Optical Fibers for Application in Diagnostics for Burning Plasmas

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Abstract. Attempts have been made to develop fused-silica-core optical fibers which can be used in burning plasma fusion devices such as International Thermonuclear Experimental Reactor (ITER). Nine kinds of silica core optical fibers were developed and irradiated in a high flux fission reactor. A transmission loss of one of fluorine doped optical fiber, F-4, was less than 20dB/m at 630nm even at the end of irradiation where a total ionizing irradiation dose was above 10^9Gy and a fast neutron fluence was above 10^{23}n/m^2. These irradiation parameters will be corresponding to those for the ITER-Engineering-Phase radiation parameters near its core region. The results showed that optical fibers could be applied near to burning plasma for visible as well as infrared diagnostics.

1. Introduction

Reliable plasma diagnostics under heavy irradiation environments are indispensable for establishing nuclear fusion technologies, for which International Thermonuclear Experimental Reactor (ITER) is expected to play important roles. Optical diagnostics have been one of key technologies for plasma diagnostics in conventional non-burning fusion devices, however, they are considered to be seriously vulnerable to radiation damages. An optical fiber has been thought to be one of the most vulnerable optical components until recently. At the beginning of the ITER Engineering Design Phase (ITER-EDA) in 1992, optical fibers were evaluated to be only usable, out of a bio-shield in ITER, due to a large radiation induced optical loss [1]. At that time, optical fibers, made of fused silica (glassy structure silicon dioxide (SiO_2)), were irradiation-tested in electronic-excitation dominant irradiation fields. The maximum electronic excitation dose rate is in the range of a few Gy/s, which will correspond to the electronic excitation dose rate just inside the bio-shield in ITER. Irradiation tests revealed large radiation induced optical loss of about 5dB/kGy in the visible wavelength range and 0.1-0.01dB/kGy in the infrared wavelength range, under cobalt-60 gamma-ray irradiations. Taking neutron effects into account, optical fibers were judged to be only usable for a reasonable period, out of the bio-shield [2].

When optical fibers are excluded from diagnostic components near burning plasmas in ITER, only a periscope type device could be a candidate for optical diagnostics near burning plasmas. However, it will mean that the mechanically-weak optical window must compose a part of the primary pressure boundary, even though the design can place those windows far away from the burning plasma. Also, complicated labyrinth-configuration must be applied to mitigate intensities of strayed neutrons through optical channels. A series of geometrically arranged mirrors must guide weak optical signals through labyrinths. There, strong temperature gradient generated by localized nuclear heating will easily distort these vulnerable mirror arrangements. Important optical diagnostics are expected at divertor regions in ITER. There, space limitation is severe and a periscope-type component will make the structure of the divertor very unreasonable, from many aspects such as construction and maintenance.

Optical fibers can be applied as other diagnostic fields such as temperature monitoring [3]. Temperature would be measured in ITER mainly by conventional thermocouples, whose thermo-electromotive force will be easily disturbed by electromagnetic noises and radiation induced electrical noises. Radiation effects will generate several luminescent phenomena in the optical fibers. A Cerenkov-radiation is a typical one, whose intensity should be proportional to the electronic excitation dose rate, which is, in general, proportional to the nuclear power of the fusion devices. There are some other radiation induced luminescence (radioluminescence) peaks in optical fibers, whose intensities would be related with nuclear dosimetric-parameters[4,5,6].

The present paper describes results of irradiation tests of optical fibers developed, being based on obtained results of irradiation tests of up to now [4,5,6,7]. Some of the optical fibers revealed good radiation resistance even in a fission reactor irradiation. Especially, a promising behavior of one fluorine(F)-doped optical fiber will be described, which showed good radiation resistance in the wavelength range from the visible region to an infrared region up to more than 10^9Gy of ionizing radiation and up to more than 10^{23}n/m^2 of fast neutron fluence. The fluorine-doped optical fiber was nominated as one of international-round-robin fibers for the ITER-EDA. It was supplied to each home team of the ITER-EDA and will be irradiation-tested with internationally standardized experimental procedures, with other round-robin fibers supplied by the European Community(EU)- and the Russian Federation(RF)-home teams[8].

