Nuclear Instruments and Methods in Physics Research A 703 (2013) 183–189

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of an ultrahigh-resolution Si-PM-based dual-head GAGG coincidence imaging system ☆

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ARTICLE INFO

Article history:
Received 17 August 2012
Received in revised form
18 November 2012
Accepted 20 November 2012
Available online 29 November 2012

Keywords:
Si-PM
Coincidence
Imaging
Ultra high resolution
GAGG

ABSTRACT

A silicon photomultiplier (Si-PM) is a promising photodetector for high resolution PET systems due to its small channel size and high gain. Using Si-PMs, it will be possible to develop a high resolution imaging systems. For this purpose, we developed a small field-of-view (FOV) ultrahigh-resolution Si-PM-based dual-head coincidence imaging system for small animals and plant research. A new scintillator, Ce doped $Gd_3Al_{12}Ga_3O_{12}$ (GAGG), was selected because of its high light output and its emission wavelength matched with the Si-PM arrays and contained no radioactivity. Each coincidence imaging block detector consists of $0.5 \times 0.5 \times 5$ mm^3 GAGG pixels combined with a 0.1-mm thick reflector to form a 20×17 matrix that was optically coupled to a Si-PM array (Hamamatsu MPPC S11064-050P) with a 1.5-mm thick light guide. The GAGG block size was 12.0×10.2 mm^2. Two GAGG block detectors were positioned face to face and set on a flexible arm based detector stand. All 0.5 mm GAGG pixels in the block detectors were clearly resolved in the 2-dimensional position histogram. The energy resolution was 14.4% FWHM for the Cs-137 gamma ray. The spatial resolution was 0.7 mm FWHM measured using a 0.25 mm diameter Na-22 point source. Small animal and plant images were successfully obtained. We conclude that our developed ultrahigh-resolution Si-PM-based dual-head coincidence imaging system is promising for small animal and plant imaging research.

1. Introduction

A high resolution PET system is needed for high resolution imaging for small animal PET studies. Although block detectors using smaller scintillators must be developed to realize a high resolution PET system, small scintillators are difficult to resolve using the Anger principle because of their relatively low light output and the relatively large channel size of the photodetectors because the resolving power of the Anger principle is roughly determined by the light output of the scintillators and the photodetector sizes [1].

A silicon photomultiplier (Si-PM) is a newly developed silicon-based photodetector that is also called a Geiger mode avalanche photodiode (G-APD) [2,3]. This photon counting device consists of multiple APD pixels operating in a Geiger mode. Some block detector designs [4–7] and small animal PET systems were already reported [8,9]. We recently developed a Si-PM-based depth-of-interaction (DOI) PET system using a phoswich structure for small animals that employed 16 detector blocks consisting of 4×4 Si-PM arrays and two types of Ce doped $Lu_{(1-x)}Gd_xSiO_5$ (LGSO) crystals with different decay times [8]. The block detector of the Si-PM-based PET system employed Hamamatsu 4×4 Si-PM arrays that were optically coupled with an 11×9 LGSO block of 1.1×1.2 mm^2 LGSO pixels. The position histogram for the 511 keV gamma ray had enough margins to use a much smaller scintillator, suggesting the possibility of developing an ultrahigh-resolution PET system with less than 1-mm scintillators. To clarify this possibility, we developed a 15×15 array LGSO block whose pixel size was $0.7 \times 0.7 \times 6$ mm^3 and combined it with a Si-PM array. We successfully resolved all LGSO pixels of the block detector [10]. We also developed an ultrahigh-resolution Si-PM-based compact gamma camera system for small animals that used $0.6 \times 0.6 \times 6$ mm^3 Ce doped Y_2SiO_5 (YSO) pixels to form a 17×17 matrix that was optically coupled to a Si-PM array [11]. Higher light output is desired to resolve smaller scintillators.

Ce doped $Gd_3Al_{12}Ga_3O_{12}$ (GAGG) is a newly developed scintillator that has large light output and longer light wavelength (500 nm) [12]. The longer wavelength of the scintillation light produces higher signals when it is combined with Si-PM since the

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0168-9002/$ - see front matter
http://dx.doi.org/10.1016/j.nima.2012.11.098

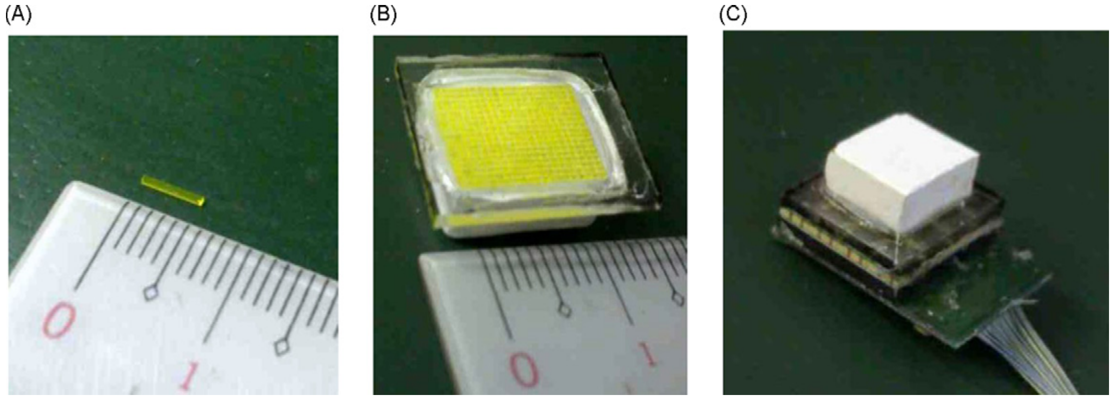

Fig. 1. $0.5\times0.5\times5$ mm^3 GAGG pixel (A), 20×17 GAGG block with 1.5-mm light guide (B) and, Si-PM based GAGG block detector (C).

