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Gamma-radiation-induced attenuation of light in pure-silica core optical fiber in long-wavelength region

Abstract. The dependences of the spectra of radiation-induced attenuation (RIA) of light in a pure-silica core (PSC) optical fiber (OF) during and after gamma-irradiation up to 590 kGy at a dose rate of 7.6 Gy/s in the near infrared range have been investigated. It was shown that starting with an absorbed dose of ~100 kGy, the RIA at 1550 nm becomes larger than at 1310 nm due to an increase in long-wavelength (LWL) RIA. The absorption band, with a maximum at a wavelength near 1800 nm, responsible for the LWL RIA is fully defined for the first time. At an absorbed dose of 590 kGy at wavelengths of 1310 and 1550 nm, the RIA is 14.1 and 23.3 dB/km, respectively. During 3.5 years of annealing of the OF at room temperature the RIA in the entire spectral range of 1100-1700 nm decreases by 40-50%. The LWL RIA can be complex, consisting of short-lived and long-lived components. The short-lived component may be LTIRA (low temperature infra-red absorption).
Key words: Optical fibers, radiation-induced attenuation, RIA, pure-silica core fiber, long-wavelength RIA.

Introduction

Optical fibers (OF) have currently found wide application in various fields of science and technology from high-speed information transmission to fiber lasers and precision sensors of various physical quantities. Nevertheless, the use of OFs in nuclear and fusion installations, including the international experimental fusion reactor ITER, leads to degradation of their optical properties due to the appearance of additional radiation-induced attenuation (RIA) of light [1-4]. This phenomenon considerably limits the use of OF in conditions of increased radiation levels and, therefore, there is an urgent need to reduce RIA to an acceptable level for a particular application.

It is known [5] that OFs will be used in the ITER diagnostic systems as transport from fiber-optic sensors operating at a wavelength of λ=1550 nm. When exposed to ionizing radiation, the optical transmittance at this wavelength is significantly reduced due to the long-wavelength (LWL) RIA with a maximum at wavelengths λ>1600 nm. Unfortunately, the physical nature and basic properties of this RIA remain questionable. It is worth noting that it is the LWL RIA that limits the radiation resistance of OF in applications in intense gamma-neutron fields and is a limiting factor for a wider implementation of OF in diagnostic and control systems in nuclear and fusion facilities. Therefore, the study of the mechanisms of occurrence and properties of long- wavelength RIA is an important and urgent task for OF applications at increased levels of ionizing radiation, especially in strong radiation fields.

It is known that the most radiation-resistant are OFs with a pure silica core (PSC) and fluorine-doped silica core [6]. During reactor irradiation, radiation color centers (RCCs) are formed in the glass network of a fiber core, which absorb the light signal propagating through the fiber at the operating wavelength. This is the main cause of the RIA. The relevant wavelength for many OF applications is telecommunication wavelengths of 1310-1550 nm. RIA at these wavelengths is determined by the "tails" of the RCC absorption bands with maximums in the short-wavelength (SWL) and LWL regions. Since the majority of RCCs are located in the visible and UV range, the main works available in the scientific literature [1, 2, 7] are devoted specifically to the study of SWL RIA. And, thus, the main RCCs responsible for SWL RIA, the mechanisms of their formation, and their main properties are known. However, all these data are practically absent in the case of LWL RIA. In general, there are no papers on systematic studies of the properties of LWL RIA in the scientific literature.

It is only known that it is determined by the appearance of an absorption band with a maximum at a wavelength of λ>1700 nm [8]. The amplitude of this band grows monotonically with irradiation and becomes the main mechanism of RIA, limiting the radiation resistance in the near-infrared range at high absorbed doses [8-10], corresponding to applications in reactor facilities.

There are two main hypotheses about the nature of this RIA. The first one was formulated back in the late 1990s and consists in the fact that the LWL RIA, according to the authors [11], is caused by changes in the vibrational spectra of the glass network due to the appearance of structural defects of the three-coordinated silicon atom type due to the breaking of regular Si-O bonds. However, in this case, the RIA would have to grow structureless with increasing wavelength in the 1500-2500 nm wavelength range, but subsequent work has shown that the absorption band of LWL RIA should reach a maximum at 1800-2200 nm [8], with its behavior similar to LTIRA (low temperature infrared-red absorption) [12, 13] of self-trapped holes (self-trapped holes STH). Therefore, a number of papers [8, 9, 14] have suggested that this RIA is also caused by STH absorption. However, it is known that STH have extremely low thermostability [15], and LWL absorption is highly stable even at room temperature.

Hence, the lack of understanding of the physical nature of LWL RIA, the mechanisms of appearance and its properties is a weighty limiting factor for further implementation of fiber-optic controls in applications in intense radiation fields.

