Radiation Detector Compensation System for Extreme Environments

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Keywords : SoC FPGA, High temperature environment, Gamma-ray irradiation

1. Introduction

Scintillator-based radiation detectors are widely utilized in various fields such as nuclear medicine, well logging, high-energy physics, reactor monitoring, and space exploration due to their excellent radiation detection efficiency, energy resolution, and robust performance in extreme environments, including high temperatures, radiation, humidity, and vibrations. However, when scintillation detectors are exposed to high temperatures or intense radiation, several factors can lead to changes in the overall gain of the detector. These include variations in the scintillator's light output, degradation of its transparency, changes in the gain of optical sensors such as Photomultiplier Tubes (PMTs) or Silicon Photomultipliers (SiPMs), and a reduction in the transmittance of optical sensor windows. These fluctuations compromise the stability of the energy-channel relationship in the gamma spectrum, causing shifts in the photopeak position. Consequently, this can introduce significant errors in qualitative and quantitative analyses using gamma spectroscopy, such as the identification of radioactive isotopes and the measurement of radioactivity concentration.

To mitigate such errors, various detector calibration and compensation methods have been developed. However, existing approaches primarily focus on compensating for temperature variations while neglecting output changes caused by radiation damage. Moreover, conventional temperature compensation methods have only been validated within limited temperature ranges, making them unsuitable for applications requiring operation at higher temperatures, such as planetary exploration or reactor monitoring systems.

In this study, as a preliminary step toward developing a radiation measurement output compensation system for extreme environments, we designed a detector capable of real-time operation under high-temperature and high-radiation conditions. In addition, gamma irradiation tests were conducted up to a total dose of 2 kGy to analyze changes in light output with increasing dose. Based on the measured results, the output variations as a function of accumulated gamma dose were quantitatively evaluated, providing a foundation for establishing a light-output compensation system for extreme-environment applications.

2. Methods and Results

2.1 Experimental setup

As illustrated in Fig. 1, the high-temperature experiment was conducted by coupling a Ce:GPS scintillator (3 × 3 × 5 mm³, OXIDE Corporation, Japan) with a PMT (R3991A-07, Hamamatsu). The signal output from the PMT anode passed through a front-end circuit, where it was amplified and shaped, before being transmitted to the FPGA (ADC-SoC).

Temperature was measured using a thermistor, leveraging its property of changing resistance with temperature. A voltage divider circuit was used to measure the voltage across the thermistor, which was then acquired by the FPGA's low-speed ADC (LTC2308). This acquired value was subsequently converted into an accurate temperature reading using a pre-built resistance-temperature lookup table (LUT).

To evaluate the change in detector output with temperature, energy spectra were acquired from a ^{137}Cs (72.61 μCi) source at 25°C intervals from 25°C to 150°C. The variation was assessed using the position of the photopeak in these spectra. The output consistency was quantified using the Coefficient of Variation (CV), which was calculated as the ratio of the standard deviation of the photopeak position to its mean value.

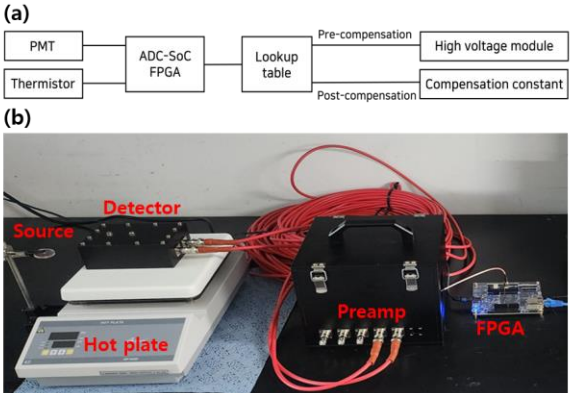

Fig. 1. (a) Schematic of temperature compensation system. (b) The radiation detector, radiation source, DAQ and Hot plate.

2.2 Temperature compensation (pre- and post-compensation)

To compensate for detector output variations caused by temperature changes, two temperature compensation methods were developed. The first method, Pre-compensation, maintains a stable detector output by adjusting the voltage supplied to the detector based on the measured temperature. The second method, Post-compensation, keeps the detector output stable without altering the supplied voltage; instead, it adjusts the magnitude of the output signal by multiplying it by a specific factor based on the measured temperature. (Fig. 1)

2.3 Radiation compensation

To observe output changes of a scintillator-based detector under gamma irradiation, irradiation tests were conducted up to 2.1 kGy. Output changes were analyzed across the dose range from 0 to 2.1 kGy in approximately 0.75 kGy increments.

