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Original Article

Fiber-optic humidity sensor system for the monitoring and detection of coolant leakage in nuclear power plants

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ABSTRACT

In this study, we developed a fiber-optic humidity sensor (FOHS) system for the monitoring and detection of coolant leakage in nuclear power plants. The FOHS system includes an FOHS, a spectrometer, a halogen white-light source, and a Y-coupler. The FOHS is composed of a humidity-sensing material, a metal tube, a multi-mode plastic optical fiber, and a subminiature version A (SMA) fiber-optic connector. The humidity-sensing material is synthesized from a mixture of polyvinylidene fluoride (PVDF) in dimethyl sulfoxide (DMSO) and hydroxyethyl cellulose (HEC) in distilled water. We measured the optical intensity of the light signals reflected from the FOHS placed inside the humidity chamber with relative humidity (RH) variation from 40 to 95%. We found that the optical intensity of the sensing probe increased linearly with the RH. The reversibility and reproducibility of the FOHS were also evaluated.

1. Introduction

The rate of failure in the coolant system of nuclear power plants (NPPs) in Korea has been slowly increasing because of the more extended operation. For example, in 2008, an accident occurred in the Kori 3 NPP and resulted in a leakage of approximately 1.24 tons of coolant from the steam generator. It is thought that this accident was caused by the growth of internal defects in the welded joint during operation [1]. In 2010, there was a reactor coolant leakage in the Hanbit 3 NPP. This accident is known to have been caused by two axial defects due to primary water stress corrosion cracking (PWSCC) in the exhaust pipe [2]. Furthermore, in 2017, the Kori 4 NPP was manually shut down owing to excessive leakage of coolant, which was due to the breaking of a valve seal by the accumulated cycle fatigue [3]. The accidents listed above were all linked to cooling water leakage due to mechanical faults in the primary and secondary systems. The number of these coolant leakage accidents increases as the operating life of an NPP increases.

Because NPPs have pipes and cables with lengths from 170 to 1,700 km and millions of components, cracks can occur in approximately 65,000 welds and 30,000 valves because of aging, due to causes such as iron plate corrosion, valve breakage, and weld cracking [4–6]. The loss of coolant due to pipe damage and defects can lead to insufficient cooling of the reactor core. Although the probability of experiencing loss of coolant due to pipe damage is very low, the failure of the emergency core cooling system (ECCS) and the depressurization system due to small break loss of coolant accident (SBLOCA) can occur at the same time, and the failure of multiple or complex safety systems destroys the reactor cooling function, causing serious accidents. More specifically, the loss of coolant can result in insufficient nuclear fuel cooling, which can lead to a core melting accident. Accordingly, coolant leakage issues require extensive attention.

Coolant leakages in NPPs are currently detected and monitored by a variety of methods. Although total quantitative leakage determination is possible with condensate flow monitors, sump monitors, and primary coolant inventory balances [7,8], these methods are not adequate to detect local leakages, especially from pipes, and they are often not very sensitive. Moreover, if leakage occurs at a point not explicitly monitored in an NPP, it is very difficult to find the location of the leakage with total quantitative leakage determination methods [9,10]. For inspecting damages and defects in various kinds of pipes in an NPP, thermal, ultrasonic, and acoustic imaging methods are typically used [11,12]. These methods have the risk that workers can be exposed to radiation when the

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radioactive coolant leaks in the primary cooling system of an NPP [13,14]. Therefore, for the safety of both the reactor and operators, the remote real-time monitoring of coolant leakage is very important in the reactor cooling system.

In this study, we developed a fiber-optic humidity sensor (FOHS) system that can implement leak-before-break (LBB) detection easily at coolant pipes in real-time. The FOHS consists of humidity-sensing material whose optical characteristics change with humidity and an optical fiber capable of transmitting the optical signal. Because the optical fiber has a small volume and low weight, it is possible to minimize the sensor size, and the FOHS can be manufactured easily. In addition, unlike with conventional electronic humidity sensors, a clear signal can be obtained with the FOHS without electromagnetic interference because the optical fiber has electromagnetic wave resistance due to the characteristics of the constituent material [15,16]. Therefore, FOHSs can be used to measure humidity in real-time remotely. Moreover, it is possible to fabricate multichannel FOHSs to detect humidity in many coolant pipes simultaneously. To evaluate the performance of the FOHS, we measured the optical signal of the reflected light while changing the humidity using a specially designed chamber in a humidity-controlled environment.