This work is devoted to a study of the behavior of LWL RIA in pure-silica-core OF during and after gamma irradiation in the near-infrared range.

Materials and Methods

In Devyatykh Institutute of Chemistry of High-Purity Substances of RAS a preform with a pure-silica-core and a F-doped cladding with refractive index difference $\Delta n \sim 0.0095$ (Figure 1) was made by MCVD (Modified Chemical Vapor Deposition). The reflective cladding (2 in Figure 1) contained about 2 wt% fluorine appearance.

An OF with an outer diameter of 125 µm in acrylate coating was drawn from the preform at the Dianov Fiber Optics Research Center of RAS. Optical loss at a wavelength of 1550 nm did not exceed 0.3 dB/km. The cutoff wavelength of the first higher mode was λ_c=1480 nm.

Investigations of optical loss in the initial and gamma-irradiated lightguide were performed by the "cut-off" technique in the range of 900-2100 nm using a spectral setup based on the MDR-12 monochromator, the light source was a halogen lamp.

To study the RIA spectra, 100 m of OF was wound on a plastic coil 160 mm in diameter and 100 mm in height. The OF was irradiated with a ^{60}Co γ-source with an average gamma-quantum energy of 1.25 MeV at a dose rate of 7.6 Gy/s. The entire irradiation process can be divided into two stages. In the first one, the OF was irradiated for 180 min followed by relaxation for 30 min. In the second one, the OF was irradiated for 1112 min followed by relaxation for 15 min. The irradiation was conducted at +25°C until the time of 1082 min, after which the temperature increased to +40°C when the ventilation was switched off.

Near-infrared spectra were recorded using an Avantes AvaNIR 128 spectrometer (900-1700 nm) with a HL-2000 halogen lamp as the light source. In the first stage of the irradiation, the recording step was 1 min, and in the second stage, 30 min, except for the second relaxation, where the step was also 1 min. To minimize the photobleaching phenomenon, the visible light was cut off using a λ>900 nm filter, so that the injected light power did not exceed 0.5 μW. The absorbed dose for the whole irradiation was ~590 kGy. The spectra of total optical loss of the irradiated OF were taken after 3.5 years of irradiation.

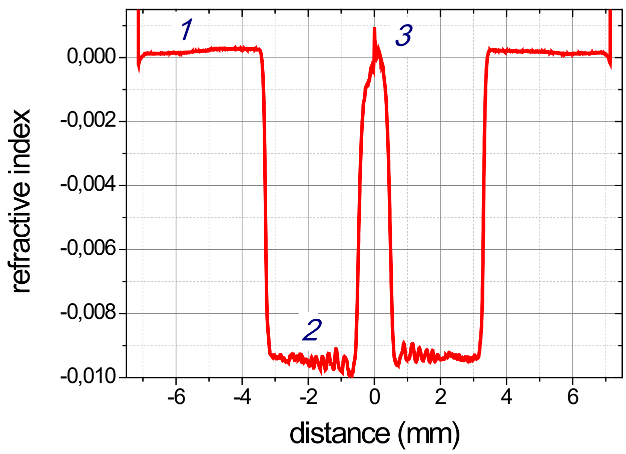

Figure 1 – Fiber refractive-index profile:
1- substrate tube, 2- F-doped reflective cladding, 3- pure silica core.

Results and Discussion

Figure 2 shows the dependence of RIA during irradiation and relaxation at wavelengths of 1310 nm and 1550 nm. At the first stage of irradiation RIA (up to 180 min) at wavelength 1310 nm is greater than at 1550 nm. At the very beginning of gamma exposure there is a sharp increase in RIA up to absorbed dose ~3.7 kGy (point 1 on Figure 2), after that RIA begins to decrease, herewith so-called transient absorption is greater at 1310 nm, at maximum it reaches 17.5 dB/km.

The spectra (Figure 3a) show that this RIA is due to the absorption band with a maximum at wavelengths λ<1000 nm. This dependence of the RIA is standard for PSC OF [16-18]. This behavior is known to be characteristic of the absorption of self-trapped holes STH, which have absorption bands at 660 and 760 nm [15, 16]. The rapid relaxation after 180 min of irradiation is also due to the thermal decay of STH at room temperature because of their low thermal stability [15, 19].

We can see from the spectra (Figure 3a) that the SWL RIA tail from STH actually decreases during irradiation (spectra 1, 2) and relaxation (spectrum 3). However, the spectra also show that the LWL RIA begins to grow as well. The LWL RIA is due to the relaxation of loss at 1550 nm to a higher level (Figures 2 and 3a).

