Radiation Resistant Er-Doped Fibers: Optimization of Pump Wavelength

K. V. Zotov, M. E. Likhachev, A. L. Tomashuk, A. F. Kosolapov, M. M. Bubnov, M. V. Yashkov, A. N. Guryanov, and E. M. Dianov, *Member, IEEE*

***Abstract*—H_2-free and H_2-loaded pieces of a carbon-coated erbium-doped fiber (EDF) are γ-irradiated to doses in the range 0.1–10 kGy. In three months after the irradiation, optical loss spectra and lasing efficiency of the fibers are studied. It is found that the slope efficiency of a laser based on an irradiated EDF quickly grows under the action of pumping at the wavelength of 980 nm, owing to photobleaching of radiation-induced color centers. Photobleaching is found to be much more efficient in H_2-loaded EDFs. No photobleaching occurs with pumping at 1480 nm. Pumping at 980 nm is argued to ensure a sufficiently long service life of H_2-loaded EDFs in space, much longer than in the case of pumping at 1480 nm.**

***Index Terms*—Erbium-doped optical fiber, radiation resistance, radiation-induced absorption (RIA), space applications.**

I. Introduction

RADIATION resistance of rare-earth-doped silica fibers, especially erbium-doped fibers (EDFs), is of interest owing to their promising spacecraft application, such as amplifiers for optical intersatellite links [1], superluminescent sources for fiber gyroscopes [2], laser altimetry, and lidars.

For many years, radiation resistance of EDFs has been considered as insufficient for such fibers to be applied in space (e.g., see [3]). However, recently we have demonstrated H_2-loaded hermetically carbon-coated EDFs with a sufficiently high radiation resistance [4], [5]. We showed that similar to the case of undoped-silica-core fibers [6], hydrogen passivates radiation-induced color centers (RICC) in EDFs reducing by many times radiation-induced absorption (RIA) [4], [5]. As the result, the lasing efficiency of such EDFs decreases only slightly at a dose of 2 kGy [5], which can be absorbed in a 10-year space mission [3]. The role of the hermetic coating in this EDF design is to prevent H_2 outdiffusion from the fiber glass.

In previous papers [4], [5], we pumped EDF-based lasers at $\lambda = 980$ nm. However, RIA strongly decreases with increasing wavelength [4], [5], [7], and an unwanted loss due to RICC is much less at $\lambda = 1480$ nm than at $\lambda = 980$ nm. Hence, a 1480-nm pump might be expected to yield a larger lasing efficiency of an irradiated EDF-based laser. Thus, the aim of this letter was to compare lasing efficiencies of lasers based on γ-irradiated H_2-loaded and H_2-free carbon-coated EDFs upon pumping at two wavelengths: 980 or 1480 nm.

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K. V. Zotov, M. E. Likhachev, A. L. Tomashuk, A. F. Kosolapov, M. M. Bubnov, and E. M. Dianov are with the Fiber Optics Research Center, Russian Academy of Sciences, Moscow 119333, Russia (e-mail: zotov@fo.gpi.ru; tomashuk@fo.gpi.ru).

M. V. Yashkov and A. N. Guryanov are with the Institute of Chemistry of High Purity Substances, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia (e-mail: tvs@ihps.nnov.ru).

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II. Experiment

We investigated a single-mode EDF (the silica core was doped with 1300-wt $\cdot$ ppm Er_2O_3 and 6.5 mol.% Al_2O_3) with a carbon coating ($\sim$60 nm in thickness) impermeable for molecular hydrogen at room temperature (the time of a 50% decrease of the initial H_2-concentration in the fiber glass due to outdiffusion can be estimated as 10^5 years at $T = 20°C$ [8]). The coefficient of H_2-diffusion through carbon strongly increases with temperature [8], which allowed us to load carbon-coated fibers with H_2 by keeping them in an H_2 atmosphere at a high temperature ($\sim$200 °C) and a high pressure ($\sim$5 MPa). The H_2-loaded EDF samples will be designated as "EDF-H."

The H_2-loaded and H_2-free EDFs were γ-irradiated at room temperature from a ^{60}Co source to five doses in the range 0.1–10 kGy. All the EDFs were irradiated simultaneously with the same duration—18 h, the dose rates being in the range 0.0015–0.15 Gy/s. We will indicate the dose in parentheses (e.g., "EDF(3 kGy)"—an H_2-free EDF irradiated to 3 kGy).

