Gamma Radiation Effects in Yb-Doped Optical Fiber

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ABSTRACT

Determination of the radiation response of doped-fiber laser materials, systems and components to relevant ionizing radiation fluxes is central to the prediction of long-term fiber-based laser performance/survivability in adverse and/or space-based environments. It is well known that optical elements that are placed into orbit around the Earth experience harsh radiation environments that originate from trapped-particle belts, cosmic rays, and solar events. Of particular interest to optical materials is the continuous flux of gamma photons that the materials encounter. Such radiation exposure commonly leads to the formation of color centers in a broad range of optical materials. Such color center formation gives rise to changes in optical transmission, loss and luminescent band structure, and, thus, impacts long-term optical device performance.

In this paper we will present the results of our investigation of gamma-radiation-induced photodarkening on the passive optical transmittance of a number of ytterbium- (Yb-) doped optical fibers. We will discuss the evolution of the optical response of the fiber across the 1.0 to 1.6 micron wavelength window with increasing gamma exposure. Results indicate that these fibers exhibit reasonable radiation resistance to gamma exposures typical of a 5-year, low-earth-orbit environment. Maximum transmittance losses of less than 10% were observed for total gamma exposures of 2-5 krad (Si).

Keywords: Radiation effects, photodarkening, radiation-induced absorption, gamma irradiation, rare-earth doped fibers, Yb-doped fibers

1. INTRODUCTION

Fibers doped with Yb have found uses both as amplifiers and lasers, producing high optical powers and pulse energies[1-5]. Due to this dopant's relatively simple band structure, Yb-doped fibers tend to have a high efficiency and experience reduced effects of excited state absorption and concentration quenching due to ion-ion interactions[5, 6]. Yb-atoms can also act as sensitizers, absorbing and transferring energy to other emitting species such as erbium[7]. Long upper-state lifetimes and a small quantum defect further make Yb an excellent candidate for highly power-efficient Q-switched lasers[8].

In comparison to conventional solid-state lasers, Yb-doped fiber sources offer the advantages of high efficiency, low waste-heat generation, diffraction-limited beam quality, ruggedness, and reliability. These advantages are especially important for practical applications and for deployment in demanding environments. Fiber lasers are being considered for space-based applications, and determination of the radiation response of doped-fiber laser materials, systems, and components to relevant ionizing radiation fluxes is central to the prediction of long-term fiber-based laser performance and survivability in space-based and other adverse environments. It is well known that optical elements that are placed into orbit around the Earth experience harsh radiation environments that originate from trapped-particle belts, cosmic rays, and solar events[9]. Of particular interest to optical materials is the continuous flux of energetic protons, hard x-rays, and gamma photons that the materials encounter[9,10]. These types of radiation exposures lead to the excitation of electrons and the subsequent formation of color centers in the materials[7,11]. This photodarkening effect in turn gives rise to changes in optical transmission, loss and luminescent band structure, impacting optical performance[12,13].

In doped fiber amplifiers, it is known that many factors can affect the fiber performance, including the method of fabrication, rare-earth-dopant concentration, and ionizing radiation exposure conditions[14]. Among rare earth doped fibers, Yb-doped fibers were found to be among the most radiation resistant[15]. However, the presence of dopants such as Al, P, and Ge vastly increases the induced loss by gamma radiation, while the exact concentrations of the rare-earth dopants only slightly affect radiation sensitivity[15]. Radiation-induced attenuation at particular wavelengths transmitted through Yb-doped fibers have shown a characteristic increase in absorption with a time-dependent saturation behavior at low dose rates of 34 rad/min (Si) and 50 rad/min (Si)[16]. Although time-resolved spectra of Yb-doped fibers across a window in the infrared (IR) have not been produced to our knowledge, spectra of this type have been generated for Er/Yb-codoped fibers[7].

