ELSEVIER

Fusion Engineering and Design 51–52 (2000) 179–183

Fusion Engineering and Design

www.elsevier.com/locate/fusengdes

Behavior of developed radiation-resistant silica-core optical fibers under fission reactor irradiation

Tatsuo Shikama [a],*, Tsunemi Kakuta [b], Naoki Shamoto [c], Minoru Narui [a], Tsutomu Sagawa [d]

[a] *Oarai Branchi, IMR, Tohoku University, Oarai, Ibaraki, 311-1313, Japan*
[b] *JAERI Tokai, Tokai, Ibaraki, 319-1195, Japan*
[c] *Fujikura Ltd., Sakura, Chiba, 285, Japan*
[d] *JAERI Oarai, Oarai, Ibaraki, 311-1394, Japan*

Abstract

Oxyhydrate (OH) doped and fluorine (F) doped fused-silica core optical fibers were irradiated in a fission reactor at 370–380 K with a fast neutron flux of about 5×10^{16}n/m^{2}s and a gamma-ray dose rate of about 500 Gy/s for about 24 days. Oxyhydrate and fluorine dopings improved radiation resistance of optical fibers especially in the visible range. A fluorine doped and heat-treated optical fiber showed best radiation resistance and its radiation induced loss in a visible range is about 20 dB/m after it was irradiated up to a fast neutron fluence of 1×10^{23} n/m^2. Results are implying that fused silica core optical fibers can be used nearer to a burning plasma for plasma diagnostics and remote sensing. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Optical fibers; Plasma diagnostics; Remote sensing; Radiation resistance; A fission reactor radiation; Doping effects

---

1. Introduction

Optical fibers have substantial potential for applications in radiation environments in nuclear fusion reactors. Fused-silica(SiO_2) core optical fibers are promising candidates but they are in general thought to be vulnerable to heavy irradiation especially associated with neutrons. Degradation of optical transmission in the visible range has been reported to be in the range of 100 dB/m at a fast neutron fluence less than 10^{21}n/m^2 [1]. In an Engineering Design Activity of International Thermonuclear Experimental Reactor (ITER-EDA) [2], optical fibers have been considered as a backup system and they were planned to be used only in places where a radiation dose rate is low, such as out of a bioshield, where a fast neutron flux is marginal.

However, it is unanimous that optical systems using optical fibers will make diagnostic systems more reliable, simpler and far less expensive. Furthermore, as shown in the previous conference on optical measurements of temperatures [3], optical fibers can be used as compact monitoring (remote

---

* Corresponding author. Tel.: +81-29-2673181; fax: +81-29-2674947.

E-mail address: shikama@imr.tohoku.ac.jp (T. Shikama).

PII: S0920-3796(00)00463-4

sensing) tools for nuclear fusion reactor environments, being free from disturbances by electromagneticaly-inductive noises. Examples will be monitors of temperatures, gamma-ray dose rates, plasma powers, strains, electric and magnetic fields, etc. [4].

Efforts to improve radiation resistance of fused silica core optical fibers (hereafter described simply as optical fibers) has been made in these 10 years. Doping techniques were found effective under gamma-ray irradiation [5]. However, previously-developed doped optical fibers showed weak radiation resistance under neutron associated radiation, and pure optical fibers especially with smallest contamination of oxyhydrate (OH) and chlorine (Cl) were recommended [2,6] for application in neutron associated radiation environments.

There are many structural and compositional imperfections in fused silica optical fibers, through chemically non-stoichiometry, micro-distortions, internal stresses caused by rapid cooling, formation of dangling bonds, impurities contamination, etc. Many of these imperfections will play as precursors for optical imperfections and will be activated by ionizing radiation to form optical absorption centers. Imperfections will also increase susceptibility to radiolysis with the result of introduction of more and more precursors in the course of high-dose-rates radiation. A fused silica is known to be far more susceptible to radiolysis than crystallized quartz. Then, decreasing imperfections as well as curing imperfections will improve radiation resistance of optical fibers.

Recent experiments showed promising results of improvement of radiation resistance of optical fibers especially for doped with fluorine (F) [7]. The paper will describe behavior of developed radiation-resistant optical fiber under a fission reactor radiation. Especially, fluorine doping effects will be described in detail.