2. Background theory

The major principle of the FOHS system is the Fresnel reflection, which is the reflection of a portion of incident light at a discrete interface between two media having different refractive indices. In the FOHS, the Fresnel reflection is generated at the interface between the humidity-sensing material and the core of a multi-mode plastic optical fiber (POF) at the end of the sensing probe. The intensity of the reflected light by the Fresnel reflection is given by

$$R = \left(\frac{(n_1 - n_2)}{(n_1 + n_2)}\right)^2 \quad (1)$$

where R is the reflection coefficient, and n_1 and n_2 are the refractive indices of the multi-mode POF core and the humidity-sensing material, respectively [17–19]. The relationship between the refractive index of the humidity-sensing material and the Fresnel reflection according to Equation (1) varies with humidity, as shown in Fig. 1. In this case, the refractive index of the humidity-sensing material is varied from 1.487 (RH 20%) to 1.47 (RH 80%) depending on the humidity [20].

With a relative humidity (RH) above 20%, the refractive index of the humidity-sensing material is smaller than that of the core of a multi-mode POF, and it decreases as the humidity increases, as shown in Fig. 1. As the humidity increases, the refractive index of the humidity-sensing material decreases and diverges from that of the core of a multi-mode POF, increasing the amount of Fresnel reflection. On the other hand, the amount of Fresnel reflection decreases as the humidity decreases. Thus, the humidity at an arbitrary point can be determined by measuring the light intensity of the reflected light according to the change in the refractive index of the humidity-sensing material. Therefore, coolant leakage can be detected via the humidity difference between dry and humid (i.e., leaky) pipes.

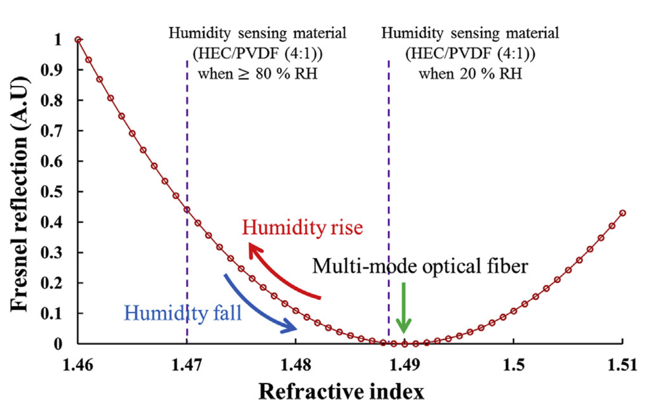


Fig. 1. Relationship between the refractive index of the humidity-sensing material and Fresnel reflection.

3. Materials and methods

We fabricated a humidity-sensing probe using a metal tube, a POF, and a humidity-sensing material, as shown in Fig. 2. The structure of the FOHS is very simple and rugged. We installed a subminiature version A (SMA) connector between a transmitting POF and a light measuring device for the stable measurements of optical signals. The sensing probe was enclosed in a stainless-steel metal tube for the stability of the structure. Normally, a POF is considered to be reliable owing to its flexibility and robustness under bending and stretching. In an NPP, the sensing probes of the FOHS can be installed to find local leakages of coolant around water pipes with simple support fixtures.

The optical characteristics, such as the refractive index, of humidity-sensing material in FOSHs, should vary according to the humidity variations with high sensitivity and fast response time. Furthermore, it should be easy to attach a sensing material to the end of an optical fiber as a sensor-tip. Therefore, a hydrogel, which was synthesized from a mixture of polyvinylidene fluoride (PVDF) in dimethyl sulfoxide (DMSO) and hydroxyethyl cellulose (HEC) in distilled water, was selected as the humidity-sensing material in this study.

To transmit light signals from the humidity-sensing probe to a light measuring device, we used a step-index multi-mode POF (GH4001, Mitsubishi Rayon) with a core/cladding structure. The cladding was made of a fluorinated polymer with a refractive index of 1.402, and its thickness was 20 μm. The core was made of polymethyl methacrylate (PMMA), which has a refractive index of 1.492, and its diameter was 980 μm. Therefore, the numerical aperture (NA) of the POF was approximately 0.5. The end of the POF was coated with the humidity-sensing material. The other side of the humidity-sensing probe was connected with the SMA connector to the optical instrument, which can measure optical signals. The experimental setup for measuring the humidity using the FOHS is shown in Fig. 3.

In this study, the sensing probe was placed inside a specially designed humidity chamber, which was connected to an air-controllable humidification driver. The RH in the chamber was detected by a reference RH meter (TES-1364, Tes Electrical Electronic). We used a halogen white-light source (DH-2000-BAL, Ocean Optics) and measured the optical intensity of light signals (reflected by Fresnel reflection) with a spectrometer (AvaSpec-HS1024, Avantes). Then, we connected the light source, spectrometer, and FOHS with a fiber-optic Y-coupler (IF-562, Mitsubishi Rayon) [21].