Before and after the irradiation, optical loss spectra and slope efficiency of the fibers were measured. The former was measured by the well-known cut-back technique. The latter was measured using a simple fiber laser assembly with a cavity formed by a 100% fiber Bragg grating on one side and a fiber endface on the other side. The cavity length was 150 cm. The slope efficiency was determined as the slope of the linear dependence of the output power on the input pump power, which was varied in the range 0–100 mW. The fiber laser was pumped by laser diodes emitting at either 980 or 1480 nm.

III. Results and Discussion

First of all, we see that the H_2-loading procedure under the above conditions did lead to H_2 penetration into the fiber glass (Fig. 1, curve 2). The H_2 concentration in the glass can be estimated from the amplitude of the H_2 absorption band at 1240 nm as $2.5 \cdot 10^{19}$ cm^{-3} [9]. Because of the H_2 absorption, the preirradiation slope efficiency of the EDF-H was somewhat lower than that of the EDF (40% and 44% with the 980-nm pump and 51% and 64% with the 1480-nm pump, respectively). However, this reduction is insignificant as compared to almost complete disappearance of lasing in H_2-free fibers already at a dose of 1 kGy (see below).

Fig. 2(a) shows the RIA decay at two characteristic wavelengths, 980 and 1550 nm, in the course of postirradiation room-temperature thermal annealing of RICC. We see that in

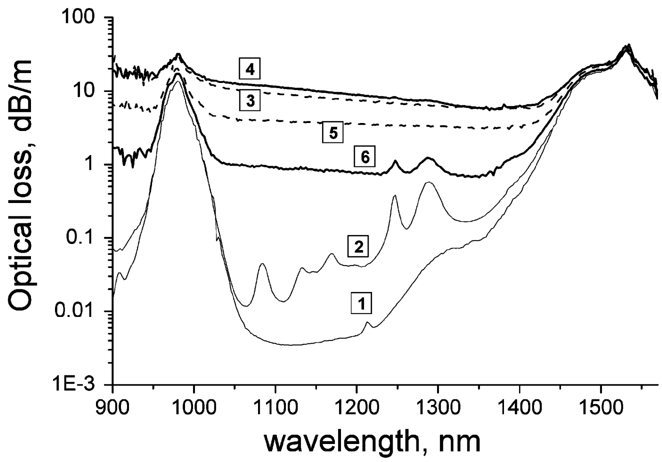

Fig. 1. Optical loss spectra: (1) EDF; (2) EDF-H; (3) EDF(1 kGy); (4) EDF-H(10 kGy); (5), (6) EDF(1 kGy) and EDF-H(10 kGy) after 3 h of operation in the laser cavity with a 100-mW pump at 980 nm, respectively. (1) and (2) were measured before the γ-irradiation, 3–6 in three months after it.

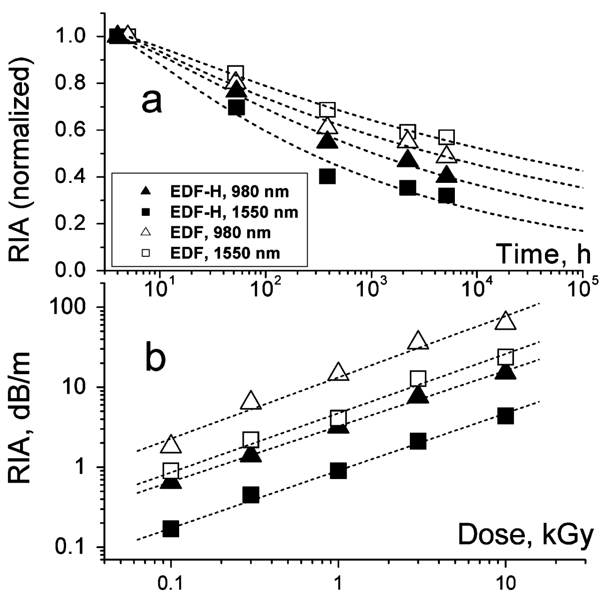

Fig. 2. (a) Temporal evolution of RIA in EDF (3 kGy) and EDF-H (3 kGy) in the course of postirradiation thermal annealing at room temperature. The RIA values were normalized to those measured 2–3 h after the γ-irradiation. The lines show approximations by the nth -order kinetic model [10]; (b) RIA measured three months after the γ-irradiation versus dose.

three months ($\sim$2000 h) the decay starts to saturate after our intense γ-irradiation. We also see that the known nth-order kinetic model [10] describes the RIA decay in our case quite well. Hence, in ten years (10^5 h) after the irradiation, the RIA would be approximately 50%–70% of the value measured in three months. In space the dose rate will be orders of magnitude smaller and the mission duration will be $\sim$10 years. Therefore, in three months our fibers model the same fibers in space much better than they do immediately after our intense γ-irradiation.

