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Effect of OH-group content on optical properties of silica core fiber waveguides during reactor irradiation

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Abstract

The transient optical loss (TOL) of silica core optical fiber waveguides of KU-1 grade (Russia, OH content 1000 ppm) and K-3 grade (Japan, OH content 10 ppm) have been measured during pulsed reactor irradiation (BARS-6 pulsed fission reactor (IPPE), pulse 80 μs, dose per pulse $<5.5 \times 10^{12}$ n/cm^2 (9 Gy), dose rate $<7 \times 10^{16}$ n/cm^2 s (1.1×10^5 Gy/s) in the visible range (fixed wavelengths 532 and 632 nm). Strong contribution from the light scattering induced by the irradiation in the silica fibers resulted in TOL. The light scattering is responsible for similarity of the spectral and temporal dependence of TOL of the optical fibers tested. The TOL of the unirradiated silica fibers is lower in the fiber with higher OH-group concentration (KU-1), whereas the difference in TOL of the KU-1 (high OH) and K-3 fiber (low OH) irradiated to a dose of $\approx 10^3$ Gy is not so significant. The lower TOL of the KU-1 fiber is probably due to the effect of OH-groups on phase stability in the trap subsystem.

1. Introduction

Research and development of optical fibers exhibiting sufficient radiation stability and acceptable level of optical loss have become important due to prospective application of the optical fibers for the diagnostics of plasma in fusion reactors even at the dose rates higher than 10^3 Gy/s [1]. The effect of the chemical composition of silica fibers and their pre-treatment on the performance of the optical fibers during various steady-state irradiations is actively studied. However, the performance of the optical fibers during intense pulsed irradiation may be also of great interest. Experiments using the intense pulsed irradiation are necessary to understand mechanisms responsible for transient optical phenomena in the optical fibers and to simulate transient operating conditions, for instance, switching on or shut-down of the plasma in fusion reactors. In this study we conducted measurements of the transient optical loss (TOL, due to both transient optical absorption and light scattering) of silica core optical waveguides with different OH-group concentration in the core during pulsed reactor irradiation.

2. Experimental

The technique of the measurements of TOL of optical fibers under pulsed irradiation of the BARS-6 fission reactor (pulse duration 80 μs, dose per pulse $<5.5 \times 10^{12}$ n/cm^2 (9 Gy), dose rate $<7 \times 10^{16}$ n/cm^2 s (1.1×10^5 Gy/s)) has been presented in [2]. The measuring system provides means of measurement with a resolution time down to 100 ns in the visible range.

Two silica fiber waveguides of KU-1 grade (Fiber Optic Research Centre, Russia, OH content 1000 ppm, core diameter 100 μm, cladding thickness 10 μm) and K-3 grade (Fujikura Ltd., Japan, OH content 10 ppm, F doped, core diameter 200 μm, cladding thickness 25 μm) were used in the experiments. The initial optical absorption coefficients of these fibers in the range of

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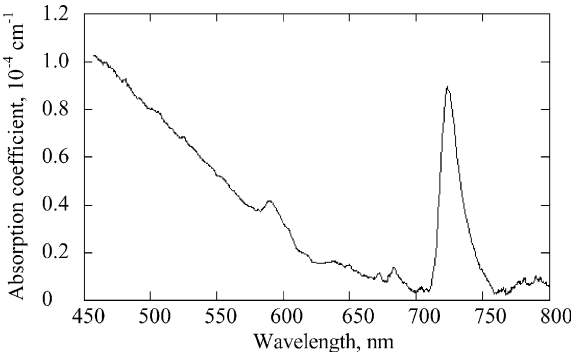

Fig. 1. Initial absorption spectrum of the KU-1 fiber in the visible range.

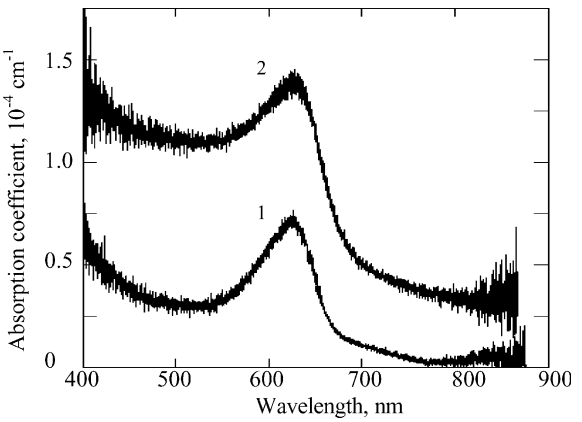

Fig. 2. Absorption spectra of the K-3 fiber in the visible range: (1) initial absorption and (2) absorption after irradiation with the dose of 10^3 Gy.