At the beginning of the second stage of irradiation we see a similar picture: RIA at 1310 nm increases sharply up to the level of 15 dB/km and then begins to decrease during irradiation (Figures 2 and 3b). Starting with an absorbed dose of 96.7 kGy (242 min. in Figure 2) the RIA at 1550 nm wavelength already becomes larger than at 1310 nm. The spectra (Figure 3b) show that this is due to the fact that the LWL RIA begins to prevail over the SWL RIA. Similar RIA kinetics are also observed during reactor irradiation of OF [3,4], which suggests similar mechanisms for the appearance of LWL RIA during both gamma- and mixed gamma-neutron irradiation.

Interesting is the behavior of RIA when the temperature increases from 25 to 40 °C (points 5-6 in Figure 2). It can be seen that there is a decrease in RIA caused by the thermal decay of the RCC. The spectra (Figure 3b) show that the SWL tail mainly decreases, indicating the low thermal stability of STH. However, there is a small relaxation in the LWL region as well (Figure 2). Indeed, it was shown in [3] that increasing the temperature during reactor irradiation from 200 to 350 °C results in a 15-30% decrease in RIA at the 1550 nm wavelength. Therefore, increasing the temperature can be used to reduce the LWL RIA.

After stopping irradiation at an absorbed dose of 590 kGy for 15 minutes, relaxation of RIA occurs at both wavelengths (Figure 2). From RIA spectra (Fig. 3b) one can see that the SWL tail relaxes to a greater extent and the LWL one much less. At an absorbed dose of 590 kGy, the RIA at 1310 nm was 14.1 dB/km and 23.3 dB/km at 1550 nm. After 15 minutes of relaxation, the RIA at 1310 and 1550 nm was 11.1 and 20.7 dB/km, respectively. The presence of a fast relaxation component of the LWL absorption (Figure 3b) may indicate that the LWL RIA is complex, the fast component of which may be LTIRA (low temperature infra-red absorption) [12], whose maximum band also lies in the spectral region of λ>1700 nm.

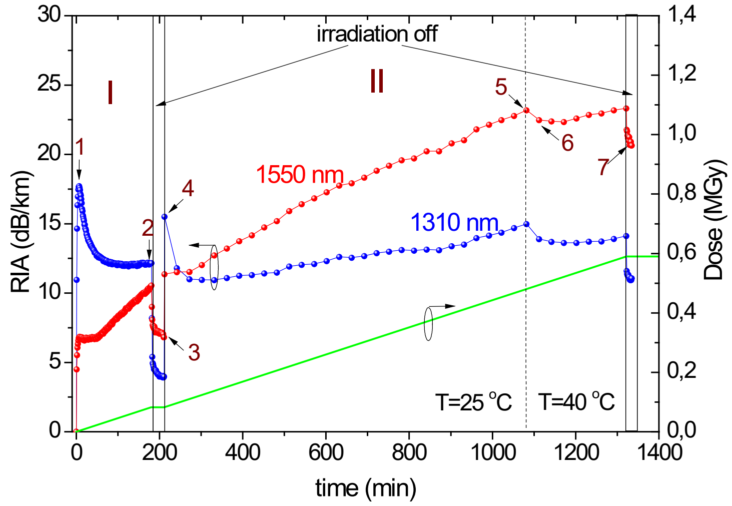

Figure 2 – RIA and dose (green curve) evolution with time of irradiation and post-irradiation recovery at wavelengths 1310 nm (red curve), 1550 nm (blue curve).

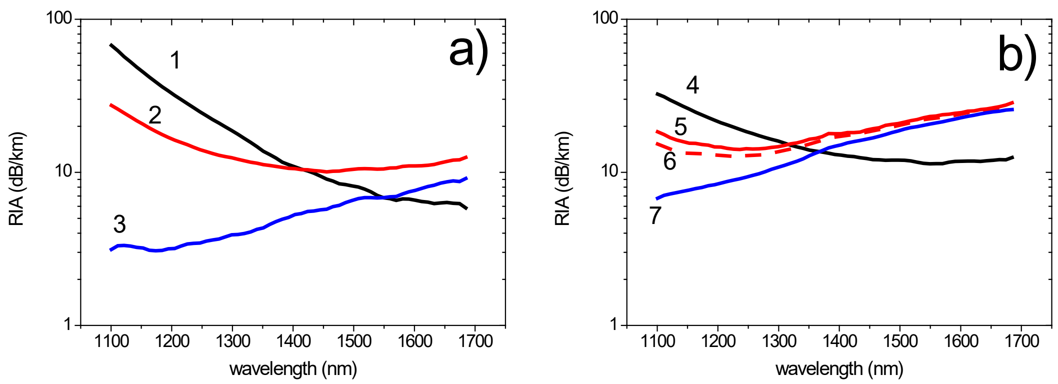

Figure 3 – a) RIA spectra during irradiation and relaxation at I stage of irradiation (points 1 – 3.7 kGy, 2 – 82 kGy, 3 – 30 min of relaxation after 82 kGy,), b) – at II stage of irradiation 4 – 82.5 kGy, 5- 479.7 kGy, 6 – 480.2 kGy, 7 – 15 min of relaxation after 590 kGy). Temperature T=25 °C for spectra 1-5 and T=40 °C for -6-7.

