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Effect of temperature and irradiation on fused silica optical fiber for temperature measurement

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Abstract

The thermal radiation and luminescence of fused silica-core optical fibers with cores that are pure or doped with moderate and large amounts of fluorine was measured at elevated temperature with and without Co-60 γ-ray irradiation to study the effect of temperature and irradiation on the optical fibers. In the temperature range up to 1000 °C, peaks from OH were observed in all fibers and the intensity was temperature dependent. When the temperature of F-doped fibers was kept at 1000 °C, unexpected peaks appeared and grew. As a result, the peaks from OH could not be observed either with or without irradiation. In the case of pure fiber, thermal radiation increased as the elapsed time increased and the intensity with irradiation was much larger than that without irradiation. However, peaks from OH could be identified clearly and discriminated from the thermal radiation. The pure fiber is a promising temperature sensor.

1. Introduction

In a fusion reactor, the diagnostic system is deployed in a strong electromagnetic field and heavy radiation environment. Conventional electric devices are disturbed by such environmental conditions. Therefore, we consider that using an optical fiber as the signal transmission device and the dosimeter itself is the best candidate for the diagnostic system. Optical fibers have several advantages over other electrical media, including no electrical noise, a wide optical signal band, and they are self powered. The effect of an irradiation environment on optical fibers has been researched [1–5]. However, the phenomena have not been investigated at elevated temperature, either with or without irradiation.

The purpose of this study is to measure the high temperature properties by applying thermal radiation and luminescence of optical fiber itself in heavy radiation fields. In this paper the thermal effect of optical fiber that is set with and without Co-60 γ-ray environment is reported. Here, we used the pure and fluorine (F) doped optical fibers that were specially fabricated for use in heavy radiation fields [3,4]. Radiation-induced damage (increase of transmission loss) mainly results from color centers in optical fiber that is generated from intrinsic imperfect structure and impurity in the fiber which is so-called precursor. To decrease the influence of the intrinsic precursor, pure silica-core optical fiber is fabricated by removing the impurity as much as possible. However, it is impossible to remove the precursor completely. Here, the radiation-induced

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color center is metastable state and can be decreased to combine with a dopant, which is some species of molecule or ion. F-doped fiber is fabricated by adding a few mol.% of fluorine in optical fiber to use the effect of dopant.

2. Experiments

We used three types of optical fiber, two types with F-doped core fibers and a pure silica-core fiber, in this experiment. The F-doped fibers consisted of a fused silica-core doped with moderate and large amounts of fluorine. These fibers were made by Fujikura Corp., in Japan and the precise fluorine content of the fiber is not reported to the public by the company. Hereafter, we call these fibers middle and large F-doped fiber, respectively. The pure silica-core fiber was fabricated by the Fiber Optic Research Centre (FORC-Troisk) and drawn by Fujikura Corp. All fibers consist of low-OH (<10 ppm) and low-Cl (<1 ppm) core and have clad doped with fluorine. The core/clad diameters of these fibers are 0.2/0.25 mm. The irradiation experiment for large F-doped fiber was performed in the Co-60 γ-ray irradiation facility in Japan Atomic Energy Agency (JAEA). The intensity of the γ-ray source is 2.0 PBq and absorbed dose rate is 1.0 Gy/s. The irradiation experiments for middle F-doped and pure fiber were performed in the Co-60 γ-ray irradiation facility in Tohoku University. The intensity of the γ-ray source was 4.07 TBq and the absorbed dose rate was 3.14×10^{-3} Gy/s. The experimental setup for γ-ray irradiation is shown in Fig. 1. In the irradiation area, optical fibers were set in an electric furnace. One end of optical fiber was covered with Aluminum foil that made the end dark. The other end was connected to a spectrum analyzer (Ando Electric, AQ-6315A). The length of the optical fiber heated by the furnace was 10 cm. The temperature was changed up to 1000 °C with the heating rate of 3 °C/min. All experiments were performed in the air.

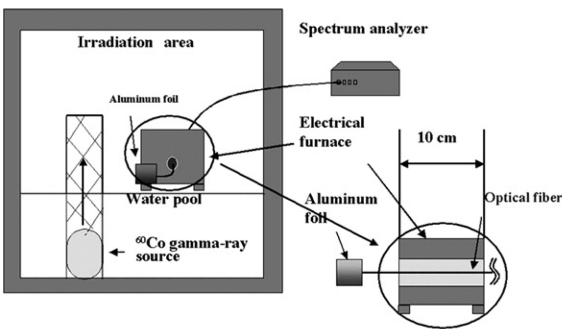

Fig. 1. Schematic diagram of experimental setups in γ-ray irradiation facility.