A schematic of the fiber-optic Y-coupler is shown in Fig. 4. The optical signal generated from the halogen white-light source moves from ① to ②and is then reflected via Fresnel reflection. The Fresnel reflection generated at the interface between the humidity-sensing material and the core of the POF at the end of the sensing probe changes as the refractive index of the humidity-sensing material changes due to the varying RH. This reflected optical signal is split into two signals of equal intensity by the fiber-optic Y-coupler. Then, the spectrometer can detect the signal transmitted to ③.

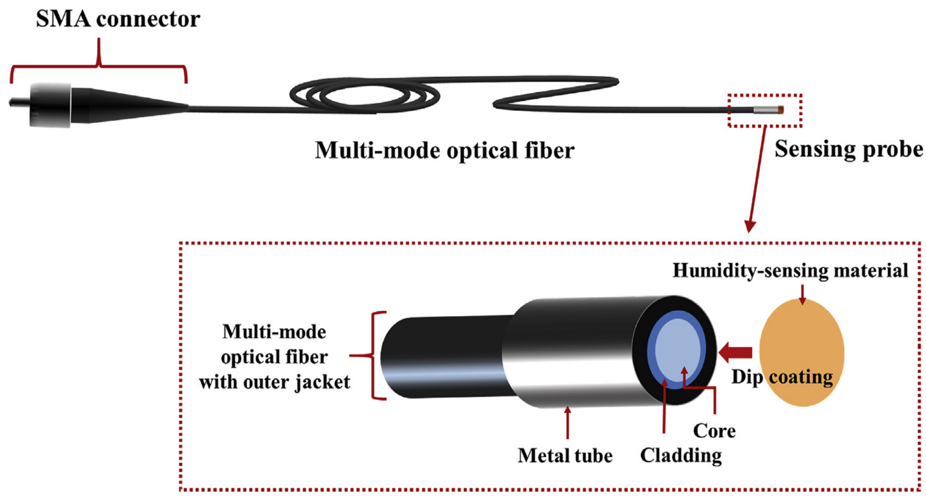


Fig. 2. Humidity-sensing probe and its internal structure.

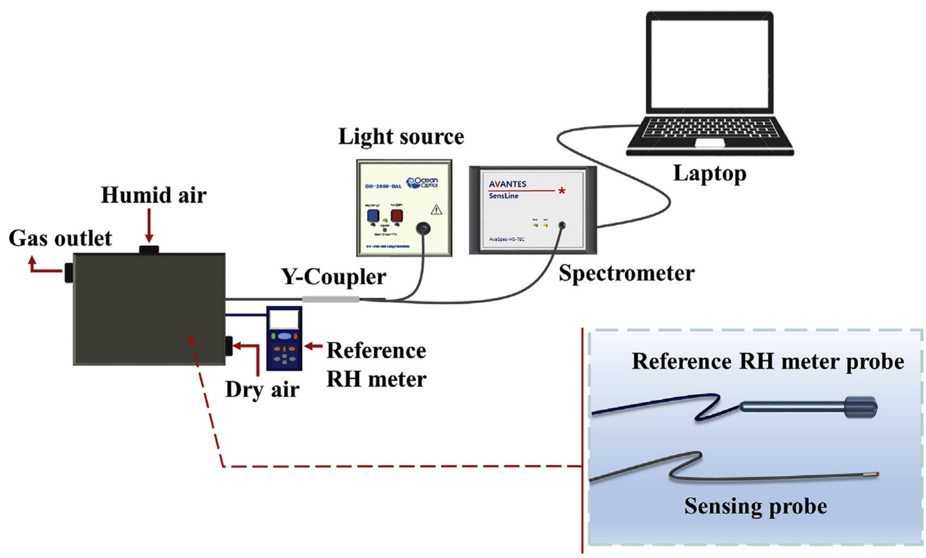


Fig. 3. Experimental setup for measuring humidity using the FOHS.