400–800 nm are given in Figs. 1 and 2. The middle parts of the fibers (length 20 m) were wound on aluminum bobbins, that were placed near the active core of the reactor. The tails of the fibers passed through a hole in a wall from the reactor hall to the measuring system.

To probe the fiber we used two continuous lasers: He–Ne laser (wavelength 632 nm) and AIG:Nd^{3+} laser (second harmonic wavelength 532 nm). The wavelengths chosen correspond (632 nm) or do not correspond (532 nm) to the range where the absorption band attributed to the non-bringing oxygen hole centre [3] is observed on fibers of low OH content (K-3) and not observed on fibers of high OH content (KU-1). The intensity of the probing light coupling to the fiber was about 0.1 W/cm^2, that was much higher than the radioluminescence intensity at the same wavelength [2]. To eliminate radioluminescence at the wavelengths that differ from the wavelength of the probing light, a monochromator was used [2].

The optical signals and the neutron flux were measured simultaneously in our experiments. The neutron pulse was registered by means of an evacuated fission chamber placed in a boron-containing case (for counting neutrons with $E > 0.5$ eV). The dose per pulse was determined from the residual activity of nickel samples. The absorbed dose was calculated with the help of the MCNP code [4] taking into account the energy transfer due to gamma irradiation, the collisions involving neutrons and neutron absorption.

3. Results and discussion

In general, different kinetics of the TOL of the fibers of different OH content has been observed (Fig. 3). In the unirradiated fiber of low OH content (K-3) and the fiber irradiated to a dose of $\approx 10^3$ Gy the TOL reaches 1.5×10^{-3} cm^{-1} at 532 nm and 2×10^{-3} cm^{-1} at 632 nm during the neutron pulses. A further slight increase of the TOL is observed hundreds of milliseconds after neutron pulses. Then the almost full recovery of transparency occurs in tens of seconds.

The TOL is relatively low in the unirradiated fiber of high OH content (KU-1). The TOL at 632 nm reaches 3.5×10^{-4} cm^{-1} during neutron pulses. Several milliseconds after neutron pulses, the TOL slightly decreases with the decay time of ≈ 500 μs. Then the TOL slowly decreases (tens of seconds), and the almost full recovery of transparency is observed. The amplitude of TOL increases up to 6.5×10^{-4} cm^{-1} with the dose increasing to $\approx 10^3$ Gy. Similar TOL behaviour is observed at 532 nm for this fiber irradiated to a dose of $\approx 10^3$ Gy. The amplitude of the TOL at 532 nm is equal to 1.5×10^{-3} cm^{-1}. The TOL of the unirradiated KU-1 fiber was not measured at 532 nm. However, negligible TOL at 488 nm was observed in the initial KU-1 fiber [2].

It seems reasonable not to attribute the different magnitudes of the TOL of two fibers to different damage production rates or different damage types. It is most probable, that the observed time dependence of the TOL shows an evolution of radiation-induced charge carriers, including charge carrier trapping, detrapping and electric polarization. The time dependencies of the TOL at different wavelengths are qualitatively similar for the same fiber, especially for the K-3 fiber. This similarity should not only be due to the common effect of charge carrier evolution, but a common optical process is responsible for TOL in the wide spectral region. It is more preferable to assume, that the optical loss observed is due to the light scattering rather than the level-to-level transitions in colour centres. In [5], the transmission loss of various silica fibers during shots of TFTR (pulse duration ≈ 1 s, dose rate ≈ 1 Gy/s) was also attributed to the light scattering (Rayleigh scattering). As in the present study, it was pointed out in the paper [5] that the