3. Results and discussion

Fig. 2 shows the experimental result for pure fiber under irradiation while changing the temperature up to 1000 °C. There are sharp peaks at 1240 and 1390 nm caused by OH contents of optical fiber, though the contents are low [6]. All fibers with and without irradiation had similar peaks and the peaks were increased as the temperature increased up to 1000 °C. Fig. 3 shows the temperature dependence of optical intensity at 1390 nm of all experimental conditions. The differences of the optical intensities for all fibers were mainly due to the different intrinsic optical absorption of the fibers and the different geometry of optical output from the ferrule of all fibers. The optical intensities at 1390 nm have temperature dependence up to 1000 °C. The luminescence at 1390 nm could be applied to measure temperature.

After the temperature reached 1000 °C, we held this temperature for 100 h. Fig. 4 shows the measured spectra from pure fiber as a function of the elapsed time after the temperature reached 1000 °C without irradiation. The spectral shape does not change though the optical intensities of the peaks

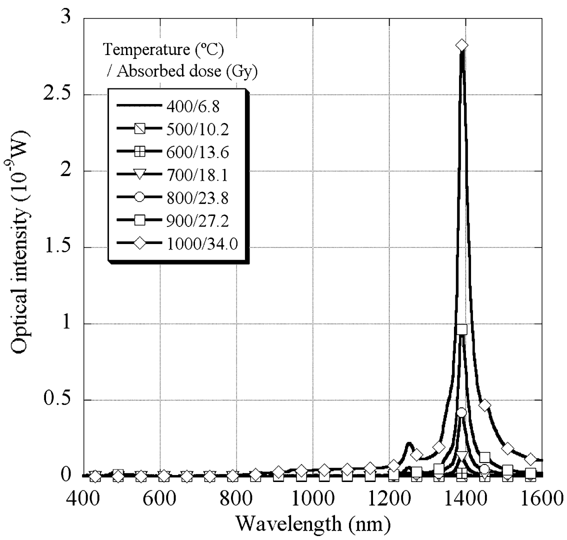

Fig. 2. Optical spectra of pure fiber while changing the temperature up to 1000 °C with γ-ray irradiation.

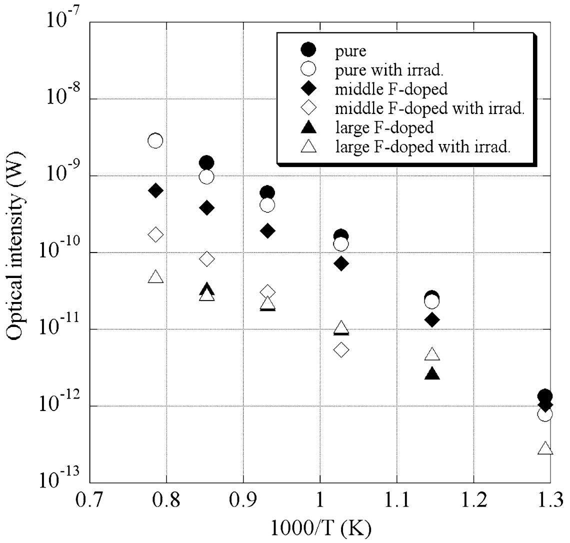

Fig. 3. Temperature dependences of optical intensity at 1390 nm of all fibers with and without γ-ray irradiation.

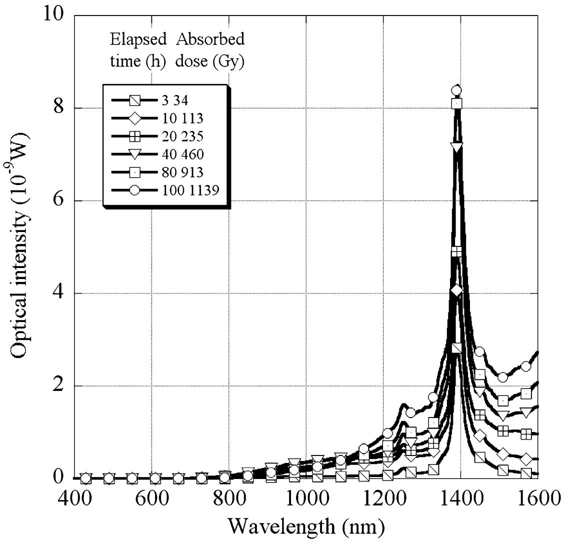

Fig. 5. Optical spectra of pure fiber at 1000 °C as a function of the elapsed time with γ-ray irradiation.