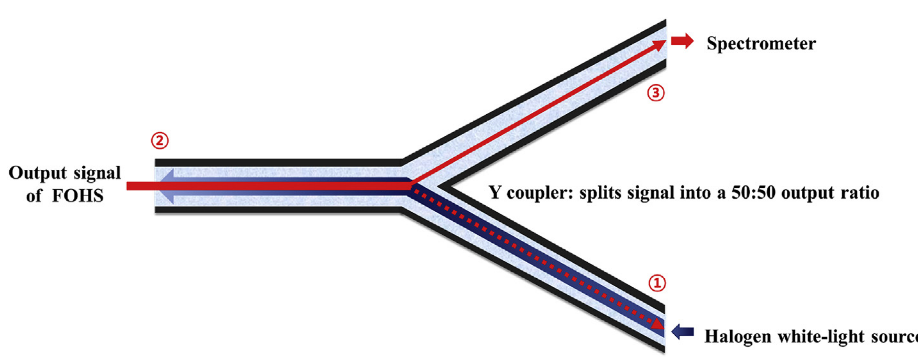


Fig. 4. Paths of light through the fiber-optic Y-coupler.

4. Experimental results

The refractive index of the sensing material can be determined by the weight ratio of PVDF in DMSO and HEC in distilled water, and it changes with the RH. The refractive indices of the PVDF and HEC are 1.426 and 1.51, respectively. Table 1 shows the mixing ratio of PVDF to HEC by weight to determine the optimal humidity-sensing material [22,23].

Table 1
Mixing ratio of PVDF and HEC.

Sample	PVDF:HEC
Sample 1	1:4
Sample 2	1:3.5
Sample 3	1:3
Sample 4	1:2.5
Sample 5	1:1.7

In this experiment, the sensitivity of a sample was defined as the variation in optical intensity for a change in RH. The sensitivity of sample 1 was approximately 0.09, and those of the other samples were less than approximately 0.02. Therefore, the sensitivity of sample 1 was more than 4.5 times higher than those of other samples. Moreover, as shown in Fig. 5, the sensitivity of sample 1 determined by the slope is much higher than that of other samples. We tested sample 1 four times in the RH range between 40 and 95% and confirmed all measured data lies within the error range of +0.165% to approximately −0.305% from the average of measured data. The output signal of sample 1 shows good stability, good linearity, and high sensitivity. Thus, sample 1 was selected as the best material for the FOHS.

To evaluate the performance of the FOHS, we used a halogen white light source. We could measure the optical intensities with different wavelengths because we used a spectrometer as a light measuring device. Therefore, we could measure the variations in optical intensity with different wavelengths from 350 to 850 nm, as shown in Fig. 6, which also shows the variations in optical intensity at four wavelengths (475, 545, 660, and 766 nm).

Fig. 7 shows variations in optical intensity as the RH changed from 40% to 95% at wavelengths of 475, 545, 660, and 766 nm. At 660 nm, the variations in optical intensity with RH were larger than those at other wavelengths. This confirmed differences in optical intensity with RH could be measured at a 660 nm wavelength using the FOHS.

To estimate the performance of the FOHS, we measured its response/recovery times and reproducibility. Fig. 8 shows the response and recovery time curves of the FOHS during the humidification and desiccation processes with RHs changing from 25% to 75%. The response/recovery time of the sensor is defined as the time taken by the optical intensity to rise and fall between 10% and 90% [24]. As shown in Fig. 8, the average response time of the FOHS is approximately 16 s in humidification from 25% to 75% RH, and the average recovery time is approximately 15 s in desiccation with RHs from 75% to 25%. Fig. 9 confirms the good reproducibility of the FOHS in humidity cycles between 25% and 75%.

Fig. 10 shows the experimental setup used to test the POF, which can be used under high gamma irradiation fields without damage. The setup consisted of a Co-60 unit, halogen white-light source, spectrometer, and multi-mode POFs.

Light at four different wavelengths (475, 545, 660, 766 nm) was transmitted through the POF, which was used in the FOHS under high gamma irradiation from the Co-60 unit for 60 min. The absorbed dose of the POF was approximately 53.6 Gy, which is much higher than that of the secondary loop of an NPP where the FOHS might be installed.

Fig. 11 shows that the signals transmitted through the POF under high gamma irradiation are very stable at all wavelengths and that the FOHS can be used in the secondary loop of an NPP without affecting the gamma irradiation.

All the experiments were conducted at room temperature. The RH detection of the FOHS should be changed depending on the ambient temperature. However, the ambient temperature in an NPP does not vary significantly, and the purpose of our proposed FOHS is to find the locations of leaks in the pipes. At the location of leaks, the humidity measured with the FOHS would change abruptly, and the RH value is more important than the absolute humidity value, which can be affected by the ambient temperature.

