QE) of SBA and UBA photocathodes has improved to the level of ~33% and ~37% at 420 nm wavelength, compared to the level of ~25% for conventional bialkali (BA) photocathodes [9,10].

Geiger-mode avalanche photodiodes (GAPDs) have been studied actively as the next generation PET photosensor, and many groups have demonstrated the usefulness of GAPDs in PET applications [11–14]. GAPDs consist of hundreds or thousands of microcells operating independently in a Geiger mode and its multi-microcell structure can provide a proportional output for moderate photon flux. The output of individual microcells is connected in parallel to form a GAPD pixel, and the total number of activated microcells reflects the number of incoming photons. Photon detection efficiency (PDE) is assessed based on combination of the QE, the geometric efficiency, and the Geiger-mode discharge probability, due to its particular operating mode. A finite number of microcells could induce a significant deviation of energy linearity when the number of photons entering the photosensor is larger than the number of microcells. Light collection efficiency (LCE) might also be decreased due to the saturation effects, and these non-linearity properties may render implementation of GAPDs with large-area microcells impractical for high photon flux detection and PET application [15–17].

A common approach is the utilization of GAPDs with small-area microcells allowing implementation of larger number of microcells to solve the linearity problem for the development of LSO based PET detector [18–20]. However, there are apparent drawbacks that small microcell GAPD has lower photon detection efficiency (PDE) due to the lower fill factor and also has lower gain due to smaller microcells.

We, therefore, propose a new approach employing the light sharing detector configuration: GAPD array having large-area microcells coupled with thick light guide. The incident photons (10000 ~ 15000 scintillation light) generated by interaction of 511 keV γ-ray with LSO were spread to neighboring GAPD pixels by light guide. After that, only a fraction of photons entered in each GAPD which could be operated linearly. Therefore, this method allows the operation of the GAPDs with large-area microcell size, without saturation effect (Fig. 1). The main advantage of this method is the increase in the available number of microcells detecting the photons employing light sharing configuration without modification of microcell size of GAPD; hence, it will improve the energy linearity and light collection efficiency (LCE), and preserve PDE and gain of GAPD with large-area microcell size.

The aim of this study is to investigate the advantages of a light sharing PET detector configuration based on thick light guide and GAPDs with large-area microcells. The performance of direct coupling with LSO and photosensor was compared to that of light sharing detector configuration based on GAPDs with large-area microcells. The performance of PET detector, LCE, linearity, and flood histogram, were evaluated using Monte-Carlo simulation and analytical assessment.

2. Materials and methods

2.1. PET detector module configurations

Ninety-nine PET detectors, consisting of different LSO crystal arrays, photosensor arrays, and light guides, were modeled. Three types of LSO crystal arrays, 4×4 array of $3 \times 3 \times 20\ \text{mm}^3$ discrete crystals, 6×6 array of $2 \times 2 \times 20\ \text{mm}^3$ discrete crystals, and 12×12 array of $1 \times 1 \times 20\ \text{mm}^3$ discrete crystals, were modeled and each crystal was polished and separated by white reflectors (RC = 0.98). Three types of photosensors [21], PSPMT with 25% QE, GAPD1 with 30% PDE having small-area microcells (3600 microcells, $50 \times 50\ \mu\text{m}^2$), and GAPD2 with 45% PDE having large-area microcells (900 microcells, $100 \times 100\ \mu\text{m}^2$) consisting of $3 \times 3\ \text{mm}^2$ pixels, were modeled. Then, $12 \times 12\ \text{mm}^2$ monolithic optical guides with a refractive index of 1.52 and 11 different thicknesses, ranging from 0 to 10 mm with a 1 mm step, were modeled so as to allow the scintillation light to spread to neighboring photosensor pixels (Fig. 2).

2.2. Monte-Carlo simulation

A Monte-Carlo simulation using DETECT2000 was conducted to investigate the light distribution after conversion of the γ-ray in LSO crystal using a light yield of 27 photons/keV [22,23]. Each of the 1000 γ-ray interactions per discrete crystal for the LSO crystal blocks was simulated with a different random number, and the average incident photons was predicted to impinge on the photosensor entrance surface. Although the recovery time needed to recharge a cell after a breakdown could depend on the microcell size and have an effect on the number of fired cells, these phenomena was not modeled in this study. The variations in uniformity caused by inhomogeneities in scintillation crystals, light guide, and photosensor pixels, and nonuniformities in white reflectors and amplifier circuits were not modeled in this study.

The photons impinging on the GAPD entrance surface were simulated and recorded for each interaction event. The number of collected photons for PMT ($N_{\text{collected photons}}$) and fired cells for