Fig. 2(b) shows the dose dependence of the RIA, which is described sufficiently well by a power law [11] with an index of $\sim$0.7. The RIA in the EDF-H is 4–5 times lower at a corresponding wavelength than in the EDF throughout the dose range under investigation. However, because the index of the power law is less than unity, the gain in the fiber service life is greater. In fact, the same RIA is reached in the EDF-H at a dose a factor of $\sim$10 greater than in the EDF [Fig. 2(b)]. Thus, the gain in service life due to H_2-loading will be also a factor of $\sim$10. The same estimation can be made from Fig. 1 (curves 3 and 4): the loss spectrum of the EDF-H (10 kGy) virtually coincides with that of the EDF (1 kGy). Note, however, that the above estimations are conservative, because they do not take into account the strong photobleaching discussed below.

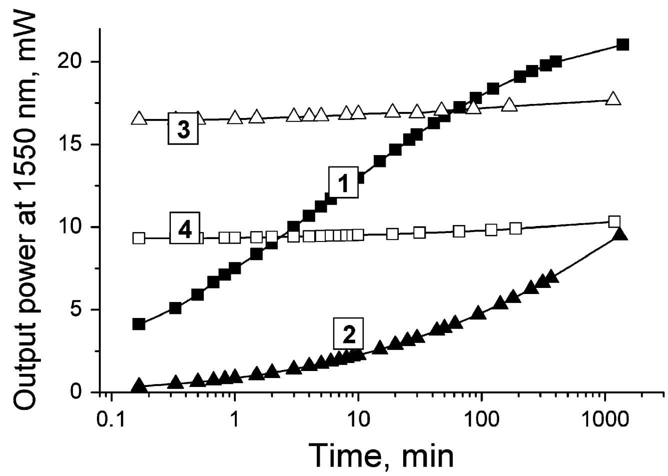

Fig. 3. Laser output power dependence on the time of fiber laser action, measured three months after the γ-irradiation: (1) EDF-H (10 kGy) and (2) EDF (1 kGy) with 980-nm pumping; (3) EDF (300 Gy) and (4) EDF-H (3 kGy) with 1480-nm pumping. The input pump power was 100 mW.

Fig. 3 shows the dependence of the fiber laser output power as a function of the duration of laser action at a constant pump power of 100 mW. Recall that the two fibers chosen for comparison with pumping at 980 nm—EDF (1 kGy) and EDF-H (10 kGy)—had approximately the same loss at the pump and signal wavelengths by the time of the experiment (Fig. 1). Both fibers demonstrated zeroth output power at the very beginning of the experiment (Fig. 3). However, already in $\sim$1 min of launching pump power into the fibers, we observe significant output signals, which continue to go up as we continue to pump the fibers. Obviously, this is the effect of bleaching RICC by laser radiation ("photobleaching") observed earlier in EDFs at least once [7]. It is important that photobleaching is several times more efficient in the H_2-loaded fiber [EDF-H (10 kGy)] than in its H_2-free counterpart [EDF (1 kGy)]. After 3 h of lasing, the RIA in the EDF (1 kGy) decreased approximately two-fold throughout the near-IR region, whereas the RIA in the EDF-H (10 kGy), by a factor of $\sim$10 (Fig. 1). This enhancement of photobleaching due to H_2 gas remaining in the fiber after irradiation will result in additional prolongation of the fiber service life in space. To our knowledge, it is the first observation of an important role of hydrogen in the photobleaching effect in optical fibers, which deserves further study as applied to both active and passive fibers.