2. Experimental procedures

Doping techniques and fabrication-process controls are thought to be effective measures to improve their radiation resistance of optical fibers. In the present studies, effects of oxyhydrate (OH) and fluorine (F) dopings on purified fused silica optical fibers were studied. Depending on results of neutron irradiation tests on trially-developed doped optical fibers [5,8,9], nine kinds of silica core optical fibers shown in Table 1 were made and they were radiation-tested in a Japan Materials Testing Reactor (JMTR). Fluorine (F) and oxyhydrate (OH) were selected as a doping agent, as the former is thought to improve radiation resistance in visible wavelength range [5] and the latter in infrared ranges [9] from previous experiments.

Two different manufacturing methods were adopted for OH doped optical fibers, a plasma assisted deposition (PAD) method and a direct method. Doped OH concentrations are < 2, 150 and 300 ppm for the PAD method and 300 and 800 ppm for the direct method. Fluorine doped optical fibers were made by a Vertical Axial De-

Table 1
Parameters of fused silica core optical fibers manufactured in the present study

Sample	OH content (ppm)	Fluorine content	Fabrication method of core silica
S-0	<2	None	Plasma-assisted deposition
OH-1	150	None	Plasma-assisted deposition
OH-2	300		
OH-3	300	None	Direct
OH-4	800		
F-1	<2	Small	VAD-A
F-2	<2	Middle	
F-3	<2	Large	
F-4	<2	Middle	VAD-B

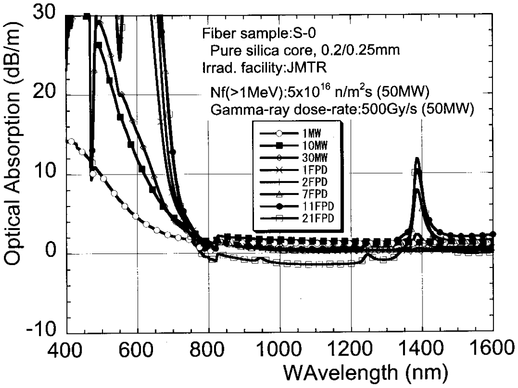

Fig. 1. Optical absorption spectra of S-0 fiber. Absorption change in the course of irradiation as a function of irradiation time, FPD, reactor full power day.

position (VAD) method with F concentration up to higher than 5%. F-1, F-2, and F-3 have different concentration-levels of fluorine. F-4 has the same fluorine concentration as F-2, but it was heat-treated after drawing.

Special care was taken to decrease concentration of contaminated chlorine as low as possible, for all specimens. All specimens have a fluorine doped cladding and a plastic jacket, with core and cladding diameters of 0.2 and 0.25 mm, respectively.

Developed optical fibers of about 1 m long, with two 20 m long pig tails, were accommodated in an instrumented irradiation rig and were inserted into a reactor core region of JMTR in Oarai Research Establishment of Japan Atomic Energy Research Institute. For optical signal transmission between a reactor core and measuring instruments, above-mentioned pig tails of 20 m long were used, whose exposure dose rates to fast neutrons and gamma-rays are negligible compared with those in a reactor core region. A fast ($E > 1$ MeV) neutron flux was about 5×10^{16}n/m^{2}s and a gamma-ray dose rate was about 500 Gy/s. Irradiation was carried out for 24 days with a reactor full power of 50 MW. A temperature of specimens were monitored by a thermocouple and it was controlled to be about 370–380 K during a reactor irradiation. Optical transmission loss and optical luminescence were measured in-situ under reactor irradiation in the wavelength range of 300–1850 nm. Detailed experimental setup could be found elsewhere [7–9]

3. Results and discussion

Fig. 1 shows radiation induced optical absorption spectra of S-0 optical fiber, whose initial OH concentration is less than 2 ppm. Large radiation induced optical absorption peak or peaks grew rapidly in the course of radiation in the wavelength range shorter than 700 nm, which was a permanent effect. In this case, absorption peaked at below 400 nm was dominant and a well-known absorption peak called Non-Bridging-Oxygen-Hole-Center (NBOHC) peak was not clearly identified at about 600–650 nm. Radiation induced absorption below 700 nm exceeded a dynamic range of a present measuring system, about 50 dB in an early stage of irradiation, namely during startup period before the reactor reached its full power of 50 MW. There, an estimated fast neutron fluence and a gamma-ray dose were about 5×10^{19}n/m^2 and 5 MGy, respectively. In the meantime, radiation induced optical absorption in infrared range, 800–1200 nm was very small, a few dB/m as shown in Fig. 1.

