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Technical Note

Development of low-cost, compact, real-time, and wireless radiation monitoring system in underwater environment

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ABSTRACT

In this study, an underwater radiation detector was built using a GAGG(Ce) scintillator and silicon photomultiplier to establish an underwater radiation exposure monitoring system. The GAGG(Ce) scintillator is suitable for small radiation detectors as it strongly absorbs gamma rays and has a high light emission rate with no deliquescent properties. Additionally, the silicon photomultiplier is a light sensor with characteristics such as small size and low applied voltage. Further, a program and mobile app were developed to monitor the radiation coefficient values generated from the detector. According to the results of the evaluation of the characteristics of the underwater radiation monitoring system, when tested for its responsiveness to radiation intensity and reactivity, the system exhibited a coefficient of determination of at least 0.99 with respect to the radiation source distance. Additionally, when tested for its underwater environmental temperature dependence, the monitoring system exhibited an increase in the count rate up to a certain temperature because of the increasing dark current and a decrease in the count rate because of decreasing overvoltage. Extended studies based on the results of this study are expected to greatly contribute to immediate and continuing evaluation of the degree of radioactive contamination in underwater environments.

1. Introduction

Since the Fukushima nuclear disaster, substantial radioactive substances have leaked into the ocean. From this incident, there has been an increasing amount of interest in the international community regarding the contamination of oceanic environments with radioactive species. Thus, various equipment that can measure the contamination levels of radioactive species in an oceanic environment has been developed. Although sampling analysis, a method used to measure the level of radioactive contaminants, can provide quantitative and qualitative results, it requires a long period of time to collect and pretreat the samples and analyze the radioactive species in the samples. Sampling analysis also lacks the capability of immediate monitoring. Another measurement method, *in situ* analysis, which measures the contaminant levels on-site with a measuring tool, is capable of immediate monitoring and analysis. However, *in situ* analysis has disadvantages such as increasing uncertainty with respect to the measurement distance, poor spatial accessibility due to its large size, and high costs. Therefore, the development of new measuring equipment to establish an immediate and persistent radiation inspection system for potential radioactive contamination in the oceanic environment has been in high demand [1].

Thus, in the present study, an underwater radiation monitoring system is established using a silicon photomultiplier (SiPM) and Ce-doped GAGG($Gd_3Al_2Ga_3O_{12}$) scintillator to research the establishment of a monitoring system for real-time underwater radiation contamination. Moreover, the applicability of the established monitoring system is evaluated.

2. Materials and methods

The photomultiplier tube (PMT) is extremely sensitive to the ultraviolet, visible, and near-infrared wavelength ranges and has been very frequently used as a light sensor for radiation detectors for more than 70 years. However, the PMT is based on vacuum tube technology and is thus very large in volume. In addition, PMTs have disadvantages of low quantum efficiency (25%), high cost, and high magnetic field sensitivity [2]. In the present study, a radiation detector is manufactured using as a light sensor, an SiPM, which has characteristics of small volume, high quantum efficiency, and

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relatively low cost. The characteristics of the SiPM used in the present study are listed in Table 1 [2,3].

NaI(TI) is commonly used as a scintillating substance. However, NaI(TI) is a deliquescent substance and not suitable for application in an underwater radiation detector. In the present study, a Ce:GAGG inorganic scintillating substance was used; it does not possess deliquescent properties and is thus suitable for underwater radiation detectors. It exhibits an efficient stopping power because of its maximum emission wavelength of 520 nm, short decay time of 87 ns, and high density of 6.63 g cm^{-3}. Thus, it exhibits a high reactivity with respect to the secondary electrons generated by gamma rays and a high probability of emitting approximately 50,000 photons with respect to gamma rays, with an energy of 1 MeV [4,5]. The size of the Ce:GAGG scintillator was $6 \times 6 \times 30$ mm^3. To maximize the light output from the Ce:GAGG and match it to the photosensitive area of the SiPM, the crystal geometry was optimized at an energy of 0.662 MeV using the Monte Carlo n-particle extended code.

