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Radiation-resistant graded-index multimode optical fibers based on fluorosilicate glass

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Using the MCVD-technology, radiation-resistant multimode optical fibers based on fluorosilicate glass with a gradient refractive index profile were developed. Radiation-induced attenuation (RIA) of light in the fibers was compared with the literature data on analogous fibers manufactured by the PCVD-technology. It was found out that RIA in the MCVD-fibers at the wavelength $\lambda = 1310$ nm under γ-irradiation at the doses of up to 10 kGy is 1−2 dB/km (19−29%) lower than RIA in the Super RadHard fiber produced by the PCVD-technology and previously supposed to have a record-high radiation resistance.

Keywords: radiation-induced attenuation of light, RIA, graded-index multimode optical fiber, radiation resistance.

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Multimode optical fibers (MOF) with a gradient refractive index profile are an important type of optical fibers for local optical-communication systems [1], communication systems with mode multiplexing [2], and optical-fiber sensors [3]. In many applications, MOF is located or may be located in the field of ionizing radiation (in outer space, nuclear facilities, military equipment) that induces in the quartz-glass network radiation color centers (RCC) which absorb the light signal and thus initiate radiation-induced attenuation (RIA) [4]. Standard MOFs with germanium-doped cores exhibit high RIAs due to formation of a large number of germanium-related RCCs [5]. Therefore, an issue of developing a technique for manufacturing radiation-resistant MOFs has arisen.

Company „j-fiber“ (Germany) succeeded in developing radiation-resistant germanium-silicate MOFs OptiGrade 50/125 R.H. [6]. It is possible to assume that, for the purpose of reducing RIA in synthesizing the germanium-silicate preform, a great excess of oxygen was created in the vapor-gas mixture, which could initiate a certain suppression of the germanium RCC precursors [7]. However, RIA in such radiation-resistant MOFs is, apparently, reduced only slightly as compared with RIA in typical germanium-silicate MOFs.

To provide a radical increase in the MOF radiation resistance, it was necessary to eliminate germanium from the chemical composition. The most suitable solution seemed to be the use of fluorosilicate glass [8–10]; therewith, desirable is to introduce into the quartz glass a significant amount of fluorine (in the fluorosilicate MOF cladding; to ensure numerical aperture NA $= 0.2$ and difference in the core and cladding refractive indices $\Delta n = 0.015$, it is necessary to have at least 4.1 wt.% of fluorine [11]). This appeared to be possible only in the framework of the method of plasma-chemical vapor deposition (PCVD) [12] which is just that is used to produce radiation-resistant fluorosilicate MOFs Super RadHard (Company „Draka“ (USA) [9] and MOFs Radiation Resistant Multi-mode Fibre (RRF) (Company „YOFC“ China) [10]. The Super RadHard MOFs are believed to exhibit record-low RIA at wavelengths $\lambda = 850$ and 1300 nm which are important for MOF applications [9,13].

In Russia, the PCVD technique is not commercially developed, and preforms are being fabricated both under

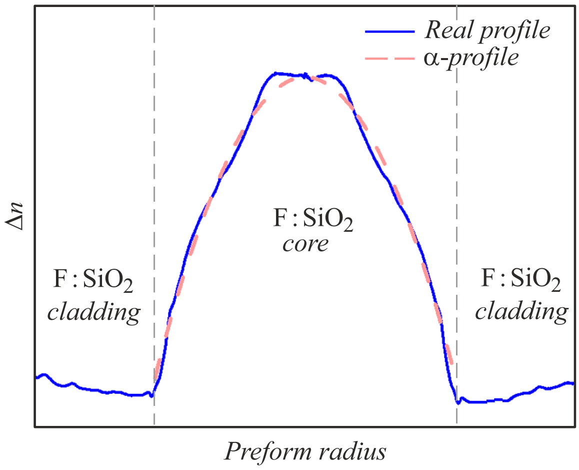

Figure 1. Profile of the preform GIMMSC(50/125) refractive index (solid line) and the model α-profile [1] included in the program of layer-by-layer deposition of glass in the MCVD-process (dashed line).

laboratory and industrial conditions by using the „non-plasma“ technique of modified chemical glass vapor deposition inside the heated support tube (modified chemical vapor deposition, MCVD) [8,14]. Both the MCVD and PCVD techniques imply layer-by-layer deposition, inside the support tube, of fluorosilicate glass of the MOF preform cladding and core from the vapor-gas mixture of oxygen, silicon tetrachloride and silicon tetrafluoride. Creation of the gradient refractive index profile (the so-called α-profile [1]) is ensured by gradually varying the vapor-gas mixture composition from layer to layer (from the maximal silicon tetrafluoride content at the core edge to the minimal one in the middle of the core). Due to a larger thickness of deposited layers of glass, deviation of the real refractive index profile from the model α-profile in MOCVD-preforms is typically more significant than that in the PCVD-preforms. Despite this, PJSC „PNPPK“ has developed MOFs GIMMSC(50/125) [15] which are fabricated from fluorosilicate glass with using the MOCVD method for producing preforms exhibiting a good compliance of the obtained refractive index profile with the calculated α-profile (Fig. 1). Optical parameters of GIMMSC(50/125) are consistent with standard OM2 [16].

