International Journal of Engineering & Technology, 7 (4.39) (2018) 78-81

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Indirect Photon-Counting Detector with a GAGG Scintillator for Low-Energy Photon Detection

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Abstract

Background/Objectives: The aim of this study was to explore the properties of indirect detection using a scintillator and silicon photomultiplier, as scintillators are highly sensitive for breast cancer detection.
Methods/Statistical analysis: Silicon photomultipliers (SiPM) and Cerium-doped $Gd_3Al_2Ga_3O_{12}$ (GAGG) scintillator crystals were used to fabricate a scintillation detector, and its characteristic of spectroscopy were compared to the results of LYSO and CsI using γ-ray spectroscopic measurement. The resulting energy resolutions of each scintillation detector, comprising a single crystal scintillator (volume size: 3×3×2 mm^3) and a SiPM (active area: 3×3 mm^2) for a γ-ray source, such as ^{241}Am, were measured and compared.
Findings: The ^{137}Cs source yields an energy resolution of 5.23 and 20.31% at 661 keV for the GAGG and LYSO scintillators, respectively. Alternatively, because the CsI scintillator did not yield a distinct energy peak, an energy resolution was not measured. The ^{241}Am source yields an energy resolution of 28.88 and 36.12% at 59.5 keV for the GAGG and LYSO scintillators, respectively. Measured energy peaks of the ^{241}Am source were 62.7 and 64.6 keV for GAGG and LYSO scintillators, respectively. The energy peak of the ^{241}Am source for CsI was not measured because the CsI scintillator did not yield a distinct energy peak of ^{137}Cs source for calibration.
Improvements/Applications: The GAGG scintillator could improve the energy resolution of low-energy source than LYSO and CsI scintillators.

Keywords: *GAGG, SiPM, Indirect photon-counting, low-energy detection, Gamma source.*

1. Introduction

The measurement of low-energy photon using arrays of silicon photomultipliers (SiPM) has received interest in academic field and industrial field [1]. Recently, the use of SiPM has been a significant increase in plenty of applications with steady design optimization and operational parameters by a number of vendors. SiPM sensors was equipped with a compact, high sensitive, fast light detection system that provides a cost effective substitute for conventional photon detection platform. Moreover, SiPM is sensors with high gain at a low operating voltage and has an inherent insensitive to magnetic fields. Thus, a significant research effort has been investigated for SiPM sensors in a variety of medical imaging modalities [2].

Energy-resolving, photon-counting detectors with energy decomposition abilities, such as a semiconductor, have been designed for X-ray imaging system in medicine [3]. A semiconductor material yields energy resolutions that are superior to those achievable with scintillators. However, their physical rigidity and detection efficiency are very low, and the semiconductor material requires expensive maintenance in comparison with that of scintillator [4]. Alternatively, CsI and LYSO are the most commonly employed scintillator crystals for indirect photon detection. Although, these materials have low energy resolutions in comparison to semiconductors, they are more sensitive to radiation. Therefore, evolution of detectors in combinations with scintillators and semiconductors is essential due to the properties and shortcoming of each of these materials. Thus, scintillation detectors continued as promising materials for use in medical X-ray or γ-ray imaging. Cerium-doped $Gd_3Al_2Ga_3O_{12}$ (GAGG) is a relatively current crystal scintillator with various properties that make it favorable for gamma spectral measurement applications and in fields such as nuclear medicine [5]. GAGG is a currently developed mixed scintillator with high stopping power due to fast response, high density, and high photon yield. Among the many scintillators, GAGG is non-hygroscopic and does not have natural radioactivity. Several studies focusing on timing and energy resolution of GAGG crystal readout have indicated that the crystal is favourablefor medical imaging applications. Furthermore, the improvement of a sub-millimeter GAGG crystal piece was investigated for SPECT and PET [6]. More recently, an estimation of the GAGG crystal with regard to low-energy radioisotopes was published [7]. Also, the X-ray luminescence efficiency subject to X-ray excitation was measured with respect to tube voltages in the range between 50 and 130 kVp [8]. In these results, the X-ray luminescence efficiency and the detector efficiency of the GAGG were evaluated with respect to tube voltage. However, there are some questions about the energy resolution of GAGG for low-energy detection with photon-counting mode.

Therefore, the aim of this work was to examine the energy resolution of a GAGG crystal coupled with a silicon photomultiplier (SiPM) for low-energy photon detection; its properties such as energy resolution were then compared to LYSO and CsI crystals.

