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4π FOV compact Compton camera for nuclear material investigations

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ABSTRACT

A compact Compton camera with a 4π field of view (FOV) was manufactured using the design parameters optimized with the effective choice of gamma-ray interaction order determined from a Monte Carlo simulation. The camera consisted of six CsI(Na) planar scintillators with a pixelized structure that was coupled to position sensitive photomultiplier tubes (H8500) consisting of multiple anodes connected to custom-made circuits. The size of the scintillator and each pixel was $4.4 \times 4.4 \times 0.5$ and $0.2 \times 0.2 \times 0.5$ cm, respectively. The total size of each detection module was only $5 \times 5 \times 6$ cm and the distance between the detector modules was approximately 10 cm to maximize the camera performance, as calculated by the simulation. Therefore, the camera is quite portable for examining nuclear materials in areas, such as harbors or nuclear power plants. The non-uniformity of the multi-anode PMTs was corrected using a novel readout circuit. Amplitude information of the signals from the electronics attached to the scintillator-coupled multi-anode PMTs was collected using a data acquisition board (cDAQ-9178), and the timing information was sent to a FPGA (SPARTAN3E). The FPGA picked the rising edges of the timing signals, and compared the edges of the signals from six detection modules to select the coincident signal from a Compton pair only. The output of the FPGA triggered the DAQ board to send the effective Compton events to a computer. The Compton image was reconstructed, and the performance of the 4π FOV Compact camera was examined.

1. Introduction

Since Pinkau proposed the first Compton imaging technique to acquire images of solar neutrons in 1966 [1], many types of Compton cameras have been used for astronomical applications, environmental remediation, industrial surveys and medical approaches [2–7]. The Compton imaging technique utilizes sequential gamma-ray interactions in a single detector or multiple detectors. When a photon undergoes multiple interactions in detectors, the angle of photon scattering can be calculated to reconstruct the source distribution based on the position and energy of the interactions in the detectors. Among the many detector materials on the market, scintillators have been used in Compton cameras owing to their high timing resolution, availability in larger volumes, usability without cooling equipment and relatively low cost. Since the first Compton telescope flew on NASA's Gamma Ray Observatory in 1984, many liquid or solid scintillators with single or array-type configurations have been coupled to photomultiplier tubes (PMTs) or position sensitive photomultiplier tubes (PSPMTs) [8–10]. However, the application of a Compton camera with scintillators is limited due to the bulkiness of conventional photomultiplier tubes.

In this study, a 4π field of view (FOV) Compton camera was manufactured using scintillators in a compact design. The detection of FOV was maximized and the relative variance was decreased because the detection cube made from CsI(Na) scintillators that was coupled compactly to multi-anode PMTs could receive radiation from any direction. In addition, the single 4π FOV Compton camera could detect radiation from all directions. Therefore, it can replace multiple conventional gamma cameras with high efficiency and low cost. The 4π FOV Compton camera can have many applications, such as homeland security, radioactive waste management and non-proliferation, where a number of conventional gamma cameras are needed. The performance of the 4π FOV Compton camera and the reconstructed image are presented.

2. Design and method

As shown in Fig. 1(a), the camera consists of six CsI(Na) planar scintillators with a pixelized structure that is coupled to position sensitive photomultiplier tubes (H8500) consisting of multiple anodes connected with custom-made circuits. The CsI(Na) scintillators, made by Hilgers, consisted of 20×20 pixels, each pixel $2 \times 2 \times 5$ mm in size. The sizes of the PSPMTs were $5 \times 5 \times 3$ cm and the total size of each detection module was $5 \times 5 \times 6$ cm. The distance between the detector modules was approximately 10 cm

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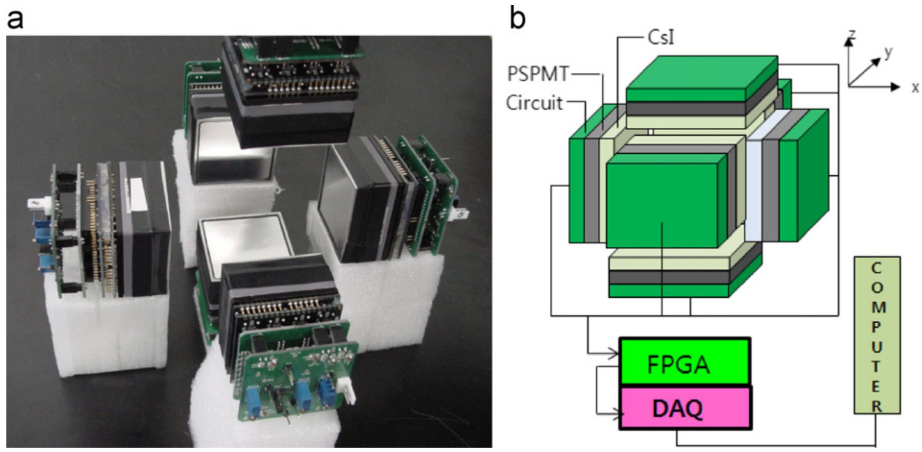

Fig. 1. 4pi FOV compact gamma camera. (a) Photograph and (b) schematic diagram.