5. Conclusion

We fabricated an FOHS using a POF, an SMA connector, and a humidity-sensing material to verify its applicability in NPPs. The humidity-sensing material was synthesized from a mixture of PVDF in DMSO and HEC in distilled water, and the end of the POF was coated via a dip-coating method. The coated humidity-sensing material acts as a reflector and its refractive index decreases with increasing humidity and, thus, allows more lights to be reflected. We confirmed that the proposed FOHS can accurately measure RHs in the range of 40%–95%. The optical intensity of the FOHS increased linearly with humidity and was measured with 660 nm-wavelength light, which was selected because the FOHS exhibited higher sensitivity at this wavelength. Sample 1 had exceptionally

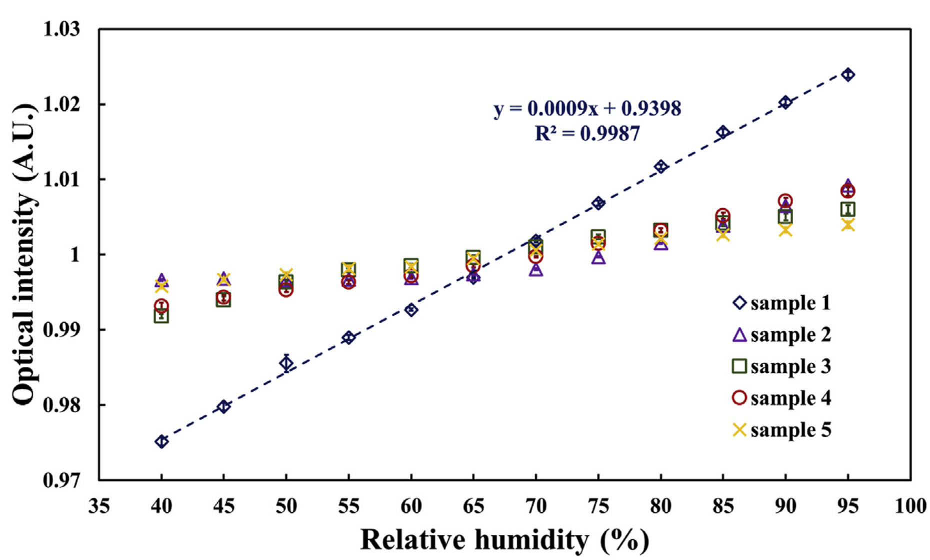


Fig. 5. Comparison of optical intensities of the FOHS with five mixing ratios of the samples according to the humidity variations in the humidity chamber.