2. Materials and Methods

2.1. Properties of Scintillators

The scintillation properties of GAGG, LYSO, and CsI used in this experiment are presented in Table 1. LYSO and CsI are the most frequently used scintillator types in PET and X-ray systems. GAGG material that exceeds the performance of LYSO and CsI in terms of intrinsic energy resolution, timing resolution, and light yield are developed. Growth of GAGG process crystal by the Czochralski and their characteristics were investigated [9]. The GAGG scintillator has 520 nm emission peak, which is corresponded with the photon sensitivity peak of SiPM sensor. The GAGG crystal is known as the light yield of 55,000 photons/MeV [10]. The GAGG crystal has a decay time approximately of 90 ns and a density of 6.63 g/cm^3. In this study, GAGG, LYSO, and CsI scintillators have a volume of 3×3×2 mm^3 and were produced by EPIC-Crystal Co., Ltd., China.

Table 1: Information of GAGG, LYSO, and CsI scintillator materials.

Scintillator	GAGG	LYSO	CsI
Density (g/cm^3)	6.63	7.4	4.51
Peak emission (nm)	520	420	550
Decay time (ns)	90	40	1,000
Light yield (photons/MeV)	55,000	32,000	52,000
Hygroscopic	No	No	Slightly
Natural activity	No	Yes	No

2.2. Detector Configuration and Radiation Source

The SiPM sensor with active area 3×3 mm^2 (ASD-NUV3S-P, AdvanSiD, Italy) was used to detect red, green, and blue lights. GAGG, LYSO, and CsI scintillators coupled to the active area of the SiPM were connected to the evaluation board, which included a preamplifier, as shown in Fig. 1.

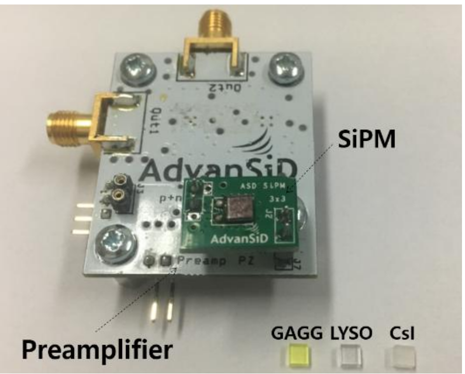

Figure 1: GAGG, LYSO, and CsI scintillators with a 3×3 mm^{2}SiPM and preamplifier.

A self-produced shaping amplifier (ARALE Lab, South Korea) was used to shape the output pulse and perform noise filtering. The shaping amplifier was simultaneously connected to the preamplifier and multi-channel analyzer (MCA) (MCA-K102, Kromek, UK), and the preamplifier voltage was varied between +5 and -5 V; the breakdown voltage was 28 V for ASD-NUV3S-P. The scintillator, SiPM, and preamplifier were housed to avoid light, as depicted in Fig. 2 (A), which shows the structure of the detector system used to perform spectroscopy. Experimental spectroscopy system consists of Scintillator, preamplifier, MCA, shaping amplifier, and power supply is illustrated in Fig. 2 (B). In the results of this experimental study, a standard radioactive source such as ^{137}Cs was used to calibrate the channel. After calibration, the gamma source ^{241}Am 59.5 keV (Spectrum Techniques, Oak Ridge, TN) was used. Additionally, a source activity was 80 µCi and was placed 50 mm away from the top of the crystal.