In the present study, an investigation of the optical transmission loss of Yb-doped optical fibers subjected to low-dose-rates, large-total-dose gamma radiation conditions was undertaken. The IR transmission of a suite of doped fibers was monitored as a function of total gamma dose over a broad wavelength window (1.0 μm to 1.7 μm). In addition, an evaluation of the spectral transmittance decrease both at a total accumulated dose of 2 krad (Si), in order to approximate reasonable short-term (~2-5 years), real-world, near-Earth-orbit exposure conditions, and at >50 krad (Si), corresponding to longer time periods at which substantial optical darkening could be observed, was performed. The spectral transmittance data showed a relatively high radiation resistance of the Yb-doped fiber under passive (not actively pumped) conditions.

Fibers used in the present study were produced by Liekki using Direct Nanoparticle Deposition (DND), which can produce a more uniform doping of the rare-earth constituent than does conventional modified chemical vapor deposition[17]. Some authors have speculated that decreases in Yb clustering might be the origin of the radiation hardness exhibited by some Yb-doped fibers[17]. A further possibility, which is known to occur in certain fluorides, is the presence of a Yb^{2+}/Yb^{3+} conversion process, which could effectively absorb energetic photons, thus diminishing the potential for gamma-induced color-center formation[18].

2. EXPERIMENT

In the present study, an investigation of the optical transmission losses of Yb-doped fibers subjected to different dose rates and a large total dose of gamma radiation was undertaken. Assorted single- and double-clad, highly Yb-doped aluminosilicate optical fibers from Liekki were tested. The fiber part numbers were Yb1200-10/125DC, Yb1200-20/400DC, Yb1200-30/250DC, Yb1200-4/125, and Yb2000-6/125DC, where the number following "Yb" denotes the nominal peak core absorption at 976 nm in dB/m, the next number denotes the core diameter in μm, the third number denotes the cladding diameter in μm, and "DC" refers to double-clad fiber. These test fibers were all based on an aluminosilicate glass host doped with Yb. The different fibers varied in core diameter and numerical aperture, and they had two different Yb-doping concentration levels. For the testing of DC fibers, light propagating in the inner cladding had to be minimized to observe the effect of radiation exposure on the core. Single-clad pigtails were therefore fusion-spliced to both sides of each DC fiber, with the DC and pigtail cores aligned prior to splicing. For the Yb1200 fibers, the pigtails were composed of SMF-28 fiber (Corning), whose core diameter (~7 µm) is smaller than that of any of the DC fibers. HI-1060 pigtails (Corning) were used for the Yb2000 fibers. The fibers were SMA connectorized (Coastal Connections) for compatibility with the fibers used to deliver light to the radiation test cell and to the spectrometer. All fibers were about 3 m in length with pigtails of about 1 m per section, measured to ±0.01 m.

Exposure of the fibers to radiation from a Co^{60} source was conducted at Sandia National Laboratories at the Gamma Irradiation Facility cell A (GIF-A) in Albuquerque, NM. In this facility, the gamma-emitting Co^{60} elements are arranged in an array and submerged in water on a movable platform, which is raised into the test cell during the tests. Spools of individual test fibers were vertically mounted on stands at various locations within the gamma test cell in order to obtain data on the effect of dose rate on radiation-induced changes in the optical transmission spectrum of the test fibers. Experimental dose rates, measured using thermoluminescent dosimeters (TLDs), ranged from approximately 14 rad/sec (Si) to 120 rad/sec (Si). Broadband optical radiation from a 75 W xenon arc lamp (Oriel Model 6263), located outside of the test chamber, was launched into the cores of the test fibers such that their optical transmittance could be monitored before, during, and after the gamma test sequence. A schematic of the experimental setup for the radiation exposures is shown in Figure 1.

