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) $2' \times 2'$ 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) $2' \times 2'$ 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 $1/4$ 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
the FWHM values for each individual source of fluctuation. In the proposed system, the FWHM_{Total} can be approximated as follows:

\[
\text{FWHM}_{\text{Total}}^2 = \text{FWHM}_{\text{St}}^2 + \text{FWHM}_{\text{Col}}^2 + \text{FWHM}_{\text{Det}}^2 + \text{FWHM}_{\text{Elec}}^2
\]

(1)

in which FWHM_{St} is the FWHM from the statistical limit of radiation detection, FWHM_{Col} is the FWHM due to variation in light collection, FWHM_{Det} is the FWHM of the photodetector output, and FWHM_{Elec} is the FWHM due to electronic noise contribution. With a PMT or a SiPM of high gain property, the contribution of electronic noise is usually negligible. The statistical contribution is the most considerable in gamma spectrometry, and variations in the light collection can also have a considerable effect. Considering the energy resolution of recent SiPMs, which reach the level of PMTs, only the first and the second fluctuation sources are expected to have significant effects on the energy resolution in the proposed system.

The introduction of a light guide affects the number of generated photoelectrons in a photodetector and variation in light collection. The attenuation of photons in the light guide and the reflection at the surfaces reduce the number of photons that reach the photodetector. This loss of photons degrades the energy resolution of a gamma spectrometer because the energy resolution from the statistical characteristics of radiation detection is proportional to the number of received photons (as shown by Equation (2)) [1].

\[
R_{\text{statistical}} = \frac{\text{FWHM}_{\text{St}}}{H_0} = \frac{2.35K\sqrt{N}}{\sqrt{N}} = 2.35
\]

(2)

in which \(H_0\) is the average pulse amplitude, \(K\) is the proportional constant, and \(N\) is the number of detected photons.

In contrast to the statistical contribution, the light guide can have a positive effect on the variation in light collection. The light collection efficiency varies, depending on the generation point of photons in a scintillator. The introduction of a light guide can reduce this variation.

The two aforementioned effects of the introduction of a light guide are complementary; however, the total energy resolution is expected to be degraded because the statistical contribution to the energy resolution predominates over the other potential sources. In the proposed gamma spectrometer, an effective design of the light guide is required to reduce degradation of the energy resolution.

3. Fabrication of the light guide and measurement

3.1. Fabrication of the light guide

Based on a previous discussion, different types of the light guides were fabricated for the gamma spectrometer. Fig. 3 shows fabricated light guides and Table 1 presents their

![Fig. 2 – Intrinsic detection efficiency of NaI(Tl), based on size [11]. NaI, sodium iodide; NaI(Tl), thallium-doped sodium iodide.](image)

![Fig. 3 – The fabricated light guides.](image)
specifications. The light guides were fabricated using polymethyl methacrylate (PMMA) because of its low attenuation coefficient and a high refractive index. Two different lengths were chosen to verify the effect of length. To connect to a cylindrical commercial scintillator, the light guide was formed in the shape of a truncated cone. An optical Teflon sheet and white TiO₂ paint were chosen for the reflective coatings because of their high reflectivity [12,13].

3.2. Systems of the gamma spectrometer

Test systems for the gamma spectrometer were set up with the fabricated light guides. As Fig. 4 shows, three different systems of the gamma spectrometer were tested for analysis. The first system (i.e., the reference system) was a general system based on a PMT. It was set up as the reference system for comparison with the other systems. The second system used a PMT-like the reference system, but the light guide connected the scintillator to the PMT. The excess area resulting from the mismatch between the light guide and the PMT was taped with PTFE to prevent interference from outside light. Because all systems were equivalent, except the light guide, the effect from only the light guide could be analyzed by comparing the reference system and the second system. The third system included both the light guide and SiPMs. This system was the proposed gamma spectrometer system.