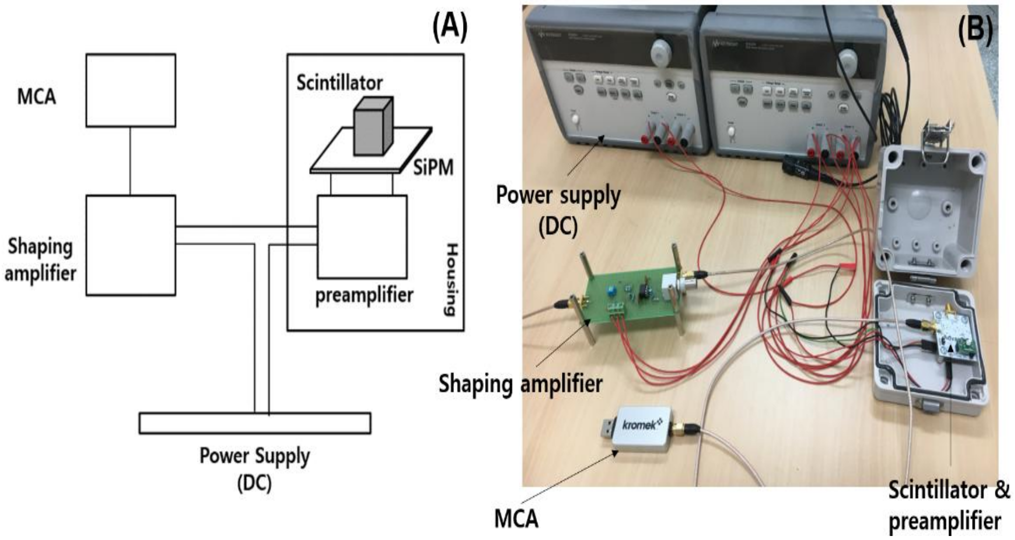

Figure 2: (A) Schematic of the spectroscopy system, comprised of a detector, shaping amplifier, and MCA. (B) is the spectroscopy system.

3. Results and Discussion

The pulse shapes were measured from the GAGG, LYSO, and CsI scintillators. Some scintillators such as GAGG [11] and CsI [12] were observed more than one decay. Relaxation of the light emitted from scintillators by incident photons is identified by a decay time parameter. Generally, the decay time of the scintillator is from nanoseconds (ns) to microseconds (μs). The pulse shapes of the driver circuit obtained from GAGG, LYSO, and CsI are shown in Figure 3. Each scintillator was irradiated with the same ^{137}Cs source. The output signal results show a 1.00 V pulse amplitude with a 2.50 μs pulse width. The fastest response was observed in the LYSO scintillator. According to the pulse height measurement results, the properties of scintillators showed that the response of the GAGG scintillator is slower than that of LYSO, but the decay time was not excessively long. This indicates that LYSO is a good candidate in applications for which high fluxed X-rays are expected. CsI scintillator-based detectors are less effective for high count rate assessments because the associated decay time is very slow.

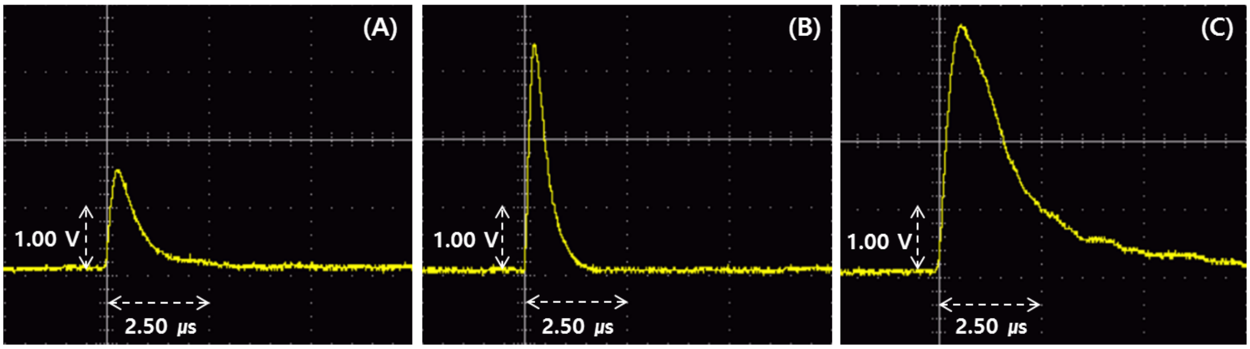

Figure 3: Output signal of driver circuit measured with (A) GAGG, (B) LYSO, and (C) CsI crystals.

The pulse height spectra of GAGG, LYSO, and CsI under a ^{137}Cs source were obtained via the detector system and are illustrated in Figure 4. The energy resolution of the peak is calculated, and its equation is the full width at half maximum (FWHM) of a given energy peak vs. the peak height as follows:

$$R_E = \frac{FWHM}{Ch} \times 100 \qquad (1)$$

where R_E is the energy resolution, and *Ch* is the channel number of the maximum peak energy. GAGG and LYSO showed a clear photo-absorption peak and Compton edge. The 662.0 keV peak of the ^{137}Cs source yields an energy resolution of 5.23 and 20.31% at 661 keV for the GAGG and LYSO scintillators, respectively. Alternatively, because the CsI scintillator did not yield a distinct energy peak, an energy resolution was not measured.