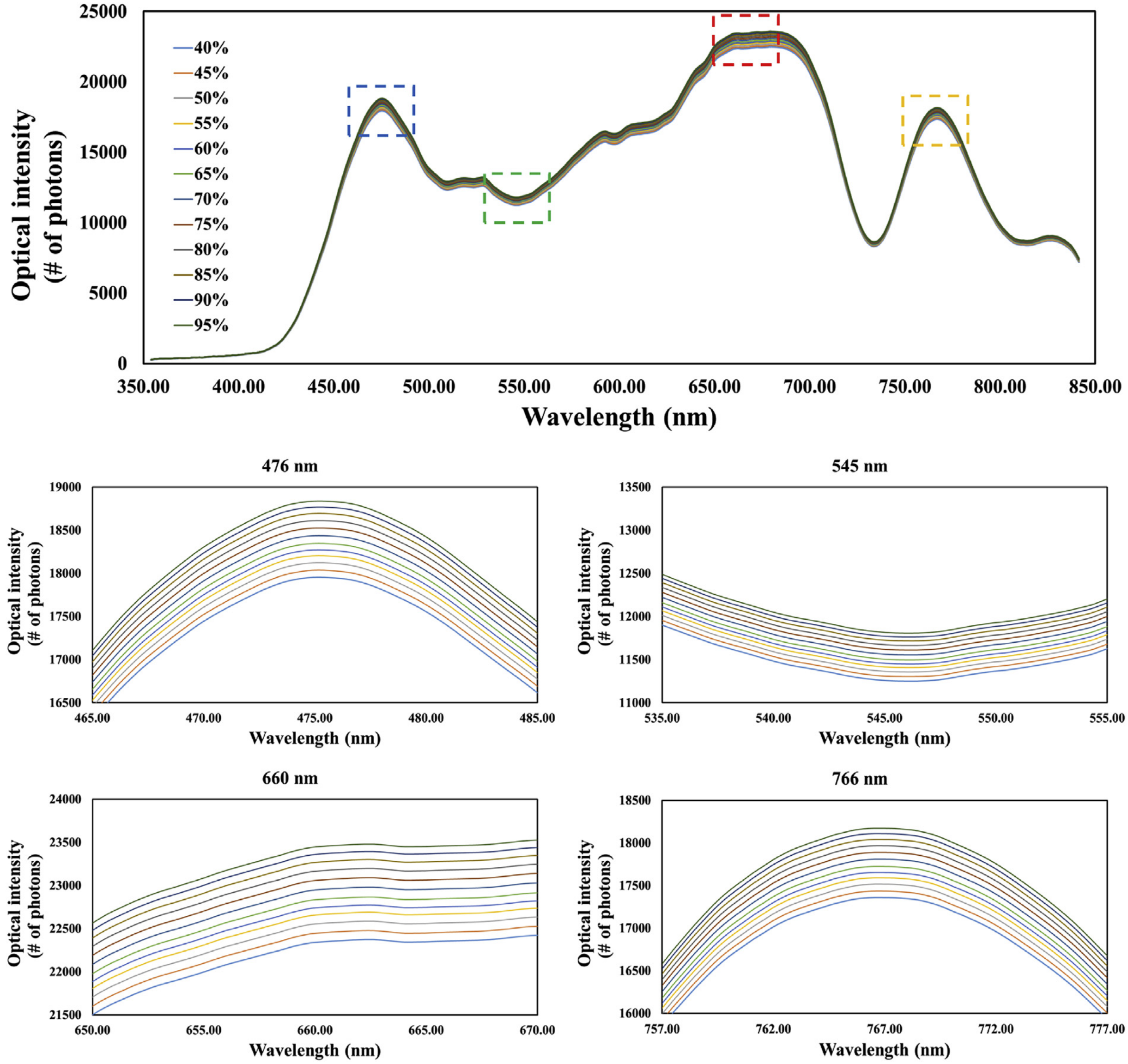


Fig. 6. Variations in the optical intensity with humidity measured at different wavelengths of light using the spectrometer and the halogen white-light source.

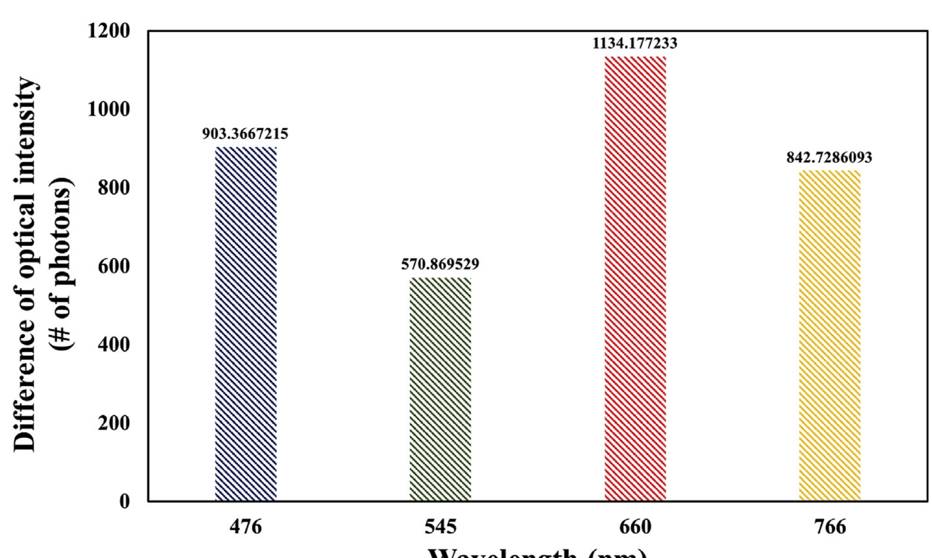
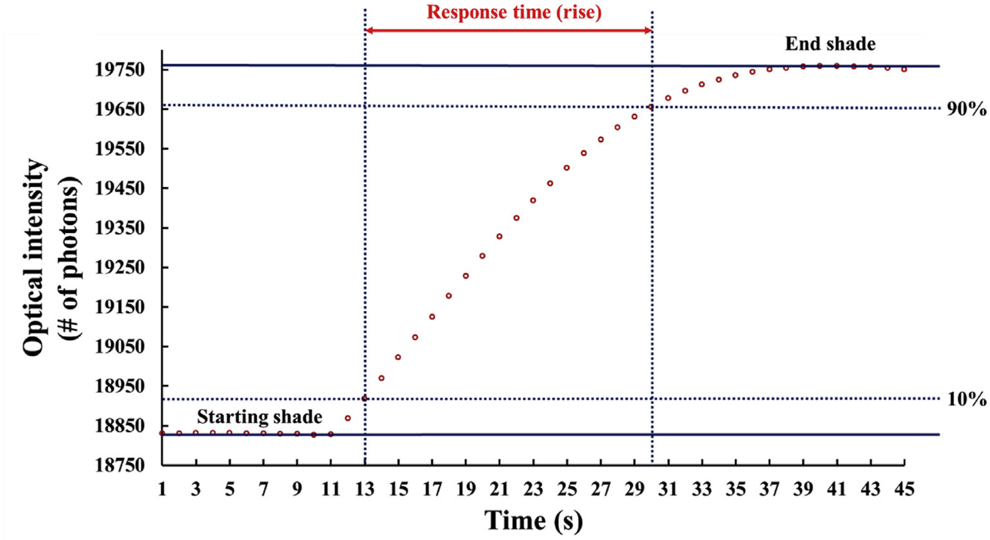
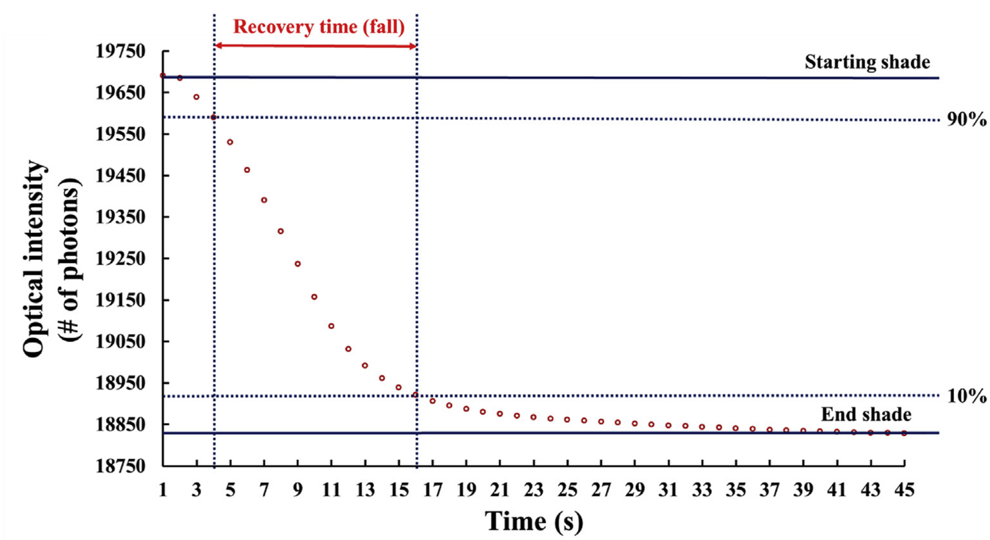