To investigate the temporal dependence of the laser output power with pumping at 1480 nm, we also used two fibers which had absorbed different doses (by a factor of 10 as before), but featured roughly equal RIA: EDF(300 Gy) and EDF-H(3 kGy). The difference in the output powers of $\sim$10 mW (Fig. 3)

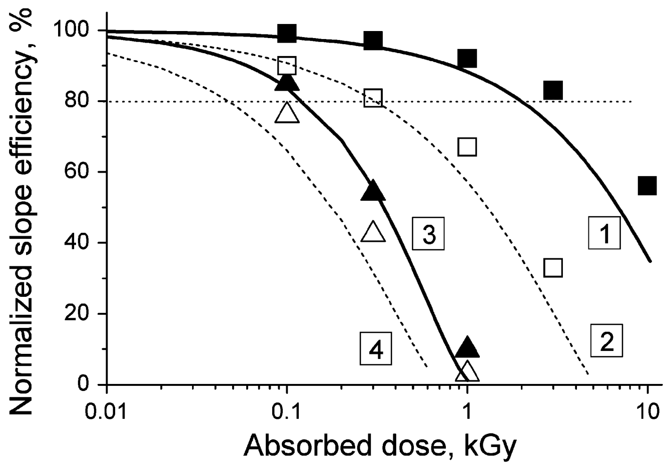

Fig. 4. Slope efficiencies versus dose normalized to the preirradiation values. The values (symbols) were measured three months after the γ-irradiation and after $\sim$10 min of fiber laser action: (1), (2) EDF-H; (3), (4) EDF; (1), (3) 980-nm pump; (2), (4) 1480-nm pump. The lines show calculations by the model [5].

can be explained by some decrease of the slope efficiency after H_2-loading (see above) and a slightly lower RIA in the EDF(300 Gy) [Fig. 2(b)]. No photobleaching was observed in both fibers upon pumping at 1480 nm (Fig. 3). Apparently, the photon energy at this wavelength turned out to be insufficient to passivate RICC. Thus, owing to efficient photobleaching, pumping at $\lambda = 980$ nm is preferable from the standpoint of radiation resistance of EDFs, particularly in the case of H_2-loaded EDFs.

Fig. 4 gives a comparison of all the fibers investigated in terms of slope efficiency measured after 10 min of fiber laser action with a given pump wavelength. The lines show the calculations of the slope efficiencies based on a simple fiber laser model described in [5]. In the calculations, the optical loss values at the pump and signal wavelengths measured after 10 min of laser action were used. As expected, the largest lasing efficiency takes place in the EDF-H with a pump at $\lambda = 980$ nm at all doses in the range 0.1–10 kGy. The EDF is strongly outperformed by EDF-H, the worst case being the EDF pumped at $\lambda = 1480$ nm. Note that the EDF virtually loses the active properties by the dose of 1 kGy with either pump wavelength, in contrast to the EDF-H (Fig. 4).

To assess the gain in the EDF service life in space that can be achieved by using H_2-loading and pumping at $\lambda = 980$ nm, let us assume, rather arbitrarily, that the limiting slope efficiency admissible in a spacecraft optoelectronic system is 80% of the preirradiation value. Then, for the EDF-H pumped at $\lambda = 980$ nm, we have the limiting dose of $\sim$3 kGy (Fig. 4), which is a factor of $\sim$10 greater than for the EDF-H pumped at $\lambda = 1480$ nm and a factor of $\sim$30 greater than for the EDF pumped at either wavelength. Thus, the fiber service life, too, is prolonged by a factor of $\sim$30. Although this estimate is rather rough, we believe that H_2-loading of a hermetically coated EDF in combination with pumping at $\lambda = 980$ nm do provide a solution to the radiation resistance problem associated with the promising space applications of EDFs.

IV. Conclusion

By comparing the two possible pump wavelengths of γ-irradiated hermetically carbon-coated erbium-doped silica fibers it has been found that pumping at $\lambda = 980$ nm is a great advantage because of highly efficient photobleaching of RICC. This photobleaching is particularly efficient in H_2-loaded fibers. Thus, in addition to direct suppression of RICC by entering into the glass network at the sites of radiation-disrupted bonds, hydrogen fosters, in some way, RICC photobleaching by 980-nm light. No photobleaching has been observed with a pump at $\lambda = 1480$ nm. The gain in the EDF laser service life in space that can be achieved by using H_2-loaded hermetically coated fibers and a pump at $\lambda = 980$ nm has been roughly estimated to be a factor of $\sim$30. We believe that this is a solution to the radiation resistance problem associated with the future spacecraft applications of EDFs.

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