Exploration of photodetectors for pulse shape discrimination in a dual particle imager

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1. Introduction

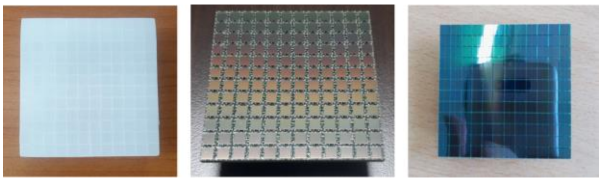
A dual particle imager (DPI) simultaneously detects gamma-rays and neutrons to reconstruct radiation images that provide visual aids on the distribution of radioactive sources and double verification of the presence of a special nuclear material (SNM) [1]. In the imaging device, it is significant to separate neutrons from gamma rays, so various pulse shape discrimination (PSD) methods are developed including the charge comparison (CC) method, the simplified digital charge comparison (SDCC) method, the pulse gradient analysis (PGA), and the neutron gamma model analysis (NGMA) [2]. Furthermore, the effect of analog-digital converters (ADCs) with different resolutions and sampling rates (e.g. 12-bit–250-MHz, 10-bit–1-GHz, 10-bit–2-GHz, and 14-bit–400-MHz digitizer) on the PSD performance are verified [3]. Despite these studies, a pixelated array module, such as a plastic (EJ-299-34) scintillator array combined with a photomultiplier tube (PMT), shows degradation in PSD performance compared to what single-crystal plastic scintillators have [4], and few studies have been conducted to tackle this problem. A previous study on the development of hand-held DPI system [5] also shows that a pixelated stilbene array coupled with a silicon photomultiplier (SiPM) array has a relatively low PSD performance with a figure of merit (FOM) of 1.55 at 300 ± 100 keVee compared to the FOM of 1.71 that a single-crystal stilbene coupled to a PMT has in the energy range mentioned above [6]. In this study, we explore scintillator pixels that exhibit PSD properties, and illustrate effects of a large light absorption area in a SiPM array on a PSD performance for the pixelated stilbene array in the DPI.

2. Methods and Results

In this section two SiPM arrays with a different active area, the pixelated stilbene array and signal processing method are given.

2.1 Pixelated Scintillator Array

The hardware system of the DPI system, termed EPSILON (Energetic Particle Sensor for the Identification and Localization of Originating Nuclei)-D(dual), developed in [10] is designed to handle signals from all 144 pixels of the stilbene-SiPM array module. The stilbene scintillator array (made by Inrad Optics) consists of 12 × 12 rectangular parallelepiped pixels with a size of 4 × 4 × 20 mm^3, as shown in Fig. 1(a), and forms a reflector with a thickness of 200 μm for a pixel pitch of 4.2 mm. On Semiconductor supplies a C-series 12 × 12 pixelated SiPM array with a pixel size of 3 mm (ArrayC-30035-144P), but does not provide a 12 × 12 pixelated SiPM array with a pixel size of 4 mm that matches the pixel size of the pixelated stilbene array. Thus, the number of 144 J-series SiPM pixels (MICROFJ-40035-TSV-TR1, On Semiconductor) with a pixel size of 4 mm are assembled in an array format. The C-series SiPM array and the self-developed J-series SiPM array are used as photon detectors, as shown in Fig. 1(b) and Fig. 1(c). Both SiPM arrays have the same pixel pitch as the stilbene scintillator array has and are directly coupled with the stilbene array as a sensor module.



(a) (b) (c)

Fig. 1. Stilbene scintillator array (12 × 12 pixels of 4 × 4 × 20 mm^3 each) (a), C-series SiPM array (12 × 12 pixels of 3 × 3 mm^2 each) (b), and a self-developed J-series SiPM array (12×12 pixels of 4 × 4 mm^2 each) (c).