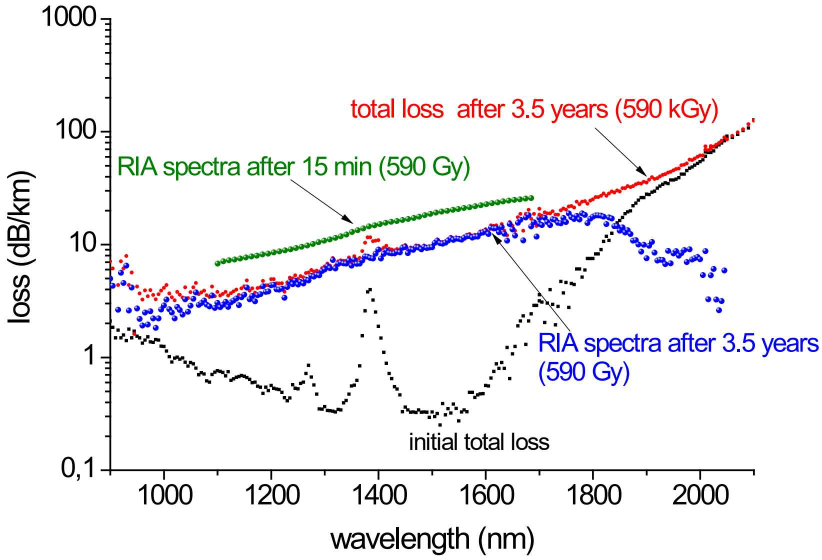

Figure 4. Spectrum of optical loss. Initial loss (black dots), loss 3.5 years after irradiation with a dose of 590 kGy (red dots), RIA spectrum after 15 min (green dots) and 3.5 years (blue dots) after irradiation.

Figure 4 shows the spectra of total and radiation-induced optical loss. From the spectra of total optical loss for the initial OF and irradiated to a dose of 590 kGy it is clear that in the LWL region starting from 2000 nm the spectra coincide (Figure 4). Similar spectra of initial and irradiated optical fibers were obtained in [10] for light guides with a germanium-doped core and in [8] for optical fibers with pure- and nitrogen-doped silica core. From the difference in the spectra of total loss of the irradiated and initial OF, we find the RIA spectrum, from which it is clear that an asymmetric band with a maximum at a wavelength near 1800 nm with a gentle SWL part and a steep decline in the LWL part is responsible for the LWL absorption. Note that a similar RIA band was observed in [8], but the LWL decline of the RIA band was not prescribed. Therefore, in this study, we observed the absorption band responsible for the LWL RIA in its full form for the first time.

This band is very similar to LTIRA by its maximum position and spectrum shape, which is caused by STH absorption [12]. The hypothesis that the LWL RIA belongs to LTIRA, as noted above, was previously stated in [9, 14, 20] and the obtained RIA spectrum (Fig.4) also supports this hypothesis. However, LTIRA is known to be stable only at low temperatures, while long-wave RIA is highly stable at room temperature. Comparing the spectrum of RIA registered after 15 min and after 3.5 years, we can see that after irradiation in the entire spectral range 1100-1700 nm at room temperature, the relaxation of RIA occurs by only 40-50%. Despite the new information obtained on the behavior of long-wave RIA, the question of determining the physical nature of LWL RIA and its main properties remains open.

Conclusion

The dependence of RIA in the PSC OF during and after gamma-irradiation up to 590 kGy at a dose rate of 7.6 Gy/s in the near-IR range has been investigated. The mechanisms affecting RIA in the near-infrared range have been established: absorption of STHs having bands with maximums at 660 and 760 nm and LWL absorption.

It was shown that starting with an absorbed dose of ~100 kGy, the RIA at 1550 nm becomes larger than at 1310 nm because of the prevalence of LWL RIA over STH absorption. For the first time, the absorption band, with a maximum at wavelength around 1800 nm, responsible for the LWL RIA is fully defined. At an absorbed dose of 590 kGy at wavelengths of 1310 and 1550 nm, the RIA is 14.1 and 23.3 dB/km, respectively. During 3.5 years of annealing of the OF at room temperature the RIA in the entire spectral range of 1100-1700 nm decreases by 40-50%.

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