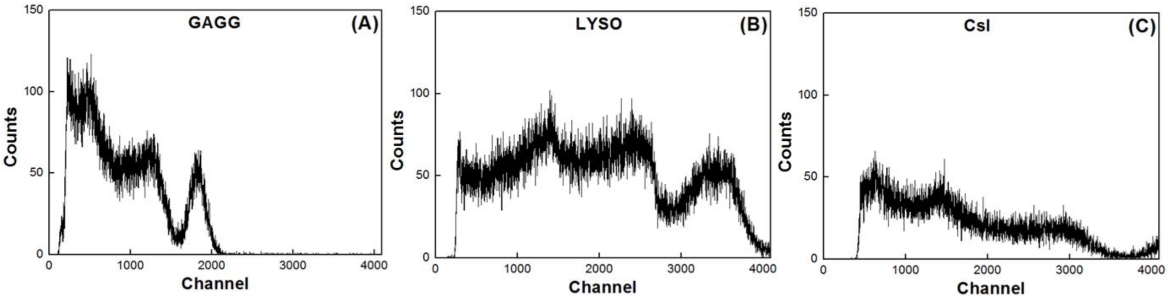

Figure 4: Energy spectrum measured using ^{137}Cs gamma source-based (A) GAGG, (B) LYSO, and (C) CsI scintillators.

The pulse height spectra of GAGG and LYSO under an ^{241}Am source were obtained via the detector system and are illustrated in Figure 5. GAGG and LYSO showed a clear photoabsorption peak. The 59.5 keV peak of the ^{241}Am source yields an energy resolution of 28.88 and 36.12% at 59.5 keV for the GAGG and LYSO scintillators, respectively. Measured energy peaks of the ^{241}Am source were 62.7 and 64.6 keV for GAGG and LYSO scintillators, respectively. The energy peak of the ^{241}Am source for CsI was not measured because the CsI scintillator did not yield a distinct energy peak of ^{137}Cs source for calibration.

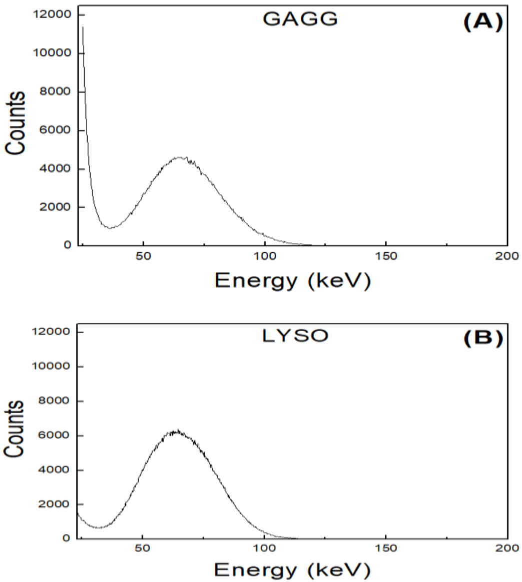

Figure 5: Energy spectra measured using ^{241}Am gamma source-based (A) GAGG and (B) LYSO scintillators.

The energy resolution of ^{241}Am and ^{137}Cs was measured with energies at 59.5 and 662 keV. In Figs. 4 and 5, the ^{137}Cs source yields energy resolutions of 5.23 and 20.31% at 661 keV for the GAGG and LYSO scintillators, and the energy resolutions are 28.88 and 36.12% at 59.5 keV with an ^{241}Am source, respectively. The GAGG scintillator presented good energy resolution compared to the results of the LYSO scintillator. The energy resolution was dependent on the *γ*-ray energy. The trend of increasing energy resolution when photon energy is decreased, as reported in previous work [13], is supported by these findings.A previous study reported that GAGG could be used in computed tomography applications under high flux X-ray exposure .

4. Conclusion

The energy resolved photon-counting method was achieved using the direct detection method with semiconductor materials for diagnostic imaging. New material, such as GAGG crystal, has been developed to detect photons because of its unique merits. Various scintillators were individually implemented for fabrication of energy-resolving detectors using an indirect method. Therefore, we tested the pulse shape and energy resolution of GAGG, LYSO, and CsI scintillators coupled with a SiPM under ^{137}Cs and ^{241}Am exposures and demonstrated the possibility for indirect energy resolved photon-counting. The detectors were also evaluated to assess their applicability in radiation detection. Although the GAGG scintillator yielded a slower response than the LYSO scintillator, the peak energy was well matched to the known peak energy from the GAGG crystal. Further work is needed to investigate noise reduction for low-energy detection by developing a shaping amplifier for energy-resolving imaging.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Ministry of Science and ICT (Grant No. NRF-2017R1C1B5017626).

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