Fig. 1 shows an image of the detector, manufactured using the SiPM and GAGG(Ce), for measuring underwater radioactive contaminants. Fig. 2 outlines the architecture of the underwater radiation monitoring system. To minimize light loss caused by attaching the SiPM and GAGG(Ce), BC-630 optical grease was used to attach the SiPM and GAGG(Ce). The BC-630 optical grease has a refractive index of $n = 1.465$ and light transmission rate of approximately 95% in a wavelength range of 280–700 nm. The reflection plane was formed using a Teflon reflector that has a maximum reflectivity of at least 90% at 520 nm, which is the emission wavelength of GAGG(Ce). In addition, light-blocking tape was used to house the detection sensor to minimize the noise generated by the external lights [6].

Previously, charge-sensitive preamplifiers that convert scintillation detector charge signals into voltage signals and shaping amplifiers that amplify and shape the converted voltage signals into Gaussian distributions simultaneously were designed for use in signal processing in the radiation detector. However, it was observed that the signal decreases because of the mismatched impedance during signal processing, and the signal-to-noise ratio decreases through the amplifying and forming process. In the case of the SiPM, when radiation enters, a pulse of at least 1 V is generated in the actuation circuit, which is different from conventional light sensors. Thus, radioactive rays can be accurately detected without the amplifying and forming process. Therefore, to reduce the noise in the signals in the present study, the signal processing part is comprised of a power supply circuit, actuation circuit, and analog-to-digital (A/D) conversion circuit for the SiPM [7,8].

Table 1
Specifications of the SiPM used in this study.

Parameter	Value
Photosensitive area	6×6 mm^2
Number of pixels	14,400
Spectral response range	270–900 nm
Peak PDE (at 450 nm)	40%
Bias voltage	Vbr + 3 V
Breakdown voltage	53 ± 5 V
Gain	1.7×10^6
Operating temperature	−20–40°C

PDE, photon detection efficiency; SiPM, silicon photomultiplier.

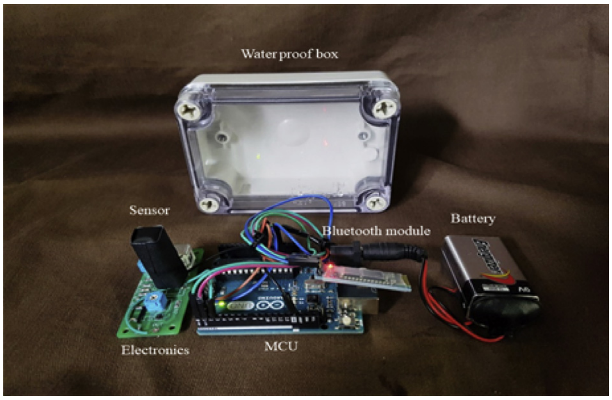


Fig. 1. Underwater radiation detector.
MCU, microcontroller unit.

An ultra high–voltage module, which can apply 0–100 V and is thus suitable for size minimization, was used to build a high-voltage bias supply circuit to supply power to the SiPM. The high-voltage bias supply was designed to apply 54.5 V to the SiPM when 5 V is applied by the microcontroller unit (MCU). A radiation sensor under the application of the power supply generates 1.2-V analog signals with pulse width of 20 µs. The A/D conversion circuit, which converts signals that are greater than or equal to a certain voltage into digital signals of 5 V, was designed to remove noise in the signals generated from the actuation circuit and deliver radiation signals only to the MCU. In designing the A/D conversion circuit, a MAX987, a comparator element, was used.

Fig. 3 shows the analog signals generated from the radiation detection sensor for Cs-137 and the digital signals generated by the A/D conversion circuit.

In order to count the digital signals, an Atemga 328 was used as the MCU module, an 8-bit microcontroller; a radiation count command and wireless data transmission command were coded in the Atemga 328 in this study. An HC-06 Bluetooth module was used as a wireless communication module and was a Class B module with a transmission power of 2.5 mW, transmission distance of about 30 m, and maximum communication speed of 115,200 bps (bits per second); device is thus suitable for underwater wireless communication. The measurement information delivered through the Bluetooth module is displayed through a mobile app or PC program. The manufactured detector is housed in a waterproof box with an IP67 waterproof rating, capable of water resistance up to a depth of 1 m.

Fig. 4 shows the mobile app and PC program used to display the count rate delivered from the underwater radiation detector. The mobile app comprises a radiation count function, camera function that shows the measurement environment, and address function that displays the measurement location information. The PC program comprises a radiation count function, alarm function that displays an alert when radiation is detected over a certain value, and graph function that displays the count rate with respect to time.