In case of Co^{60} gamma-rays radiation tests at 300 K, radiation induced absorption increased to a level of 1 dB/m(10^{3}dB/km) at a total ionizing dose of 1×10^5Gy and then a growing rate of absorption showed clear saturation behavior. A magnitude of radiation induced loss in a visible range is about 10 dB/m at 1 MGy [5]. Thus, neutron associated radiation (a fission reactor radiation, which will be more relevant to a fusion radiation environments than a pure gamma-ray radiation) seems more effective to introduce optical absorption in a visible range. However, we should be careful to compare results of a fission reactor radiation and those of a pure gamma-ray radiation. In general, estimation of ionizing radiation dose rate in a fission reactor is not easy and we rely heavily on calculated estimation. Also, a gamma-ray radiation is usually carried out at room temperature with relatively long optical fibers, namely longer than a few tens of meters. In the meantime, a short optical fiber of about 1 m long will be irradiated at elevated temperatures in a fission reactor. A magnitude and a spectrum of radiation induced optical loss in a visible range were found to depend strongly on irradiation temperatures [10].

Fig. 2 shows radiation induced optical absorption spectra of S-4 optical fiber, whose initial OH concentration was 800 ppm. The OH doping clearly improved radiation resistance in the visible range. A radiation induced absorption below 700 nm exceeded the dynamic range of the measuring system of about 50 dB only after it was irradiated for seven reactor full power days (FPDs), namely total fast neutron fluence of about 3×10^{22} n/m^2. Fig. 2 also shows change of absorption spectrum compared with S-0 optical fiber in Fig. 1. In the OH doped optical fibers, radiation induced absorption peaked below 400 nm was strongly suppressed and the NBOHC absorption peak could be clearly observed in the beginning of irradiation.

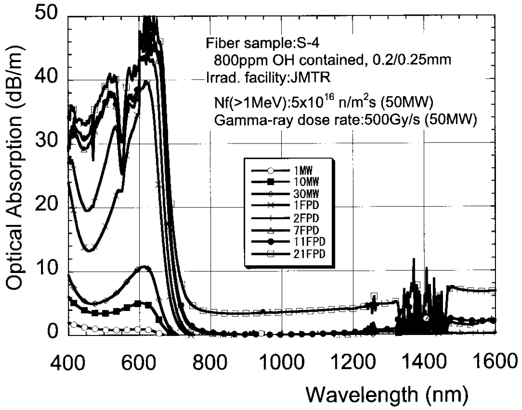

Fig. 2. Optical absorption spectra of S-4 fiber.

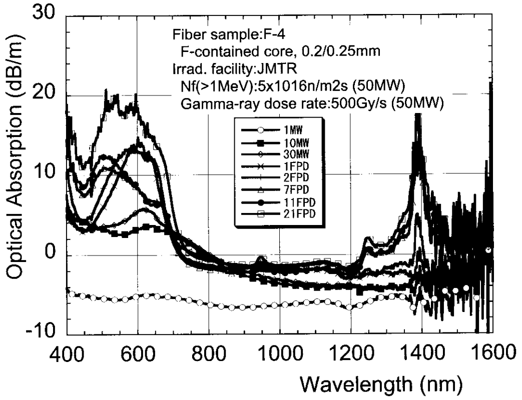

Fig. 3. Optical absorption spectra of F-4 fiber.

The OH doping caused so-called radiation hardening in a infrared range of 800–1200 nm. Namely, optical transmission was improved in the initial stage of irradiation. However, radiation induced permanent optical absorption, which would increase linearly with increase of the radiation dose, exceeded initial improvement at about 10 FPDs. A radiation induced optical absorption in 800–1200 nm was about 10 dB/m at a fast neutron fluence of 1×10^{23} n/m^2.

When results on S-2 optical fiber made by a PAD with 300 ppm OH with those on S-3 made by a direct method with 300 ppm OH, no significant difference could be identified, though there are some differences in details. So, a manufacturing process here may not play an important role.