Due to a restriction on the limiting fluorine concentration in the MCVD-preform quartz glass, the GIMMSC(50/125) numerical aperture appeared to be NA ~ 0.16 in case the transmittance band width is no less than 600 MHz · km, while that of world analogues MOFs Super RadHard, RRF and OptiGrade 50/125 R.H. obtained by PCVD is NA $= 0.2$ [6,9,10]. Power of light introduced into MOF is proportional to NA^2, i. e. is about 1.56 times (by ~ 1.9 dB) lower for GIMMSC(50/125) than for PCVD MOFs.

However, not only the introduced light power is important for a MOF in the radiation field, but also the rate of its decrease in the process of the signal propagation through a MOF due to the RIA effect. Thus, the goal of this paper was estimation of the radiation resistance of the developed MOF GIMMSC(50/125) and its comparison with data on world analogues.

Gamma-irradiation of MOFs was performed using the ^{60}Co source at the dose rate of 1.2 Gy/s to the dose of 10 kGy. During irradiation, a MOF transmittance spectrum was measured in the near-IR range (950 to 1750 nm); RIAs were calculated based on the transmittance value.

Fig. 2 presents the RIA dependence on the radiation dose at wavelength $\lambda = 1310$ nm of one of the GIMMSC(50/125) MOFs, which proved to be approximately in the middle of the spread of a batch of 14 nominally identical MOFs (the spread limiting values are indicated with the error bars). Fig. 2 also shows RIAs in MOFs produced by „Draka“, „j-fiber“ and „YOFC“. For the MOFs of two last companies, RIA values are known from literature ([6] and [10]) only for two fixed doses of 1 and 250 kGy, respectively, while for MOF Super RadHard produced by „Draka“ the dose dependence of RIA is known [13].

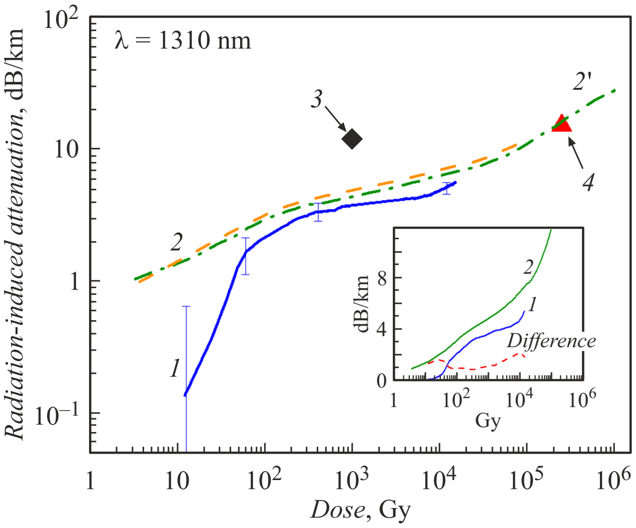

Figure 2. MOFś RIA versus the radiation dose at wavelength $\lambda = 1310$ nm at room temperature. *1* — GIMMSC(50/125) at the γ radiation dose rate of 1.2 Gy/s and introduced light power of 0.5 μW; *2* and *2'* — Super RadHard produced by „Draka“ at the introduced light power of 7 μW and γ-radiation dose rate of 1 and 0.5 Gy/s, respectively [13]; *3* — OptiGrade 50/125 R.H. produced by „j-fiber“ at the introduced light power of 1 μW [6]; *4* — RRF produced by „YOFC“ at the dose rate of 1 Gy/s [10]. The inset presents RIAs of GIMMSC(50/125) (1.2 Gy/s) (*1*) and Super RadHard (1 Gy/s) (*2*) and their difference (dashed line).

In the fluorosilicate-glass MOFs, RIAs in the near-IR range at wavelengths λ close to 850, 1300 and 1550 nm are defined by absorption in radiation-induced self-trapped hole states (STH) in the quartz glass network [17]. The STH distinguishing feature is that their concentration increases extremely strongly with increasing dose rate [18] and probing light intensity [17].