become large. It is reported that the OH in optical fiber is influenced by the experimental atmosphere [7]. Thus, it is considered that the amount of OH, which is the origin of the peaks, increased during heat treatment at 1000 °C in the air. Fig. 5 shows the results for pure fiber kept at 1000 °C with irradiation. There was an apparent irradiation effect and the optical intensity over whole range of wavelengths except for the sharp peaks of OH (hereafter, described as background for simplicity) increased as the absorbed dose increased. The optical intensities of background are based on the Planck's radiation theory. Though the optical fiber itself has thermal radiation because all materials emit thermal radiation depending to the temperature while the material is heated, its intensity is small as seen in Fig. 4. Therefore, it is assumed that the background is caused by the thermal radiation not from optical fiber but from the electric furnace in this experiment. The pure optical fiber is damaged by γ-ray irradiation, particularly at the core/clad interface; this results in a change in the reflective index and the thermal radiation of the furnace is observed and increased with the γ-ray absorbed dose (damage) increased.

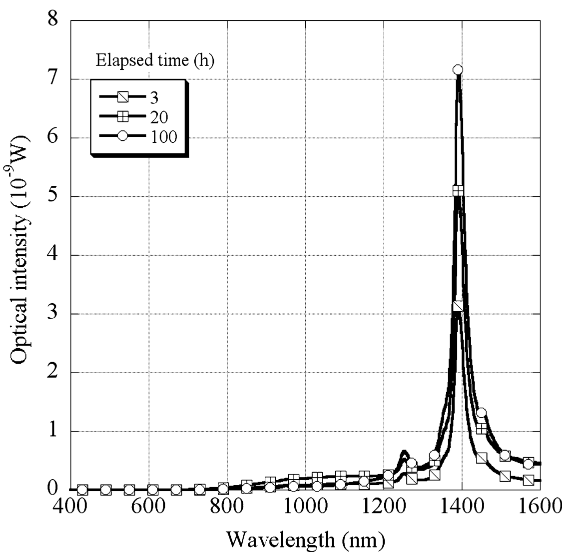

Fig. 4. Optical spectra of pure fiber at 1000 °C as a function of the elapsed time without γ-ray irradiation.

The obtained spectra of middle F-doped fiber kept at 1000 °C without irradiation is shown in Fig. 6. At the elapsed time of 10 h, a broad and small peak appeared at 1200 nm. As the elapsed time increased, the peak shifted to longer wavelength and the intensity increased. As a result, the sharp peak at 1390 nm could not be observed. The result from large F-doped fiber was similar to that of middle F-doped fiber. The experimental results for pure and F-doped fiber are clearly different as seen in Figs. 4 and 6. All fibers have the same fluorine-doped clad. Therefore, it is considered that the difference of these spectra when temperature was kept at 1000 °C was caused by the difference of their core, that is, pure and F-doped silica. It has been

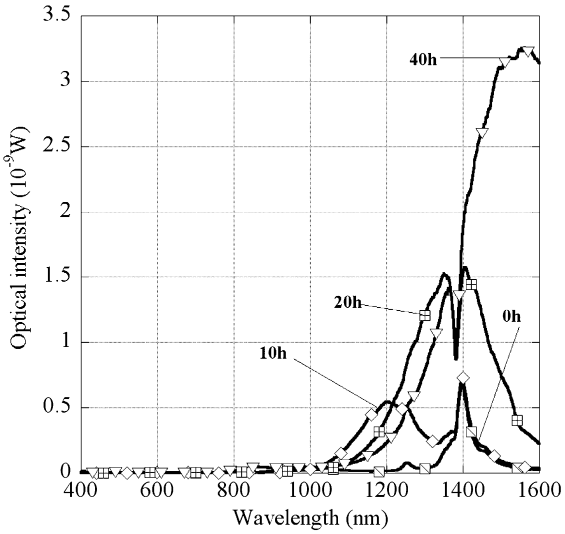

Fig. 6. Optical spectra of middle F-doped fiber at 1000 °C as a function of the elapsed time without γ-ray irradiation.

