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Original Article

REPLACEMENT OF A PHOTOMULTIPLIER TUBE IN A 2-INCH THALLIUM-DOPED SODIUM IODIDE GAMMA SPECTROMETER WITH SILICON PHOTOMULTIPLIERS AND A LIGHT GUIDE

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ABSTRACT

The thallium-doped sodium iodide [NaI(Tl)] scintillation detector is preferred as a gamma spectrometer in many fields because of its general advantages. A silicon photomultiplier (SiPM) has recently been developed and its application area has been expanded as an alternative to photomultiplier tubes (PMTs). It has merits such as a low operating voltage, compact size, cheap production cost, and magnetic resonance compatibility. In this study, an array of SiPMs is used to develop an NaI(Tl) gamma spectrometer. To maintain detection efficiency, a commercial NaI(Tl) 2′ × 2′ scintillator is used, and a light guide is used for the transport and collection of generated photons from the scintillator to the SiPMs without loss. The test light guides were fabricated with polymethyl methacrylate and reflective materials. The gamma spectrometer systems were set up and included light guides. Through a series of measurements, the characteristics of the light guides and the proposed gamma spectrometer were evaluated. Simulation of the light collection was accomplished using the DETECT 97 code (A. Levin, E. Hoskinson, and C. Moison, University of Michigan, USA) to analyze the measurement results. The system, which included SiPMs and the light guide, achieved 14.11% full width at half maximum energy resolution at 662 keV.

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1. Introduction

Gamma spectrometry is the analytic study of the identification and quantification of radionuclides. It is applied in many fields such as nuclear and radiation physics, geochemistry, health physics, and astrophysics. Gamma spectrometers are categorized into two main groups: inorganic scintillation detectors and semiconductor detectors. Semiconductor detectors such as germanium detectors have better energy resolution (a few tenths of a percent) than inorganic scintillation detectors (5–10% for sodium iodide). However, except for applications that require high-energy resolution, inorganic scintillation detectors are generally preferred because semiconductor detectors have a high price and low detection efficiency. The thallium-doped sodium iodide [NaI(Tl)] scintillation detector is still a common choice for gamma spectrometry because its advantages are a high light yield, high density, reasonable cost, and availability in large sizes [1]. The NaI(Tl) scintillation detector is generally composed of a NaI(Tl) scintillator, a photomultiplier tube (PMT), and a data acquisition system.

A silicon photomultiplier (SiPM), which is also called a solid-state photomultiplier or a multipixel photon counter, is a novel semiconductor photo-sensor [2,3]. A single SiPM is an array of several thousand microcells connected to one output. Each microcell operates digitally and individually as a single Geiger-mode avalanche photodiode. When a photon is absorbed in the Geiger-mode avalanche photodiode, the generated photoelectron causes a massive avalanche and makes a constant output pulse, regardless of the number of incident photons. The generated current pulses from all microcells are summed at the output node so that the amplitude of the output signal from a single SiPM is proportional to the number of reacting microcells and absorbed photons [2,4–6]. A main feature of the SiPM is the high gain at the level of 10^6 (comparable to vacuum PMTs), which has allowed the SiPM to become an alternative to PMTs. Silicon photomultipliers have several merits over PMTs such as a lower bias voltage, compact size, insensitivity to magnetic fields, and cheap production cost. Silicon photomultipliers have been applied in various fields [3,7–9].

In this study, an array of SiPMs instead of the existing PMT was used to develop a gamma spectrometer. In other studies that replaced a PMT with a SiPM [9,10], a small scintillator (<1 cm) was used to match the size of the SiPM. By using a small scintillator that was directly coupled to the SiPM, the light collection efficiency was maximized so that the gamma spectrometer could have a good energy resolution of approximately 8% at 662 keV. However, this small detector volume significantly decreased the detection efficiency for gamma rays. In this study, a commercial NaI(Tl) 2′ × 2′ scintillator was used to maintain the advantages of high detection efficiency and low production cost. A light guide was instead used for the transport and collection of the generated photons from the large scintillator to the SiPMs without loss. This approach can make a gamma spectrometer smaller, cheaper, and easier to use without reducing the detection efficiency, and it is more suitable to general use in which energy resolution is not critical.

2. Theoretical prediction

A gamma spectrometer can be divided into two main parts: a radiation sensor and a data acquisition system. This study focused on the former, which comprises a scintillator, a photodetector, and a preamplifier.

Fig. 1 shows the comparison of the proposed SiPM-based gamma spectrometer and the general gamma spectrometer. A cylindrical NaI(Tl) 2′ × 2′ scintillator (2R2) is applied in both designs. An array of SiPMs is much smaller than a PMT; therefore, there is a need for an additional component for a connection without the loss of photons. A light guide is used for this purpose. One side of the light guide has the same area as the NaI(Tl) scintillator; the other side is a little smaller than the array of SiPMs. Except for these connections, the remaining surface of the light guide is coated with reflective materials [e.g., titanium oxide (TiO_2) or polytetrafluoroethylene (PTFE)].

The most important properties of a gamma spectrometer are its detection efficiency and energy resolution [1]. These properties are related to the components of the gamma spectrometer and vary by the system.

The detection efficiency for gamma rays is defined as the probability that a gamma ray emitted from a source will interact with the detector. It is classified as either “absolute detection efficiency” or “intrinsic detection efficiency.” The intrinsic detection efficiency is generally used and is dependent on the volume, shape, and density of a detector. Much research has already been performed regarding the NaI(Tl) scintillator. The detection efficiency of the NaI(Tl) scintillator can be found in Fig. 2 [11]. With a crystal of ½′ or $^3/_8$′ thickness (which is usually the case with SiPMs), the detection efficiency is only 30% at a gamma ray energy of 500 keV. By contrast, the detection efficiency of a crystal of 2′ thickness is nearly 80%, which is more than double the efficiency of the former sizes.

The energy resolution is the ability to discriminate between different energy peaks in the measured energy spectra. The energy resolution of a radiation detector is generally represented using the full width at half maximum (FWHM) of a photo-peak.

The gamma spectrometer is composed of several components, and each component can be a source of fluctuation. If all components are symmetric and independent, the total fluctuation can be predicted statistically [1]. The FWHM of the total system resolution ($FWHM_{Total}$) is the quadrature sum of

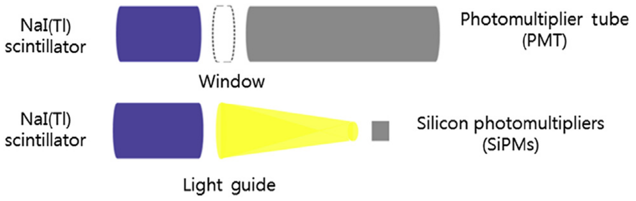

Fig. 1 – Schematic comparison of the general gamma spectrometer (based on the vacuum photomultiplier tube), and the proposed gamma spectrometer using a light guide and silicon photomultipliers. NaI(Tl), thallium-doped sodium iodide.

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