One can see that the dose dependences of the Super RadHard and GIMMSC(50/125) RIAs are quite similar in shape; in our experiment, the GIMMSC(50/125) RIAs are 1–2 dB/km lower at an order-of-magnitude lower probing light intensity as compared with the conditions for Super RadHard (0.5 and 7 μW, respectively) and at a somewhat higher dose rate in our case (1.2 and 1 Gy/s, respectively) [13]. Hence, being measured under identical conditions, RIAs of these MOFs will differ even stronger. However, even comparison of RIAs obtained under different measurement conditions shows that, when the MOF length exceeds 2 km, the GIMMSC(50/125) light power will be higher than that of Super RadHard due to lower RIA regardless that the introduced light power is ~ 1.9 dB lower due to a smaller numerical aperture (see the Fig. 2 inset). In arbitrary units, the Super RadHard RIA in the dose range of 10^2–10^4 Gy is 19–29% higher than that of GIMMSC(50/125).

Notice that, at the dose of 250 kGy, RIA of RRF produced by „YOFC“ agree well with RIA of Super

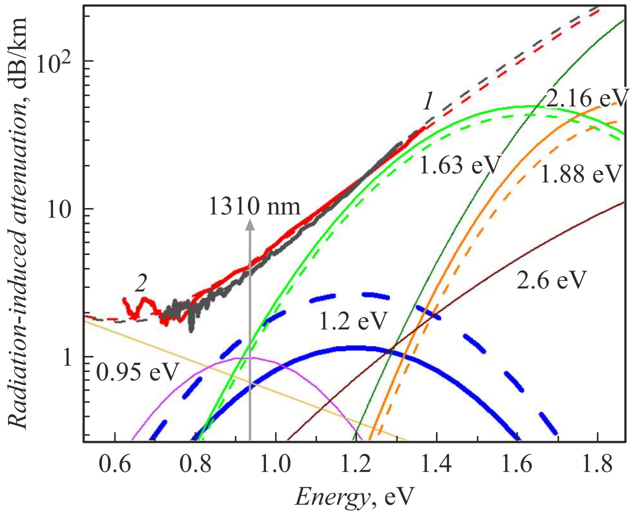

Figure 3. RIA spectra at the dose of 1 kGy at room temperature and their decompositions for radiation-resistant MOFs. *1* — GIMMSC(50/125) produced by PJSC „PNPPK" at the dose rate of 1.2 Gy/s (Gaussian components for GIMMSC(50/125) are represented below curves *1* and *2* with solid lines); *2* — Super RadHard produced by „Draka" at the dose rate of 0.5 Gy/s [13] (Gaussian components for Super RadHard a represented below curves *1* and *2* with dashed lines). Solid lines *1* and *2* represent the experimental curves, dashed lines are the sums of Gaussian components.

RadHard, while RIA of germanium-silicate MOF OptiGrade 50/125 R.H. is, as expected, ~ 3 times higher (Fig. 2).

To clarify the physical nature of the Super RadHard RIA exceedance over the GIMMSC(50/125) RIA, we have compared RIA spectra of these MOFs in the wavelength range of 950−1700 nm (Fig. 3). The RIA spectra decomposition into Gaussian components, for which STH absorption bands known from literature were used [4,18], points to the STH band with the center at 1.2 eV ($\sim 1\,\mu$m) [18] as to the source of exceedance of RIAs at wavelength $\lambda = 1310$ nm in Super RadHard over those in GIMMSC(50/125) (Fig. 3).

Thus, fluorosilicate MOFs GIMMSC(50/125) developed by PJSC „PNPPK"exhibit a higher radiation resistance than similar MOFs produced by glqq Draka" and „YOFC": at wavelength $\lambda = 1310$ nm, RIA of GIMMSC(50/125) is 1−2 dB/km lower, which allows compensating the introduced light power deficiency due to a smaller aperture. In arbitrary units, RIA of Super RadHard in the dose range of 10^2−10^4 Gy is 19−29% higher than that in the case of GIMMSC(50/125).

The question to be answered is whether the superiority of the GIMMSC(50/125) radiation resistance is a property of MCVD fluorosilicate MOFs themselves (a lower fluorine concentration, a higher support tube temperature during the glass deposition than those in PCVD) or a result of the production process optimization carried out at PJSC „PNPPK".

When the paper was already being prepared for publication, there appeared an interesting result of activities devoted to achieving high radiation resistance of germanium-silicate MOFs with a high germanium oxide content (20 mol.% GeO_2) [19], which, possibly, opens new promises for developing the radiation-resistant MOF technology.

Conflict of interests

The authors declare that they have no conflict of interests.

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