2. Experimental Procedures

Nine kinds of silica core optical fibers were irradiated in Japan Materials Testing Reactor (JMTR) in Oarai Research Establishment of Japan Atomic Energy Research Institute (JAERI). Main features of the irradiated optical fibers are tabulated in Table 1. One group of optical fibers is oxyhydrate (OH) doped(OH-1 to OH-4), and the other group is doped with Fluorine (F) (F-1 to F-4). A standard sample (S-0) is non-doped, making OH concentration as low as possible. OH and F doping agents were found to improve radiation resistance of silica core optical fibers in gamma-ray radiation [7]. They are also found to cause a so-called radiation hardening in the course of gamma-ray irradiation. The radiation hardening is a phenomenon that an optical transmission loss initially increases but subsequently decreases with increase of an accumulated radiation dose.

TAB 1: PARAMETERS OF OPTICAL FIBERS

Sample	OH content (pm)	Fluorine content	Manufacture method
S-0	<2	None	PAD
OH-1	150	None	PAD
OH-2	300	None	PAD
OH-3	300	None	Direct
OH-4	800	None	Direct
F-1	<2	Small	VAD-A
F-2	<2	Middle	VAD-A
F-3	<2	Large	VAD-A
F-4	<2	Middle	VAD-B

The fluorine doping improved radiation resistance especially in the visible and the ultraviolet regions in the case of gamma-ray irradiation. Although recent results in a JMTR irradiation revealed inferior behavior of fluorine doped (F-doped) fiber compared with OH doped fiber in a infrared region [6], the F-doping will still be one of candidate procedures for improving radiation resistance especially for visible applications. Some of high-energy neutron associated irradiation showed inferior behavior of OH-doped (hydrated) fibers compared with low OH concentration fibers (anhydrated) [2]. However, previous results showed that OH-doping caused the phenomenon of radiation hardening even in a fission reactor radiation [6]. Also, some of OH-doped optical fibers showed better radiation resistance, compared with F-doped and non-doped ones, in infrared region, in previous JMTR irradiations.

The standard (S-0) and some of the OH-doped optical fibers (OH-1 and 2), whose OH concentration is low, were made by a plasma-assisted deposition (PAD) method. The OH-doped fibers of OH-3 and 4 were made by a direct method. The F-doped fibers (F-1 to F-4) were made by a vapor axial deposition (VAD) method, having different concentration of fluorine. F-1 has the lowest, F-2 has the middle and the F-3 has the largest fluorine concentration. F-4 has different sintering and annealing procedures from the other ones and has the same fluorine concentration as that of F-2. All the examined optical fibers have an identical cladding of fluorine doped fused silica. The optical fibers were inserted into a reactor, and their optical transmission loss was measured during reactor irradiation in the wavelength range of 350-1850nm. Total length of the optical fibers is about 50m, and length of the irradiated part is about 0.5m. Details of experimental setup are described elsewhere [4]. The irradiation temperature was 400K and fluxes of fast ($E>1MeV$) and thermal ($E<0.687eV$) neutrons are 6x10^{16} and 8x10^{16} n/m^{2}s, respectively. An ionizing dose rate is calculated to be about 0.5kGy/s. The total irradiation period is about 26 reactor full power days (FPD).