2.4 Result and Discussion

In the temperature range of 25°C to 150°C, the coefficient of variation for the photopeak position of ^{137}Cs was 1.23% for the Pre-compensation method and 1.84% for the Post-compensation method. These values are significantly lower than the coefficient of variation before temperature compensation, which was 20.16% (Fig. 2 and Table 1).

Furthermore, gamma irradiation was performed up to 2.1 kGy, radiation-induced output degradation was also evaluated. The photopeak position decreased from 232.6 (arb. unit) to 141.6 (arb. unit) at 2.1 kGy, corresponding to a 39.1% reduction in output. (Fig. 3 and Table 2)

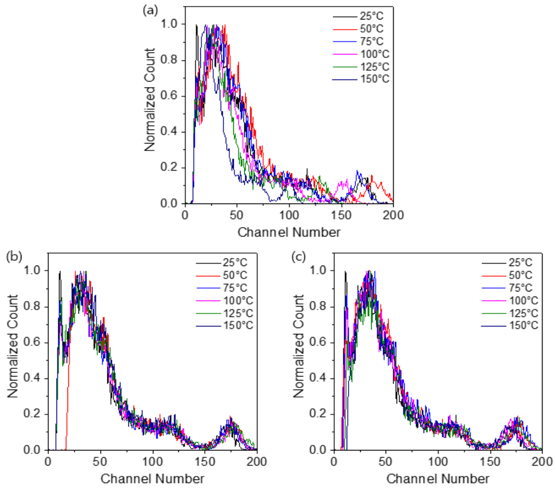

Fig. 2. ^{137}Cs energy spectra from 25°C to 150°C. (a) Un-compensated (Reference at 25°C), (b) Pre-compensation, (c) Post-compensation

Table 1: Comparison of the Mean Value, Standard Deviation, and Coefficient of Variation of the Photopeak Position with and without Temperature Compensation

Case	Avg of peak values (arb unit)	Standard deviation	The coefficient of variation(%)
Un-compensation	149.33	30.11	20.16%
Pre-compensation	174.17	2.14	1.23%
Post-compensation	171.72	3.16	1.84%

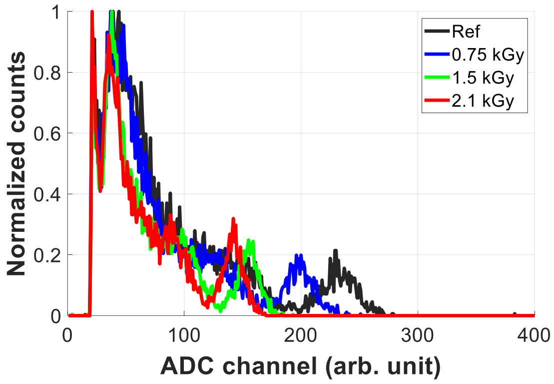

Fig. 3. Energy spectrum after gamma irradiation (up to 2.1 kGy).

Table 2: Comparison of the Photopeak Position.

Radiation dose (kGy)	0	0.75	1.5	2.1
Peak position (arb. unit)	232.6	198.1	155.1	141.6
Energy resolution	14.6%	14%	13.9%	15.2%

3. Conclusions

This study confirmed that both temperature-compensation methods operate effectively over a wide temperature range from 25°C to 150°C, demonstrating the capability to maintain stable detector output despite temperature variations. In addition, the output changes of a scintillator-based detector under irradiation were quantitatively analyzed, and the feasibility of post-irradiation thermal annealing after recovery to room temperature was verified.

These results represent a preliminary step toward our ultimate goal of developing an intelligent radiation sensor for extreme environments. Future work will focus on developing dedicated hardware for radiation-damage compensation and further refining thermal annealing techniques.

Ultimately, the goal is to realize a robust detector capable of autonomously restoring its performance after exposure to high radiation doses, thereby significantly extending its operational lifetime and detection reliability in environments that are difficult for humans to access, such as nuclear reactors or deep space. This advancement is expected to contribute substantially to reliable radiation monitoring and measurement under the most challenging conditions.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) funded by the Ministry of Science, Commercializations Promotion Agency for R&D Outcomes, and ICT (RS-2023-NR077190, RS-2023-00234651, RS-2022-00165164)

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