2.2 Hardware Configurations for Signal Processing

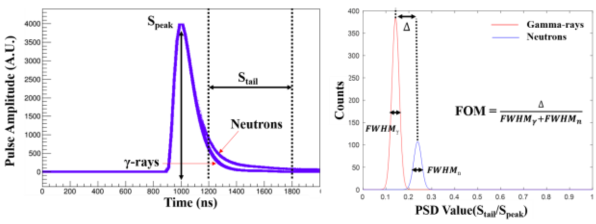
Fig. 2. Design of *EPSILON-D* developed in the previous study [5].

The developed DPI system, shown in Fig. 2, employs a row/column readout with resistive dividers that directly processes 24 analog signals from each row and column to ADCs. The readout circuit reduces the standard outputs of the 12 × 12 SiPM array from 144 to 12 for each orthogonal X and Y direction in which the interaction positions of individual scintillation events are identified. The signal outputs from the X and Y lines are amplified using 24 trans-impedance amplifiers (TIAs) with a feedback resistance (R_f) of 100 Ω, and then the signals are shaped by shaping amplifiers. These 24 analog signals are connected directly to ADCs

(ADC3421, Texas Instruments), with quad channels, 12-bit resolution, and a sampling rate of 50 MHz. The energy determination of an event is provided as the moving sum of all ADC values derived from columns and rows within a predetermined time by firmware. In addition, the event position is pinpointed to a pixel in which the largest signal in the column and row occurs.

2.3 PSD method

PSD based on charge integration is implemented to exploit the characteristic difference observed in the tail region of the measured pulses, as shown in Fig. 3(a). The ratio of tail-integral to the peak provides a discriminating parameter that separates neutron and photon pulses. Figure 3(b) shows the histogram distribution of the tail-to-peak ratio that yields two normally-distributed data corresponding to the neutron and photon detection. The quality of PSD performance is described using a FOM defined by the ratio of the peak center difference to the sum of the total width at half the maximum (FWHM) of the two distributions.



(a) (b)

Fig. 3. Illustration of the PSD method (a) and FoM evaluation method (b).

3. Results and discussion

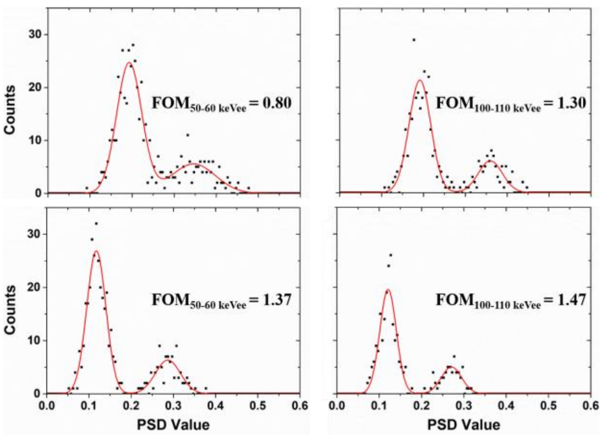


Fig. 4. *FOM* values in a low energy range for a single-pixel PSD distribution obtained from each C-series (top row) and J-series SiPM-Stilbene array sensor module (bottom row).

FOM values in two different low-energy regions (50-60 keVee, 100-110 keVee) for C-series and J-series SiPM-stilbene array modules are shown in Fig. 4. The C-series SiPM-stilbene array sensor module has a *FOM* value of 1.30 in the energy range of 100-110 keVee, whereas the J-series SiPM-stilbene array module has a superior *FOM* value of 1.37 in the energy range of 50-60 keVee. Because there are slight discrepancies in light yield and light collection efficiency among those pixelated pixels, summing all PSD distributions of pixels with these differences will lead to the overall PSD distributions that appear to be degraded, though a pixel-by-pixel gain calibration is made for every pixel [5].

4. Conclusions

We demonstrate the pixel size matching between the pixelated stilbene scintillator array and SiPM array can improve the PSD performance even with the use of ADCs that has a low bit resolution (12 bit) and a low sampling rate (50 MHz). In the coded-aperture based dual-particle imaging system will be used to detect the accurate location of unknown and shielded radiation sources in real-time and to develop equipment for nuclide analysis in the field of medical, nuclear industry, and homeland security.

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