3. Results and Discussions

Figure 1 shows growth of radiation induced optical transmission loss of the non-doped optical fiber of S-0, in the initial stage of the reactor radiation. Large radiation induced optical

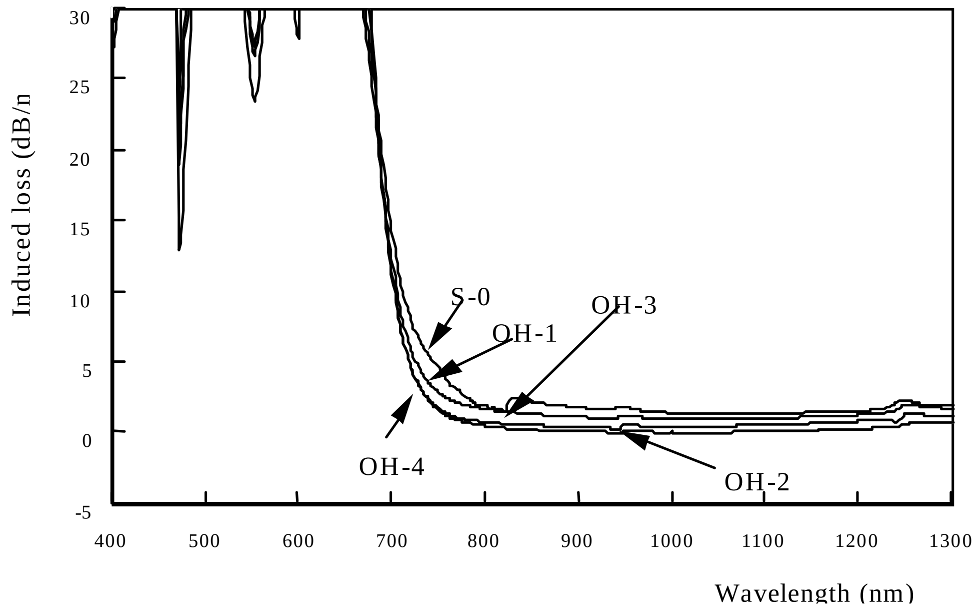

FIG.1 Radiation Induced loss of Reactor Radiation (Hydrated Fibers)

absorption grew in the wavelength below 700nm. The major increase is due to the growth of absorption band centered at about 600-650nm, which is similar to that reported also in gamma-ray irradiation. The responsible optical absorption center is assumed to be non-bridging-oxygen-hole-centers (NBOHC). Results also show a growth of well-known OH-absorption bands in infrared regions, indicating an increase of OH concentration in the course of irradiation. It was reported that the undoped optical fiber whose OH concentration is very low (anhydrated) showed better radiation resistance compared with OH-containing optical fibers (hydrated) in the gamma-ray irradiation as well as a high-energy neutron associated irradiation [2]. Thus, it was recommended to use purified fibers for applications in neutron associated radiation environments [1]. However, the present results clearly show that the OH would be introduced even in an OH-undoped fiber in neutron-associated irradiations.

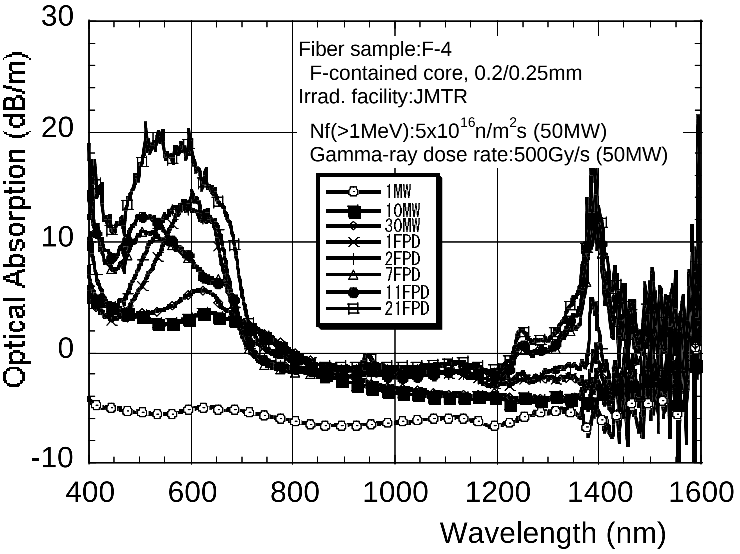

FIG.2 Radiation Induced loss of Reactor Radiation (F-4)

The present results showed that the OH-doped fibers of OH-1 to -4 and the undoped fiber of S-0 behaved similarly in the course of a fission reactor irradiation and that the strong absorption bands grew in the wavelength below 700nm. The S-0 showed large increase in the initial stage of irradiation and the white light from a halogen lamp, which went through the irradiated S-0 fiber, was colored reddish. Thus, the OH-fibers and the S-fiber could not be used for visible application, in neutron-associated heavy irradiation environments, though some of them showed good radiation resistance in the infrared region.