Collection and coupling optics gathered light from the xenon lamp and focused it into a length of silica fiber that was connected to the input channel of a Piezosystems Jena 1:9 fiber switch. Up to nine standard low-OH silica (SiO_2) delivery fibers (Ocean Optics P100-10-VIS/NIR) were connected to the switch output and were used to carry light into the test fibers located in the test cell. The delivery fibers were selected based on their relatively flat transmission spectrum and the absence of any large absorption features over the IR wavelength range of interest. Delivery fibers entered the test chamber through access ports in the chamber wall and were connected to the input end of the doped fibers under test via standard SMA fiber connectors. Doped-fiber outputs were collected by another set of delivery fibers, which carried light transmitted by the test fibers out of the test cell and into another 1:9 fiber switch. The output of this second switch was coupled into an Ocean Optic NIR 512 spectrometer, which was used to record the spectrum. The fiber transmission spectrum over the wavelength range of 1000 nm to 1700 nm was scanned at 1 minute intervals for each of the fibers under test throughout the 7-hour gamma exposure. The 1:9 splitters were used to sequentially query the fibers, resulting in the generation of data files consisting of spectrometer counts at a given time in a given channel. In addition, background losses in the delivery fibers were accounted for by monitoring the time-dependent spectral transmission of additional SiO_2 fibers, referred to as background fibers, which were mounted on the same stands as the test fibers. Samples of the pigtail fibers used to couple the signal into the double-clad fibers were also used as background control fibers whenever a double clad fiber was being tested. All data were taken with the fibers in a passive condition (i.e. the fibers were not optically pumped during radiation exposure).

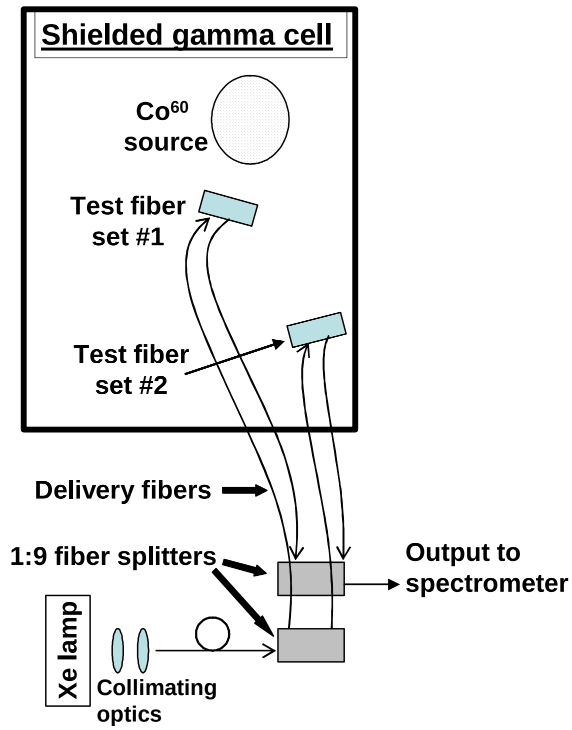

Figure 1: Experimental setup of test fibers located in gamma test chamber (GIF-A) at Sandia National Laboratories. Fiber dose rate is dependent upon position of fibers within the gamma cell.

3. RESULTS AND DISCUSSION

The raw data, an example of which is given in Figure 2, clearly show the broad arc-lamp spectrum. The first data processing step involved the determination and subtraction of the baseline noise from the test and background fiber data, resulting in the removal of the offset from the horizontal axis. The second step involved ratioing the test fiber data to the background fiber data, resulting in a normalized transmittance plot that is independent of the lamp source. Lastly, a length normalization to a standardized 1.0 m was applied to the data.