Table 1
Comparison of property of scintillators.

Scintillator	Ce:GAGG	LYSO:Ce	BGO	CsI:Tl
Density (g/cm^3)	6.63	7.1	7.1	4.5
Light yield (ph/Mev)	46,000	30,000	8000	60,000
Decay time (ns)	90	40	300	1000
Peak emission (nm)	520	420	480	545
Energy resolution (%@662 keV)	4.9	9	12	5%

Si-PM's quantum efficiency is higher for the light with longer wavelength. Block detectors with higher resolution may be realized by combining the GAGG arrays with Si-PM arrays. Consequently, we developed an ultrahigh-resolution block detector using $0.5\times0.5\times5$ mm^3 GAGG pixels coupled with a Si-PM array and measured the performance. We also developed a dual-head coincidence imaging system using the block detectors, measured its performance, and demonstrated its usefulness in molecular imaging research. Although some dual-head coincidence imaging systems were developed for small animals and plants [13–15], most of those were used BGO, relatively low light output scintillators, and the spatial resolution was limited around 1.5–2 mm. In this paper, we show the system with less than 1 mm resolution by the use of GAGG scintillators.

2. Materials and methods

2.1. Si-PM-based GAGG block detector

Fig. 1(A) shows a single GAGG pixel used for the GAGG block. The GAGG pixel size was $0.5\times0.5\times5$ mm^3, and all the surfaces were mechanically polished (Furukawa Machine and Metal Co., Tokyo). The major properties of the GAGG are density of 6.6 g/cm^3, decay time of ~90 ns, light yield of ~46,000 photons/ MeV [12]. We listed the properties of scintillators in Table 1 for comparison [12].

The GAGG pixels were combined to form a 20×17 block with 0.1-mm thick $BaSO_4$ reflectors between them [16]. The outer size of the GAGG block was 12.0×10.2 mm^2. It was optically coupled to a 1.5-mm thick Acrylite (No. 000, Mitsubishi Rayon, Tokyo) light guide using a transparent silicone rubber (Shin-etsu Silicone, KE-420, Tokyo) (Fig. 1(B)). The GAGG block was optically coupled to a Si-PM array (Hamamatsu MPPC S11064-050P) (Fig. 1(C)). The Si-PM array has 4×4 channels whose size is 3×3 mm^2. The number of pixels per Si-PM of the array is 3600 and the pixels size is 50×50 um^2.

2.2. Dual-head coincidence imaging system using Si-PM-based GAGG block detectors

2.2.1. Dual-head coincidence imaging system

A dual-head coincidence imaging system using the two GAGG block detectors is shown in Fig. 2(A). Two Si-PM-based GAGG block detectors were positioned at the top of the flexible arm. One lineally moves to change the distance between the block detectors. The flexible arm was installed on an X–Y–Z table that can precisely move the dual-head coincidence imaging system in any direction.

Fig. 2(B) shows the system's detector part. The GAGG block detectors are housed in 5-mm thick tungsten plastic containers (density: 12) to reduce the gamma ray from outside the field-of-view (FOV). Tungsten plastic was employed due to its low manufacturing cost compared with tungsten. The Si-PM signals were fed to the electronics with 1.2 m long fine coaxial cables.

2.2.2. Electronics circuit and data acquisition system

The Si-PM array signals were individually amplified by voltage feedback high-speed operational amplifiers and summed for rows and columns using summing amplifiers. Such signals were weighted summed with position dependent linear gains for each row and column signals to produce weighted sum signals. These weight summing calculations were performed using operational amplifiers and produced two weight summed signals for two opposite X directions (X^+ and X^-) and Y directions (Y^+, and Y^-). These weight summed signals were analog-to-digital (A–D) converted using four free running A–D converters (100 MHz). Signals exceeding the threshold were digitally integrated for 470 ns. The 2-dimensional position histogram was derived by calculating the center of gravity for the X and Y positions ($X^+/(X^++X^-)$ and $Y^+/(Y^++Y^-)$), and the energy was calculated by (X^++X^-) for each pixel of the 2-dimensional position histogram. These calculations were performed digitally by field programmable gate array (FPGA). This electronics circuit is the same as that used for the Si-PM-based PET system [8]. The same temperature dependent gain control system as employed for the Si-PM-based small animal PET system was also used [17].

2.2.3. Image formation

All coincidence lines of responses between two GAGG block detectors were acquired in a list mode. Planner images were derived using a focal plane method to form a 39×33 matrix data. The pixel size was 0.3×0.3 mm^2. Detector pixel number differences within ±2 were added to the pixel, similar concept to the single slice rebinning used for PET image reconstruction. The normalized data were measured using a plane phantom