The fluorine doped optical fibers, F-1 to F-4 in Table 1 showed better radiation resistance in visible regions. In general, the white light from the halogen lamp went through the fibers without becoming reddish substantially under JMTR irradiation. However, the fibers of F-1, 2, and 3 grew substantial absorption centered at about 630nm (NBOHC absorption peak). The peak loss was more than 40dB at the end of 26FPD irradiation. Fig. 2 shows behavior of F-4 fiber, which showed the best radiation resistance in the visible region in the present irradiation test. A transmission loss at 630nm was less than 20dB/m even at the end of irradiation where the total ionizing irradiation dose was about 10^9Gy and the fast neutron fluence was about in the range of 10^{23}n/m^2. These irradiation parameters are corresponding to the accumulated radiation doses at the end of the ITER-Engineering-Phase operation in the vicinity of burning plasmas. The F-4 fiber also showed good radiation resistance in the infrared region. Fig. 3 shows the growth of radiation induced optical absorption at 850nm in F-4 in the course of the reactor irradiation. Comparing with the OH-doped and non-doped optical fibers shown in Fig. 1, the fluorine doped fibers (F-1,2,3) showed larger radiation induced loss in the infrared region. Also, the radiation induced large OH absorption bands in infrared regions in the F-doped fibers as shown in Fig. 2. But, the F-4 showed a radiation-hardened behavior, namely improving optical transmissivity under irradiation in the infrared region as shown in Fig. 3. Thus, the F-4 fiber can be applied near burning plasma regions in ITER throughout its operation period, being disturbed, to some extent, by the growth of the OH absorption peaks in the infrared regions and by the NBOHC absorptions in the visible regions.

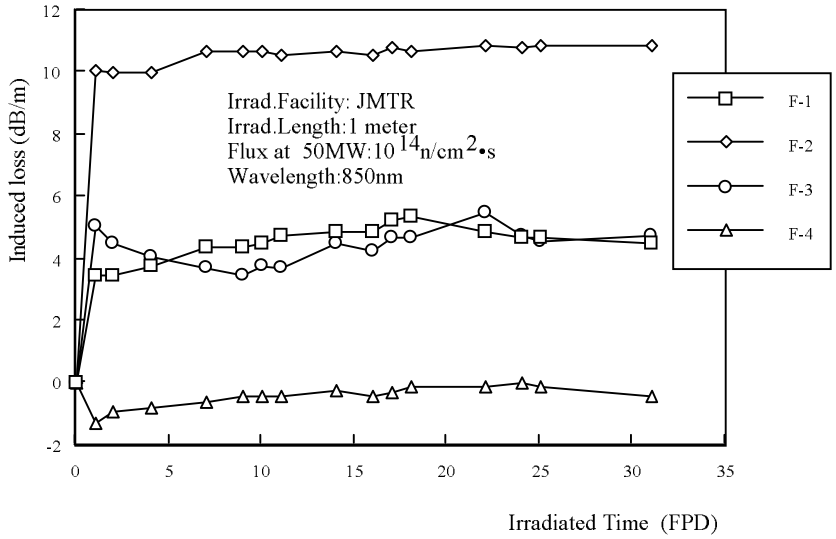

FIG.3 Radiation Induced loss of Fluorine-doped Core Fiber During Reactor Radiation at 850nm

4. Conclusion

Fused silica core optical fibers are under development for applications in burning fusion devices. One fiber, F-4, which was doped with fluorine and was sintered and annealed in special ways, showed good radiation resistance. The results are indicating that F-4 could be applied for visible as well as infrared applications near burning plasmas.

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