Fig. 7. Comparison of the differences in optical intensity measured at four different wavelengths of light (476, 545, 660, and 766 nm).



(a)



(b)

Fig. 8. Measurements of response(a) and recovery times(b) of the FOHS.

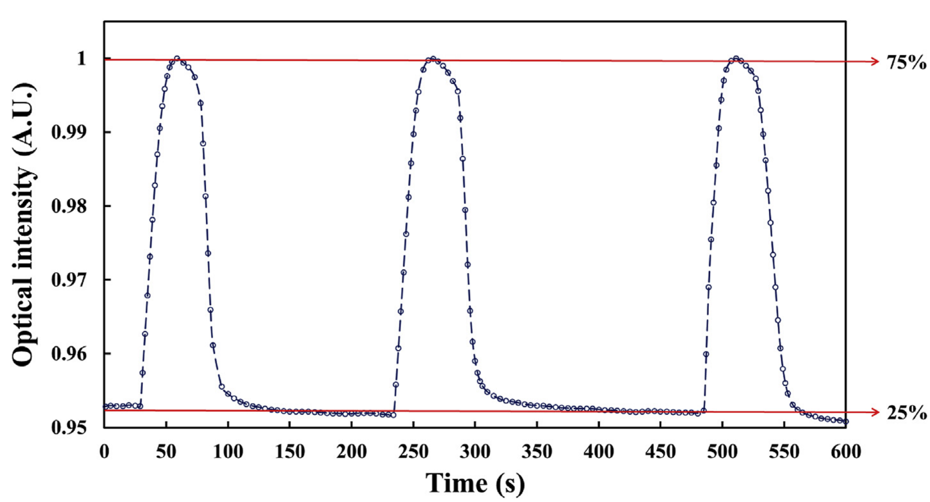


Fig. 9. Measurement of the reproducibility of the FOHS.