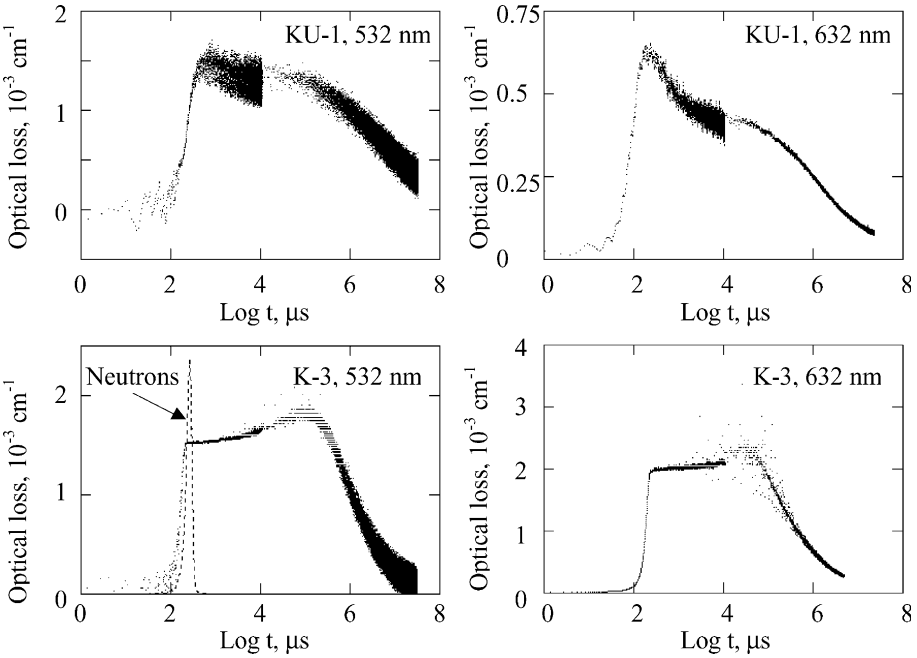

Fig. 3. Time dependence of the TOL induced in the KU-1 and K-3 fibers by the pulsed reactor irradiation. Absorbed dose of 1 kGy.

time behaviour of the transmission loss was complicated, with substantial self-annealing.

As expected for the light scattering, the TOL of the K-3 fiber (unirradiated and irradiated) and irradiated KU-1 fiber is high in the regions where the optical absorption before reactor pulses is high. However, the situation may be opposite for the unirradiated KU-1 fiber. It requires further experiments. Probably, the TOL of the KU-1 fiber is initially concentrated in the region of the 'non-bringing oxygen hole centre' band. It should be noted, that the nature of this band and optical properties in its region are not well enough understood.

It is interesting that the TOL of two fibers shows a transient process at the times from 10^{-3} to 10 s. If the TOL is attributed to the light scattering, then we can conclude, that the transient process is accompanied by the increasing optical inhomogeneity. The optical inhomogeneity was shown to appear in silica glasses during irradiation due to the thermodynamic instability of the uniform distribution of trapped charge carriers (see [6]). In this case, the microscopic regions with relatively low and high concentrations of trapped charge carriers (different phases of the trap subsystem) may appear. Phase transitions in these microscopic regions may be responsible for optical inhomogeneity and light scattering. Also, the observed changes of TOL during the transient process is consistent with the dynamics of an unstable phase decomposition discussed in [7]. According to [7], the dynamics of phase decomposition is divided into three stages: (1) initial exponential growth of the new phase, (2) transient process with abnormally large fluctuations and (3) final exponential decay of the old phase.

Summarising we can propose the following explanation on the TOL. The charge carriers produced in the fiber cores during reactor pulses are immediately trapped and then the causes increase in optical losses (absorption and scattering). High concentrations of the trapped charge carriers and, probably, their spatial distribution are unstable. Initial decay of the trapped charge carrier concentrations after the reactor pulse is clearly seen in the time dependence of TOL of the KU-1 fiber (Fig. 3, decay time ≈500 μs). Due to the unstable spatial distribution of the filled traps, the decomposition in the trap subsystem is initiated right after the reactor pulse (K-3 fiber) or milliseconds after the pulse (KU-1 fiber) and is accompanied by appearance of the optical inhomogeneity. After the transient process the TOL shows the final decay of the trapped charge carriers.

4. Conclusion

The TOL induced by the pulsed reactor irradiation in the KU-1 and K-3 fibers is characterised by a long lifetime (tens of seconds) and may be a problem for diagnostic systems using silica fibers.

A strong contribution from the light scattering in the silica fibers under the pulsed reactor irradiation resulted

in TOL. The light scattering induced by the irradiation is responsible for similarity of the spectral and temporal dependence of TOL of the optical fibers with different chemical compositions and pre-treatments. The TOL of the unirradiated silica fibers is lower in the fiber with a higher OH-group concentration (KU-1), whereas the difference in TOL of the KU-1 (high OH) and K-3 fiber (low OH) irradiated to a dose of $\approx 10^3$ Gy is not so significant.

High concentrations of the trapped charge carriers are responsible for the appearance of the prominent optical inhomogeneity of the silica fibers and increase of the light scattering therein during and after irradiation. High OH-group concentrations partially prevent the radiation-induced optical inhomogeneity, probably owing to the effect on phase stability in the trap subsystem.

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