A 2’ × 2’ NaI(Tl) scintillator from Saint-Gobain crystal (Saint-Gobain Ceramics and Plastics, Inc., Hiram, OH, USA) was used as the scintillator. An optical grease (BC-630 silicone optical grease; Saint-Gobain Ceramics and Plastics, Inc.) was used for optical coupling between the components. It has a refractive index similar to that of the light guide and a high transmission characteristic. A PMT (Model 9255B; ET Enterprises, Uxbridge, United Kingdom) and a 4 × 4 array of SiPMs from SensL (Cork, Ireland) were used as the photodetectors. To sum all signals from each channel of the SiPM, a summing circuit followed the array of the SiPMs. This circuit was developed for signal processing of the dosimetry application at Korea Advanced Institute of Science and Technology (KAIST; Daejeon, South Korea) [14]. All components used in the test systems are summarized in Table 2.

3.3. Measurement results

All measurements were performed by the aforementioned gamma spectrometers under the same conditions. The bias voltage of the PMT was 900 V, which showed the best energy resolution. The distance between the gamma ray sources and the scintillator was 5 cm. Sodium-22 (22Na), cesium-137 (137Cs), and cobalt-60 (60Co) were the gamma ray sources. All systems were calibrated with a 22Na gamma source.

Table 3 shows a summary of the estimated energy resolution in the reference gamma spectrometer system. The energy resolution values at all energy peaks were similar with those reported in other studies. The best was 5.62% at 1274.5 keV and the worst was 8.37% at 511 keV.

![Fig. 4 – The three gamma spectrometers systems. NaI(Tl), thallium-doped sodium iodide; PMT, photomultiplier tube; SiPM, silicon photomultiplier.](image-url)
Measurements by the second system showed the effect of the fabricated light guides on energy resolution. Fig. 5 shows the degradation of the energy resolution with the light guides, compared to the results of the reference system. The energy resolution was degraded in the range of 4–8%. The PTFE-coated light guides showed the least degradation, and the 60-mm long bare light guide showed the worst degradation. With the bare light guides, degradation was worse in the long light guide. However, with the Teflon-coated light guides, degradation was virtually constant, regardless of the length.

The third system was also tested, and included the light guides and the array of SiPMs. The bias voltage for the SiPMs was given as 30.5 V (which was 3 V above the breakdown voltage), and the sources and distance were the same as in the previous measurements. All systems were calibrated using the peaks of $^{22}\text{Na}$ and $^{137}\text{Cs}$. The estimated energy resolution values versus the corresponding peak energy are indicated in Fig. 6. For reference, the measurement results from a 1-cm$^3$ cubic thallium-doped cesium iodide [CsI(Tl)] crystal is also marked.

Silicon photomultipliers directly coupled to a standard cubic CsI(Tl) scintillator showed results that were similar to other reported results [9,10]. The best energy resolution of 8.6% was achieved at 662 keV. This finding was no better than other results using similar systems. This finding indicated that the setup used in the energy resolution measurement was not optimized and the result could be improved through further work such as the thermal stabilization of the SiPMs.

The degradation of the energy resolution was worse for the third system than for the second system. Fig. 7 shows the degradation of energy resolution with the SiPMs and light guides, compared to the results of the reference system. Except for the 17-mm PTFE-coated light guide (Fig. 8), the energy resolution of the systems was insufficient for discriminating between the 1173 keV and 1332 keV peaks of $^{60}\text{Co}$.

In the proposed gamma spectrometer, the reduced number of collected photons was unfavorable for distinguishing low energy gamma rays from noise because the dark count noises from the SiPMs were combined as signal pulses. However, the low energy peak of $^{57}\text{Co}$ (122 keV) was distinguishable from the 17-mm PTFE-coated light guide (Fig. 9). Fig. 10 shows the measured energy spectrum of $^{137}\text{Cs}$. The observed high counts at approximately 250 keV were back-scattered photons from the aluminum darkbox in which the measurement was performed.