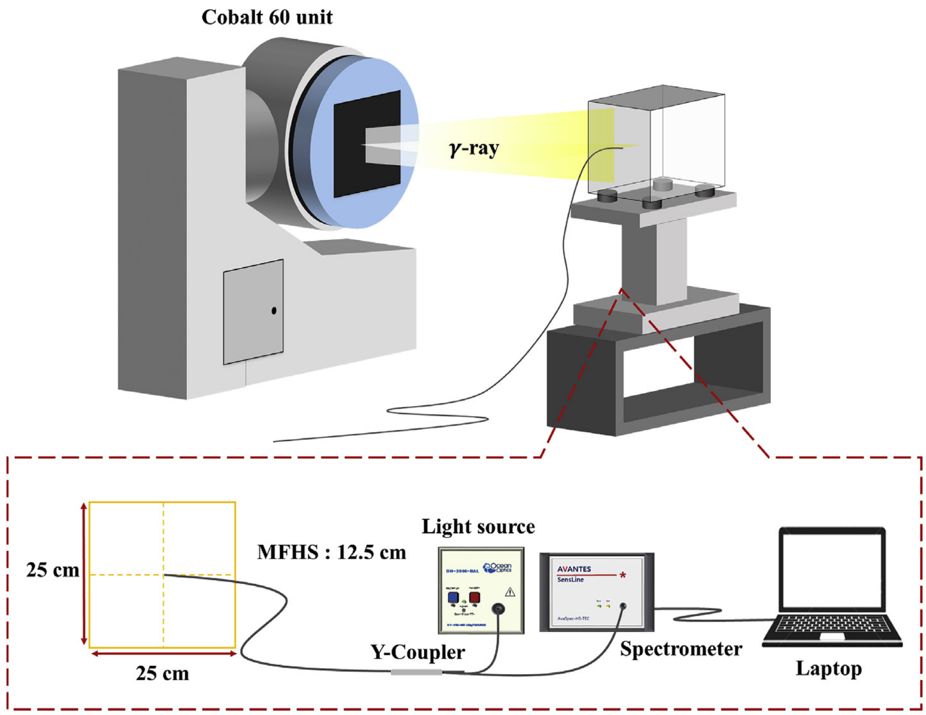


Fig. 10. Experimental setup for measuring the optical signals transmitted through the POF under high gamma irradiation fields.

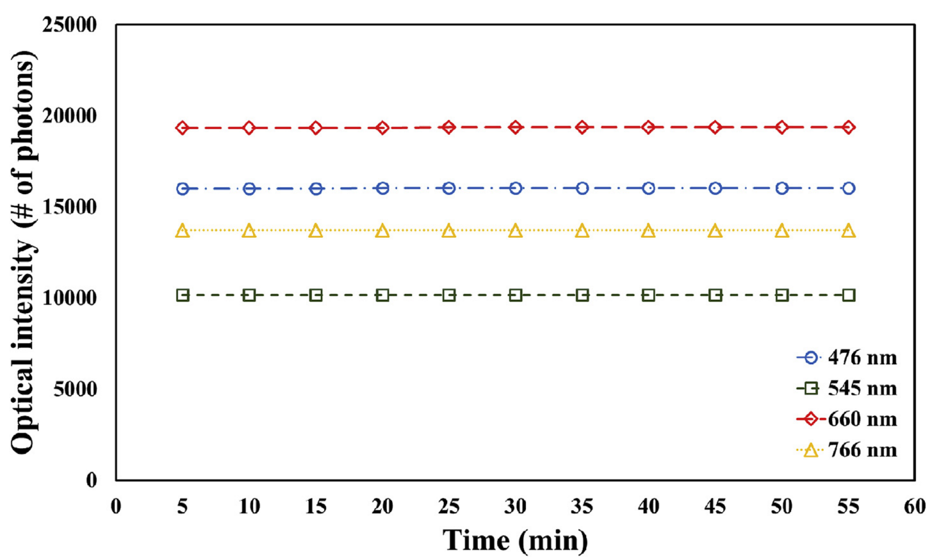


Fig. 11. Variations in optical signals transmitted through the POF with different wavelengths of light under high gamma irradiation fields.

high sensitivity and good linearity at RHs between 40% and 95%. The respective measured response and recovery time of the FOHS were 16 and 15 s during humidification and desiccation processes with RHs ranging from 25% to 75%. Furthermore, we confirmed that the FOHS was both reversible and reproducible. Finally, we verified that the FOHS can be operated under high gamma irradiation fields through a simple experiment with a Co-60 unit.

We expect the FOHS to detect coolant leakages in NPPs in an efficient and timely manner. However, the FOHS fabricated in this study is a single-channel sensor and can measure only one point of the pipe. Further studies will be carried out to develop a distributed multi-channel FOHS system for the detection of coolant leakages in NPPs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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