Fig. 5 shows the experimental setup for underwater radiation measurements, which were performed in a laboratory-scale water tank with water from the Paldang Dam [9] [10]. The developed radiation detector was placed 30 cm above the bottom of the water tank, and radiation sources were placed from 1 to 5 cm for each 1-cm mark. To test the temperature dependence of the detector, an underwater heater was used to change the water temperature from 25 to 40°C. The radiation sources used in the experiment were Cs-137(0.662 MeV), with a half-life of 30.17 yr, and Co-60(1.173 and 1.332 MeV), with a half-life of 5.27 yr.

3. Results and discussion

Fig. 6 presents a graph plotting the responsiveness of the underwater radiation detector with respect to the different intensities

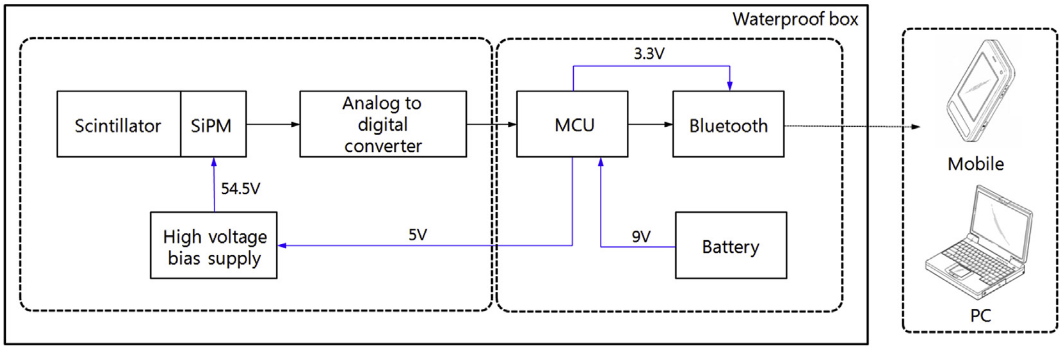


Fig. 2. Underwater radiation monitoring system architecture.
MCU, microcontroller unit; SiPM, silicon photomultiplier.

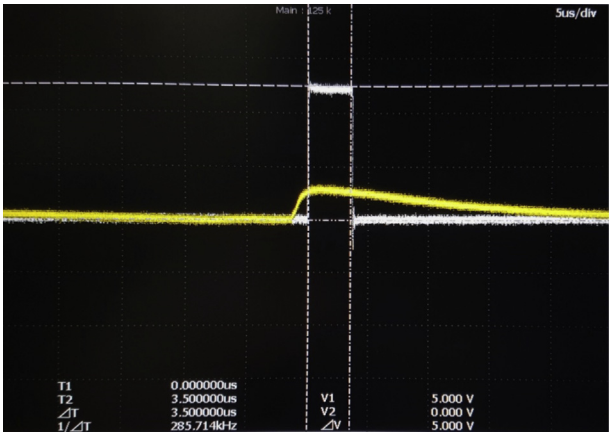


Fig. 3. Output for actuation circuit and A/D conversion circuit.

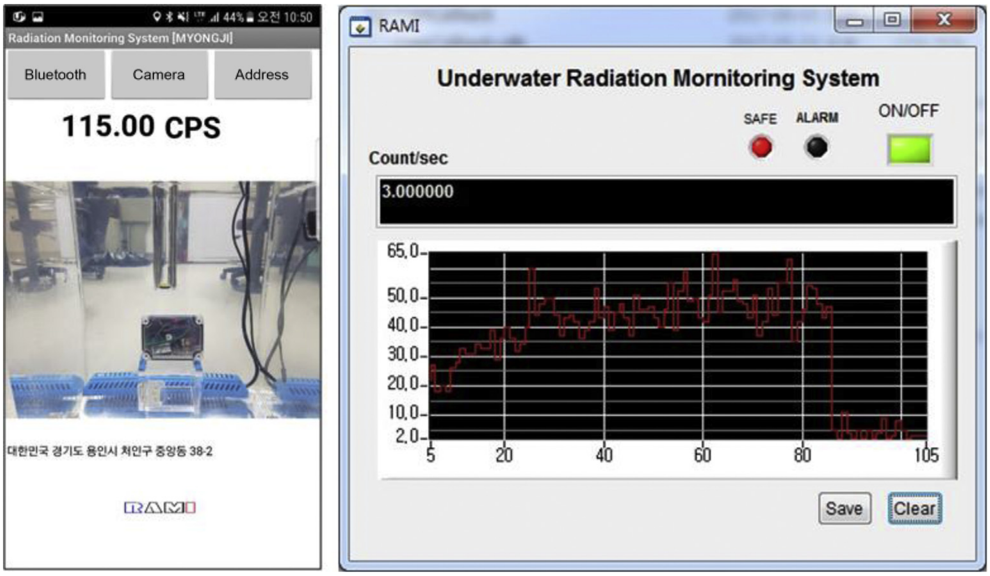
of Cs-137 (3.70 × 10^4, 1.85 × 10^5, 3.70 × 10^5 Bq). As the intensity of the radiation source increases, the radiation flux increases, resulting in a linear increase in the radiation exposure. As shown in Fig. 6, the responsiveness doubles when the 3.70 × 10^5 Bq radiation source is used, compared to the case of using the 1.85 × 10^5 Bq source. The results indicate a linear trend with an R-squared value of 0.9960.