Fig. 3 shows radiation induced optical absorption spectra of F-4 optical fiber. Improvement of radiation resistance of F-4 fiber is remarkable, compared with no-doped S-0 in Fig. 1 and OH-doped S-4 in Fig. 2. Radiation induced optical absorption was about 20 dB/m at a fast neutron fluence of 1×10^{23} n/m^2. A radiation hardening effect could be observed at an initial stage of irradiation in the wavelength range of 400–1400 nm. Optical transmissivity in 800–1200 nm was rather improved up to a fast neutron fluence of 1×10^{23} n/m^2. Above 1200 nm, measurements were disturbed by increase of OH absorption and data-scatters. The observed data-scatters above 1200 nm is considered due to micro-bending losses. F-4 fiber has a relatively high fluorine concentration and difference of optical reflection index between its core and cladding is small, thus it is expected to be susceptible to a micro-bending loss. In the instrumented irradiation rig, tested optical fibers were bent with a curvature of about 50 mm, which will cause internal stress in the fibers.

Fig. 4 shows radiation induced optical absorption spectra of F-2 optical fibers, which has the same fluorine concentration as F-4, but was not heat treated after drawing procedures. It is clear that F-4 has better radiation resistance than F-2,

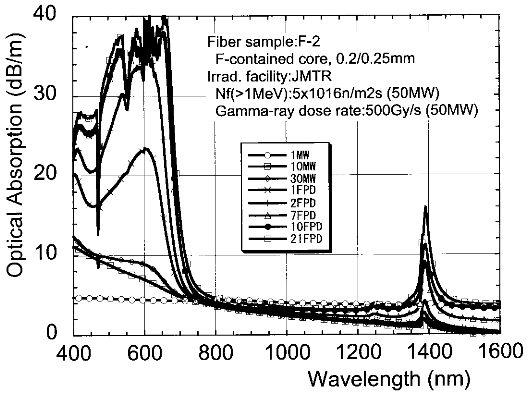

Fig. 4. Optical absorption spectra of F-2 fiber.

that can be interpreted that not only fluorine doping but also heat treatment has improved radiation resistance of F-4. OH and F are supposed to cure structural defects related with oxygen deficits. The present results will support that a doping technique associated with an appropriate heat-treatment is effective to cure structural imperfections and decrease concentration of precursors which will be activated to optical absorption centers by radiation. Also, the present technique improved resistance to radiation damage caused by energetic neutrons, when results are compared with previous ones.

4. Conclusion

Presently developed fused silica core optical fibers showed good radiation resistance in a fission reactor radiation, up to a fast neutron fluence of 1×10^{23} n/m^2 Especially, fluorine doped and heat-treated optical fibers showed best radiation resistance. Results indicated that the doping will be effective to neutron associated radiation damage. Visible observation could be realized with the F-doped heat treated optical fibers up to a fast neutron fluence of 1×10^{23} n/m^2. In the case of plasma diagnostics and remote sensing in nuclear fusion devices, results indicated that optical fibers could be used near to a burning plasma, probably inside of a vacuum vessel.

References

[1] E.H. Farnum, T. Shikama compiled, Dynamic Effects of Irradiation in Ceramics, A US/Japan Workshop, Santa Fe, New Mexico, 11–14 November 1992, LA-UR-92-4400, Los Alamos National Laboratory, New Mexico, 1992.
[2] S. Yamamoto, Radiation Effects on Diagnostic Components, “ITER-EDA, Design Description Document, WBS 5.5M, ITER-JWS-Garching, Germany, 1998.
[3] F. Jensen, T. Kakuta, T. Shikama, T. Sagawa, M. Narui, M. Nakazawa, Fus. Eng. Des. 42C (1998) 449.
[4] M.I. Belovolv, ITER-T-492 Task Related Optical Fiber Meetings, 7–9 July 1999, Moscow, to be compiled by S Yamamoto as ITER-EDA-Task report in, 1999, p. 1999.
[5] T. Kakuta, K. Ara, N. Shamoto, T. Tsumanuma, K. Sanada, K. Inada, Fujikura Giho 50 (1994) 86.
[6] D.W. Cooke, B.L. Bennett, E.H. Farnum, J. Nucl. Mater. unknown (1996) 232.
[7] T. Shikama, et al., presented at VSJ-SPIE Int. Conf. on Optical Technology and Image Processing in Fluid, Thermal and Combustion Flow, 7–9 December 1998, 1998 Yokohama, Japan.
[8] T. Shikama, T. Kakuta, M. Narui, T. Sagawa, N. Shamoto, T. Uramoto, K. Sanada, H. Kayano, J. Nucl. Mater. 421 (1994) 212–215.
[9] T. Shikama, T. Kakuta, M. Narui, T. Sagawa, J. Nucl. Mater. 1800 (1998) 253.
[10] T. Kakuta, private communication, to be published in J. Nucl. Mater.