Distributed Radiation Sensor Based on Optical Fiber Sensing Technique

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1. Introduction

In order to ensure the safety of nuclear power generation systems, it is necessary to monitor various status information of nuclear power plant facilities and structures under normal and abnormal conditions. Fiber-optic sensing technology has attracted attention as a monitoring sensor suitable for nuclear power environments due to its ability to operate stably even under extreme conditions and to accommodate multiple physical quantity measurements [1]. Silica-based fiber-optic sensors have the advantage of transmitting optical signals in high temperature, high pressure, high humidity, and high radiation environments without being affected by electromagnetic interference. In addition, various physical quantities such as temperature, vibration, strain, and radiation can be measured using various sensing technologies. In particular, distributed measurement technology, which measures external physical quantities spatial-continuously by analyzing scattered optical signals, is considered suitable for monitoring the status of equipment and structures [1].

In this paper, we propose a distributed radiation sensor based on fiber optic sensing technology. We employ a measurement technique that analyzes changes in the optical signals caused by radiation with high spatial resolution. And the radiation-sensitive optical fiber is used as the sensor and the optical transmission medium. The results of the gamma-ray irradiation experiment verify the potential of the distributed radiation measurement.

2. Methods and Results

In distributed sensors, optical fibers serve both as a medium to transmit light and as sensing components that respond to changes in the external environment. Typically, when an optical fiber is exposed to radiation, defects are induced inside the optical fiber, resulting in transmission loss of light passing through the optical fiber [2]. In this study, aluminum (Al)-doped optical fibers were utilized. Al-doped optical fibers are highly sensitive to radiation and exhibit relatively high transmission loss when exposed to radiation. Radiation-induced attenuation (RIA) is linearly related to the aluminum concentration in the fiber core, and RIA is maintained when not exposed to radiation, making these optical fibers suitable for radiation sensors [3].

To analyze the variation of optical transmission loss caused by radiation at a specific point, the optical frequency domain reflectometry (OFDR) method [4, 5] is adopted. OFDR works by injecting light from a tunable wavelength laser source into a fiber undetected test (FUT) and analyzing the backscattered Rayleigh signal in the frequency domain. This technique allows real-time measurement of the variation of optical transmission loss at each point with an excellent spatial resolution of a few millimeters over a distance of up to hundreds of meters. Therefore, by performing high-resolution real-time analysis of the variation of RIA at a specific point along the fiber, spatial continuous detection of radiation can be achieved along the entire length of the fiber.

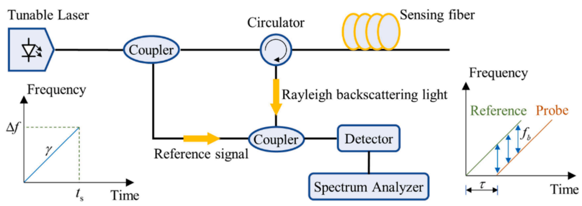

Fig. 1. Schematic illustration of the OFDR sensing principle [5].

To verify the ability to spatially detect radiation, a gamma-ray irradiation experiment was performed at the Advanced Radiation Research Institute. The experimental setup is shown in Figure 2. The fiber under test (FUT) was placed in a straight line on the experimental table. While irradiating the FUT with gamma rays, the Rayleigh scattered light was measured in real time to analyze the intensity change. Two lead blocks were placed in front of a portion of the FUT to shield the gamma rays and mitigate their effects. The lead blocks were 0.2 m long and approximately 0.45 m apart from each other. In addition, five alanine dosimeters were used to measure the reference dose of gamma rays at different locations along the fiber.

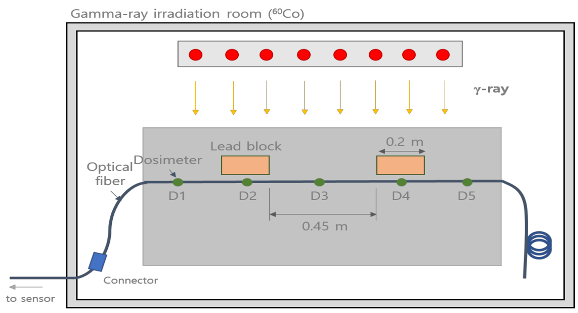

Fig. 2. Gamma ray irradiation experimental setup of a distributed radiation sensor.

The results of measuring the scattered light signal using the distributed sensor are shown in the figure 3. The gamma-ray irradiation was performed for 2 hours, and the total irradiation dose was approximately 1.5 kGy. Figure 3(a) presents the intensity of the scattered light signal as a function of the position along the FUT during gamma ray irradiation. It is observed that the intensity of the scattered light decreased as the optical fiber was exposed to more radiation. The loss occurring in front of the FUT accumulates and becomes more pronounced along the fiber. Additionally, the sections of the optical fiber shielded by the lead exhibited relatively less change. Figure 3(b) shows the calculated differential loss at each position. This is the difference in scattered light intensity between adjacent points, calculated for intervals of approximately 0.18 meters. Significant differential loss was observed in segments not shielded by lead blocks, whereas segments shielded by lead blocks exhibited relatively smaller differential loss. The differential loss increased linearly with irradiation time. The doses measured at the locations corresponding to each dosimeter were 1.45, 0.16, 1.57, 0.14, and 1.41 kGy, respectively. The maximum measurable radiation dose is expected to be approximately 5 kGy for a 1 m sensor length, but this varies depending on the FUT length, Al concentration, and other factors. The results measured by the sensor are related to radiation dose, confirming that high-resolution, spatially distributed measurements are possible.

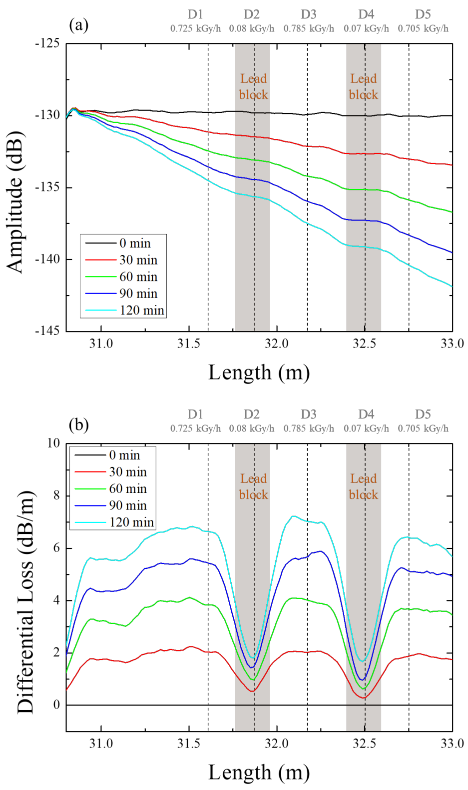

Fig. 3. (a)The intensity of the scattered light signal and (b) the calculated differential loss as a function of the position along the FUT during gamma ray irradiation.

3. Conclusion

We present the implementation of a distributed gamma-ray sensor based on optical fiber sensing technology. Utilizing highly radiation-sensitive Al-doped optical fiber and OFDR technology for high spatial resolution analysis of the position signal changes, the sensor was able to spatially and continuously measure gamma-ray dose along the entire length of the optical fiber. Such a distributed radiation sensor could be deployed on nuclear power plant equipment and structures for continuous condition monitoring in environments where radiation exposure is possible.

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