In the collapse of an atomic nucleus, radiation is emitted isotropically. The density of the radiation passing through a unit area decreases with the distance to the center of the radiation source, as shown in Eq. (1).

$$R = \frac{n}{4\pi d^2} \tag{1}$$

Here, n is the amount of radiation emitted from the radiation source per unit time and d is the diameter (cm) of a sphere with the radiation source as the center. According to the inverse square law of distance, the further the detector is from the radiation source, the smaller the amount of radiation detected. Fig. 7 presents a graph plotting the responsiveness of the detector as a function of the distance to the radiation source. The manufactured detector is confirmed to exhibit a decrease in the count rate according to the inverse square law of distance, with respect to the Cs-137(3.70 × 10^4 Bq) and Co-60(3.70 × 10^4 Bq) radiation sources. Further, the detector is confirmed to have an R-squared value of 0.99453 for Cs-137 and 0.99405 for Co-60.

Fig. 8 presents a graph plotting the dependence of the detector with respect to the change in water temperature. The water temperature increases from 25 to 40°C, and the coefficient value with respect to the Cs-137(3.70 × 10^5 Bq) gamma radiation source was


Radiation Monitoring System [MYONGJI]

115.00 CPS

대한민국 경기도 용인시 처인구 중앙동 38-2

RAMI

Underwater Radiation Mornitoring System

Count/sec 3.000000

Fig. 4. Mobile app and PC program for underwater radiation monitoring.

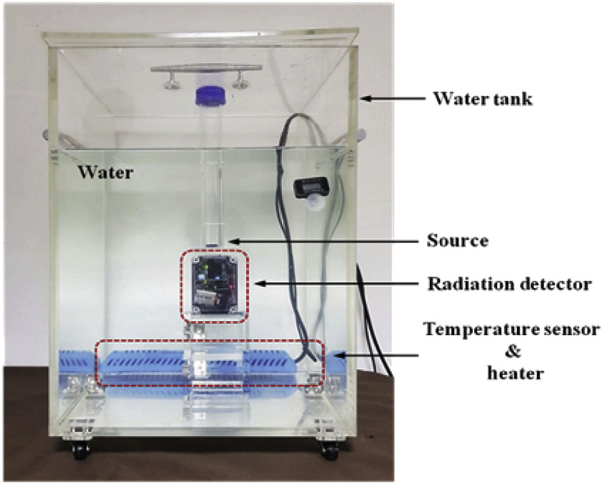


Fig. 5. Experimental setup for measuring underwater radiation.

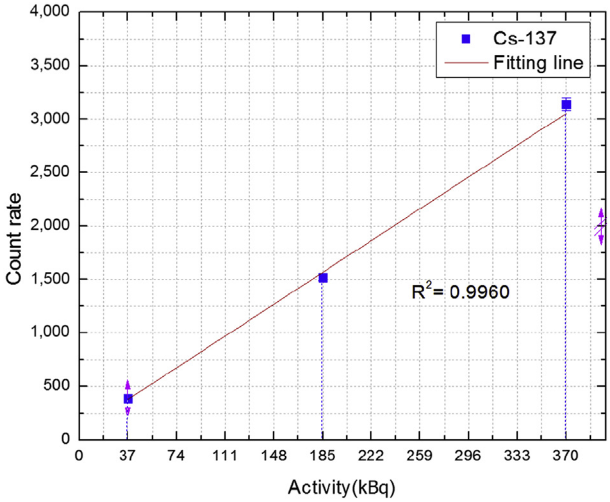


Fig. 6. Responsiveness of the underwater radiation detector with respect to the Cs-137 intensity.