In Fig. 10, the peak to Compton ratio for $^{137}\text{Cs}$ is 0.47. Compared to another study which used a small scintillator [9], this low Compton ratio was an advantage of using a large scintillator.

The difference as the bias voltage of the SiPMs changed is shown in Figs. 8 and 9. When the bias voltage of the SiPMs increased, the energy resolution improved over the whole

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>511</th>
<th>661.6</th>
<th>1173.2</th>
<th>1274.5</th>
<th>1332.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy resolution (%)</td>
<td>8.37</td>
<td>7.31</td>
<td>7.26</td>
<td>5.62</td>
<td>6.56</td>
</tr>
</tbody>
</table>

Table 3 – The energy resolution of the reference system.

Fig. 6 – The estimated percent energy resolution versus the peak energy. CsI, cesium iodide; NaI, sodium iodide; PTFE, polytetrafluoroethylene; SiPM, silicon photomultiplier.
range. This is largely because of an increase in the photon detection efficiency (PDE) of the SiPMs. However, in the low energy region of approximately 122 keV, the energy resolution was degraded because of the increase in the dark count rate (DCR) of the SiPMs. For this reason, the bias voltage should be optimized, depending on the target energy range.

4. Discussion with simulation

To analyze the measurement results in detail, additional measurements and light collection simulations were performed.

4.1. Measurement of the effects of the light guide on the energy resolution

The main reason for the degradation of energy resolution was apparently because of the loss of photons during light
collection. A comparison of pulse heights (i.e., the center channel of a photopeak) between the reference system and the second system is shown in Fig. 11. In spite of having the same source (i.e., $^{137}$Cs), the height of measured pulses in the second system was only 20–30% of the height measured in the reference system. Because the measured height is proportional to the number of measured photons, this reduced height indicates that 70–80% of photons were lost in the light guide. Because of the relationship between the number of measured photons and the statistical contribution (Equation (2)), this loss of photons causes significant degradation of energy resolution.

In addition to the decreased number of photons, a reduction of variance in the light collection occurred. Table 4 shows the comparison of the measurement results in which the center channel of a photopeak has a similar number. All measurements were performed with the same PMT and common gain. Because the gain of all systems was the same, these similar channel numbers suggest that the pulse height, number of incident photons, and statistical contribution to the resolution were similar. However, the second system showed better energy resolution in the Table 4. This may reflect the effect of the light guides on the variation of light collection efficiency. As previously mentioned, the light guide makes light collection efficiency more uniform, and this factor can have a positive effect on the energy resolution. This tendency was stronger with a longer light guide.

### 4.2. The process and parameters of light collection simulation

Light collection simulation was performed for the analysis of the measurement results. The collection of light generated from a scintillator in a detector was simulated using the DETECT 97 code (A. Levin, E. Hoskinson, and C. Moison, University of Michigan, USA), which is a simulation code based on the Monte Carlo method. Fig. 12 shows the process flow of the DETECT simulation. Input geometry and the materials for the simulation were applied identically with the scintillator, the PMT, and the array of SiPMs used in the previous measurement. In addition to the fabricated light guides, the surfaces of the light guide, except for both connection sides, were assumed to be polished or coated with reflective material. The length of the light guide varied from 0 mm to 80 mm. Optical parameters of the NaI(Tl) and PMMA were based on those reported in previous studies [15–17]. The optical characteristics of the PTFE coating were also applied to the simulation [12,13].

In the simulation, three different compositions were described, as shown in Fig. 13. A current spectrometer, which was based on the PMT, was the reference (Fig. 13A). In addition to a commercial scintillator, a short window of 5 mm length was assumed between the scintillator and the PMT. Also simulated were a system with a bare light guide (Fig. 13B) and a system with a reflector-coated light guide (Fig. 13C). Because of the symmetric structure, the positions of photon generation in the scintillator were defined at 16 points over the longitudinal section of the scintillator. The locations of the generated points represent equally divided volumes of the scintillator. At each point, photon generation was repeated 3000 times with isotropic directions. The number of collected photons at the detector surface was recorded. The random seed number was changed 500 times to increase the accuracy.