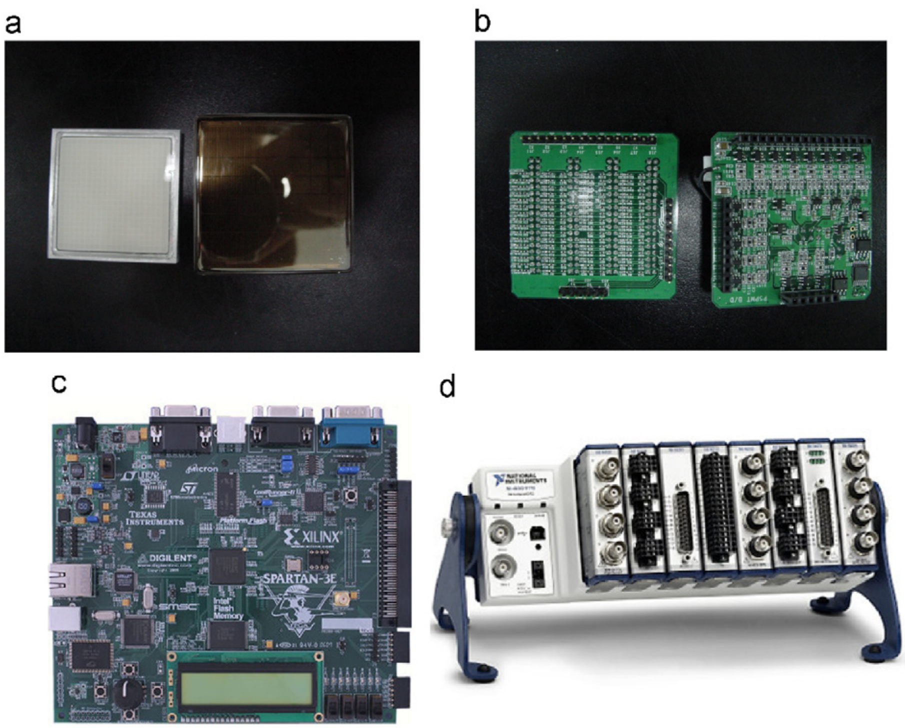

Fig. 2. Components of the 4π FOV Compton camera. (a) CsI(Na) scintillator, H8500 PMT, (b) voltage divider and front end circuit, (c) FPGA (SPARTAN3E), and (d) DAQ board (cDAQ-9178).

to maximize the camera performance, as calculated by the simulation [11].

As shown in Fig. 1(b), the signals from the CsI(Na) coupled multi-anode PSPMT (Fig. 2(a)) were transmitted to the electronic circuits that correct the non-uniformity of the PSPMT (Fig. 2(b)), and the timing and amplitude information were collected using a FPGA (Fig. 2(c)) and DAQ board (Fig. 2(d)), respectively. The FPGA triggered the DAQ board to select the effective Compton events and send them to a computer. The Compton images were reconstructed using the list mode, maximum likelihood expectation maximization (MLEM) method [10], and the detection efficiency was determined.

The source distribution could be estimated from the scattering angle calculated using Eqs. (1) and (2) and the interaction positions of Compton scattering followed by photoelectric events.

$$\cos\theta_e = 1 - \frac{m_e c^2 E_1}{E_0(E_0 - E_1)} \quad \text{if } E_0 \text{ is known} \tag{1}$$

$$\cos\theta_e = 1 - \frac{m_e c^2 E_1}{(E_1 + E_2)E_2} \quad \text{if } E_0 \text{ is unknown and } E_0 = E_1 + E_2 \tag{2}$$

E_0 is the energy of the incident radiation; E_1 the energy deposited in the first detector; E_2 the energy deposited in the second detector; m_e the mass of an electron; c the speed of light; θ_e the scattered angle

The sequential order of radiation interactions could not be determined physically. There were many sequential estimation methods for the Compton camera but they could only estimate the high probability sequence. Consequently, only two sequential interactions were accepted and both interactions could be the first interaction. Therefore, two types of back-projections were considered for every two sequential interactions. The detection efficiency was calculated using the effective events for Compton imaging divided by the number of incident photons to all detectors.