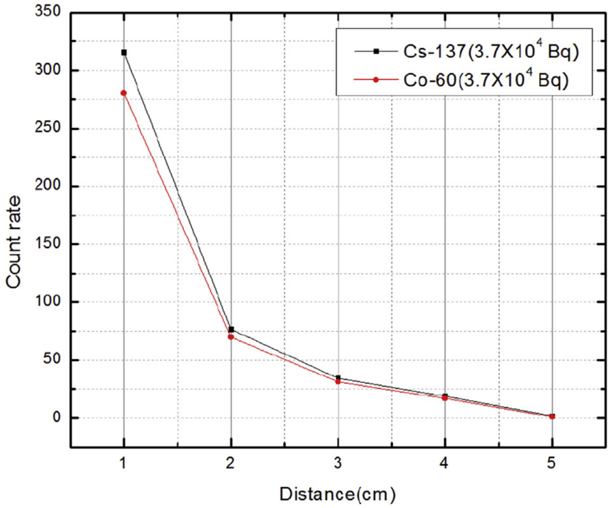


Fig. 7. Responsiveness of the underwater radiation detector as a function of distance.

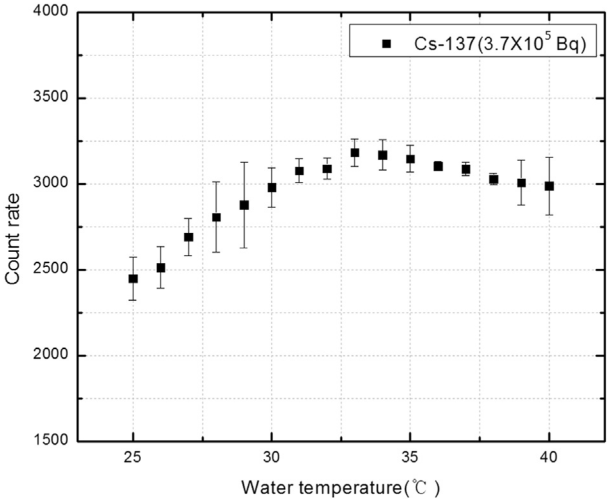


Fig. 8. Temperature dependence of the underwater radiation detector with respect to the change in water temperature.

measured for an interval of 1°C. According to the results, the count rate is observed to increase up to 33°C with the increase in water temperature because of the increase in dark current of the SiPM. From 34°C, the breakdown voltage of the SiPM increases and the overvoltage decreases. As a result, the photo detection efficiency (%) (PDE (%)) and gain of the SiPM, as well as the count rate, decrease. The relationship between the overvoltage and breakdown voltage is shown in Eq. (2). V_{OV} is the overvoltage, V_{BI} is the voltage applied to the SiPM, and V_{BR} is the breakdown voltage [11,12,13].

$$V_{OV} = V_{BI} - V_{BR} \quad (2)$$

4. Conclusions

In the present study, a wireless radiation monitoring system for measuring radioactive contaminants in water was established using an SiPM and GAGG(Ce) scintillating body. In addition, the characteristics of the detector were evaluated. As a result of the evaluation of the characteristics, the detector was confirmed to exhibit a linear response with respect to the intensity of the radiation sources, where the responsiveness decreases according to the inverse square law of distance with respect to a gamma radiation source. Moreover, in the temperature dependence test of the detector with respect to the temperature change in an underwater environment, it was confirmed that the count rate of the detector increases up to 33°C and then decreases from 34°C, when the water temperature increases up to 40°C, which is the maximum operating temperature of the SiPM. This is caused by the temperature dependence of the SiPM, and further research on the circuit design or algorithm for temperature compensation will be necessary. In addition, further research on topics to extend the results of the present study will greatly contribute to a persistent, quantitative, and immediate monitoring system for radioactive contamination in a water environment regarding radioactive waste leakage or nuclear power plant accidents.

Conflicts of interest

All authors have no conflicts of interest to declare.

Acknowledgments

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