![Fig. 12](image1.png)  
**Fig. 12** – A diagram of the DETECT simulation process.

![Fig. 13](image2.png)  
**Fig. 13** – A schematic of the geometry of the simulation. (A) The PMT-based current gamma spectrometer. (B) The SiPM-based gamma spectrometer with a bare light guide. (C) The SiPM-based gamma spectrometer with a reflector-coated light guide. PMT, photomultiplier tube; SiPM, silicon photomultiplier.
of the simulation. Therefore, a total of 1.5 million repetitions of the simulation were performed at each generation point. In the second system (Fig. 13B) and the third system (Fig. 13C), the complete simulation was repeated as the length of the light guide changed.

4.3. Results of the light collection simulation

The light collection efficiency in each system (based on length), was calculated using the number of collected photons. The light collection efficiency was compensated, based on the volume ratio at each radius. The variation of light collection efficiency, based on the generation point, was also calculated. The simulation errors at each point ranged 0.5–0.9%. In the reference system (Fig. 13A), the light collection efficiency was 46.63% with a window of 5 mm length, which is common in commercial scintillators. This value was a little higher than values reported in other studies of light collection simulation; however, it was still acceptable.

Fig. 14 shows the light collection efficiency and its variation in the spectrometers, including the spectrometers with the light guides. The lines with the error bars indicate the changes in the collection efficiency, and the lines with symbols indicate the standard deviations in the collection efficiency by the light generation points in the scintillator.

In the system with the bare light guide, the light collection efficiency and its variation decreased with increasing length. These decreases were more rapid than exponential absorption in the PMMA. This finding may be because of the escape of photons from the bare surfaces. The coated light guide showed a different tendency from the bare light guide. The lines of light collection efficiency and its variation had maximum values between the 5-mm and 20-mm lengths. The average light collection efficiency in the 17-mm and 60-mm PTFE light guide were only 30% and 20%, respectively, of the average light collection efficiency in the 17-mm and 60-mm light guides. The light collection efficiency in the short light guides was high and had a positive effect on the statistical resolution. However, the variation in the light collection efficiency was also high, and this had a negative effect on the resolution. By contrast, in the long light guides, light collection efficiency and its variation were low, and these factors had a negative and a positive effect, respectively, on the resolution. These tendencies are in agreement with the previous measurement results. For these reasons, further study for optimization of the light guide is required.

4.4. Conclusion

In this study, a gamma spectrometer was developed using an array of SiPMs instead of a PMT. In contrast to other studies that used a small scintillator directly coupled to the SiPM, a NaI(Tl) 2' × 2' scintillator was used in this study to maintain high detection efficiency. To avoid the loss of generated photons, a light guide was used for the transport and collection of generated photons from the large scintillator to the SiPMs.

Test light guides were fabricated with PMMA and reflective materials. The gamma spectrometer systems, which included the light guides, were set up. Through a series of measurements, the characteristics of the light guides and the proposed gamma spectrometer were evaluated. Simulation of 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. In the measurement and simulation, the fabricated light guides had complementary effects on the energy resolution. As the length of the light guides increased, the number of collected photons decreased, and had a negative effect because of the statistical characteristic. By contrast, the variations of the collection efficiency reduced when the length increased, and it had a positive effect on energy resolution.

The final system, which included the SiPMs and the light guide, achieved 14.1% FWHM energy resolution at 662 keV, even though it maintained a detection efficiency that was as high as that in general gamma spectrometers. This energy resolution was sufficient to distinguish between the two energy peaks of 60Co, and distinguish the 122 keV peak of 57Co from noise. The energy resolution of this gamma spectrometer can be improved through optimization of parameters that include the bias voltage of SiPMs, the length of the light guide, and the reflective coating of the light guide. This gamma spectrometer can be useful when high detection efficiency is preferred over energy resolution.

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