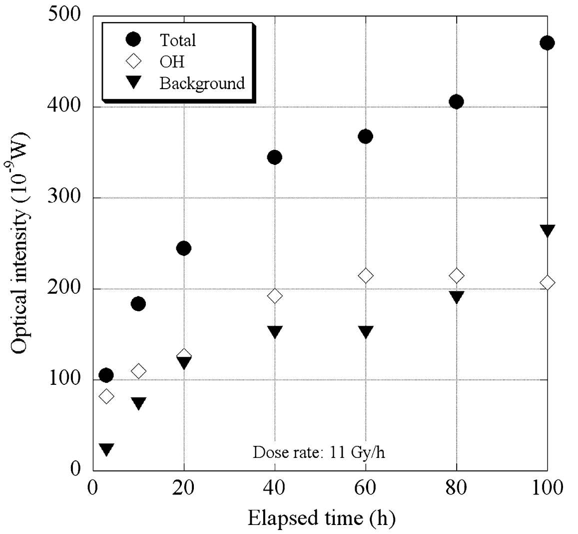

Fig. 8. Time dependence of optical intensity of pure fiber at 1390 nm with irradiation.

reported that devitrification occurred and crystals grew in optical fiber above 850 °C [7] and that dopant in the core was the main element initiating nucleation within the glass matrix [7,8]. In Fig. 6, nucleation and crystal growth in fluorine-doped core could account for the growth and shift of the peak with the elapsed time. F-doped fiber cannot be used in a high temperature environment such as at 1000 °C though the F-doped fiber has good radiation resistance.

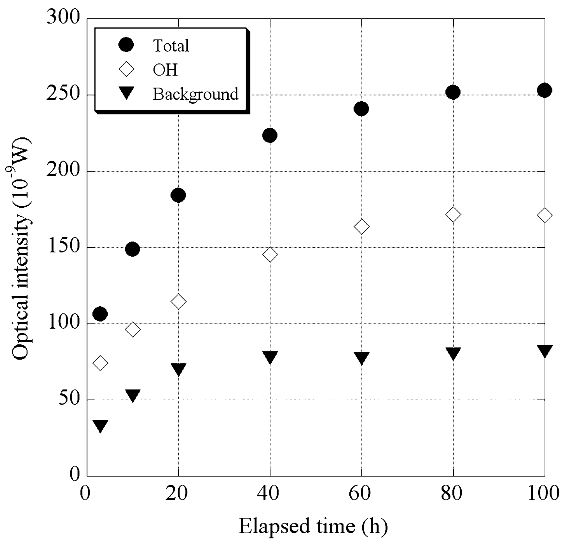

Fig. 7. Time dependence of optical intensity of pure fiber at 1390 nm without irradiation.

Figs. 7 and 8 show the elapsed time dependence of pure fiber at 1390 nm kept at 1000 °C without and with irradiation, respectively. The optical signal of the peak at 1390 nm consists of the optical signal arising from OH and the background. In these figures, the background is calculated from Planck's radiation theory and the OH is calculated by subtracting the background from the intensity at 1390 nm. In Fig. 7, the intensity of 1390 nm, OH and background were saturated as the elapsed time increased. The background was approximately half of the OH at all elapsed times. Thus, the intensity at 1390 nm mainly depends on the OH without irradiation. With γ-ray irradiation, the optical intensity at 1390 nm and the background increased as the elapsed time increased though the OH was saturated. Most of the intensity at 1390 nm arise from OH at first. However, the increasing rate of background with irradiation is larger than that without irradiation as seen in Figs. 7 and 8. Therefore, not only OH but also background contributed to the intensity at 1390 nm as the elapsed time increased in Fig. 8 and the intensity at 1390 nm was not saturated because of the increase of the background with irradiation. It was confirmed that there was no clear difference in the time dependence of the calculated intensity of OH in pure fiber kept at 1000 °C between with and without γ-ray irradiation. In consequence, it is available to measure the temperature by the calculated intensity of OH. However, the change of the intensity with the elapsed time is a problem for a measurement instrument. It was already noted that the OH in optical fiber depends on the experimental atmosphere. Thus, it is assumed that the intensity of OH can keep a constant value in the high temperature environment by using the jacket that has a good temperature resistance and can prevent the amount of OH in pure fiber from changing.

4. Conclusions

The thermal radiation and luminescence of optical fiber itself under changing temperature up to 1000 °C was measured with and without γ-ray irradiation. The three types of optical fiber used in this experiment – pure, moderate and large amount of F-doped fiber – have similar luminescent peaks whose wavelengths are at 1240 and 1390 nm. The thermal radiation based on Planck's radiation theory has also been measured over the whole wavelength range. The optical intensities of all fibers at 1390 nm have a temperature dependence up to 1000 °C. When the temperature of F-doped fiber was kept at 1000 °C, a peak that arises from the nucleation and growth of dopant crystals in the core is generated and grows, and the peak at 1390 nm could not be observed. In the case of pure fiber, the thermal radiation became larger as the elapsed time increased with γ-ray irradiation, though that without irradiation was not so large. The intensity of the peak at 1390 nm with irradiation increased as the result of the increase of the thermal radiation. However, the calculated intensities of OH have the same temperature dependence with and without irradiation and are consequently a candidate for use as a temperature measurement probe in high temperature environment.

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