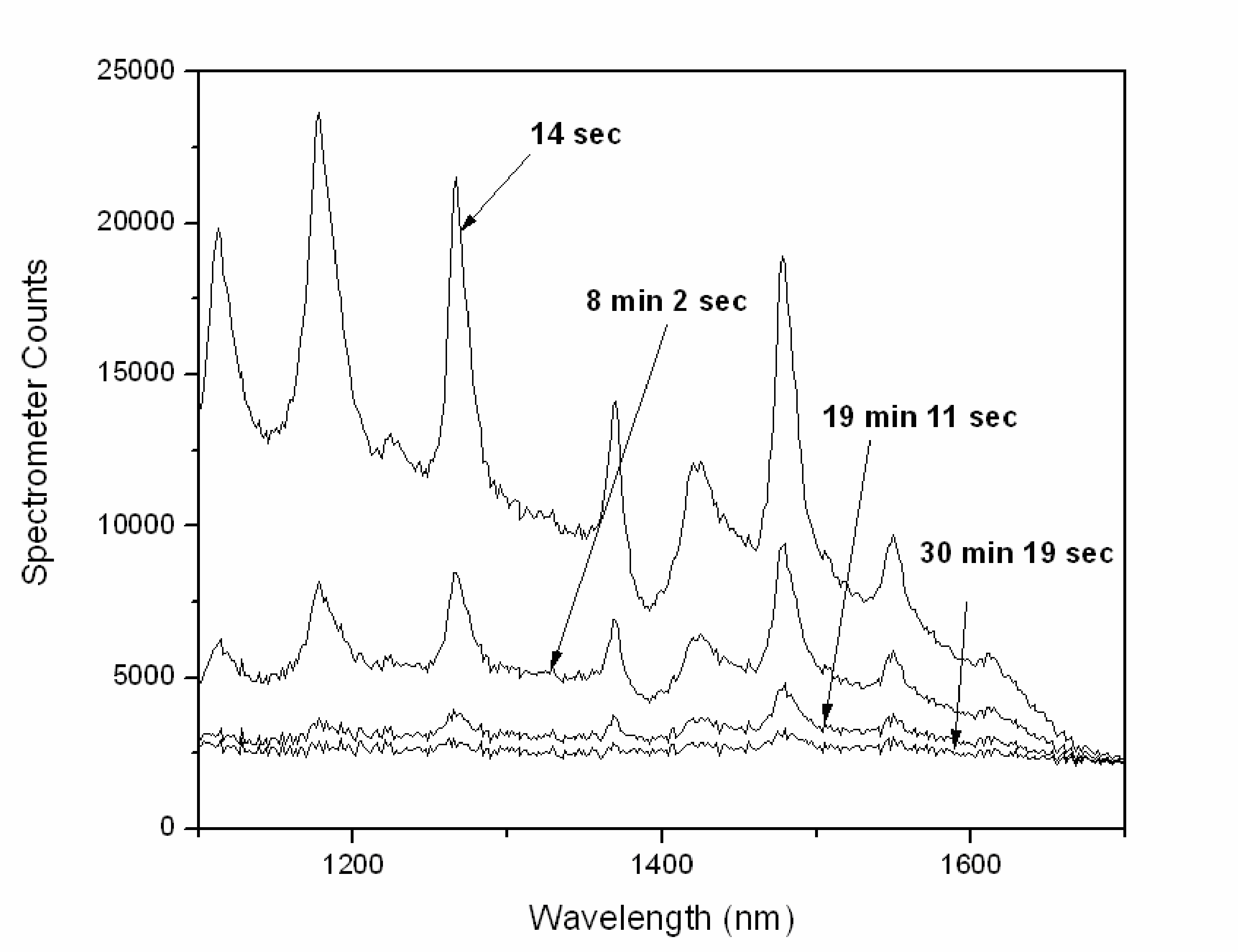

Figure 2: Data plot of spectrometer counts vs wavelength of a Yb1200-4/125 fiber before processing. The lamp spectrum and an offset from the horizontal axis are clearly visible.

All Yb-doped fibers exhibited photodarkening during the 7-hour gamma-radiation exposures. Figure 3 shows the spectral response for samples with low accumulated doses that were exposed at the lowest dose rate. From Fig. 3, it can be seen that at doses of approximately 400 rad (Si) the transmittance decreases by less than 4%, while doses of 2.3 krad (Si) show a decrease of only approximately 8%, indicating relatively high radiation resistance.

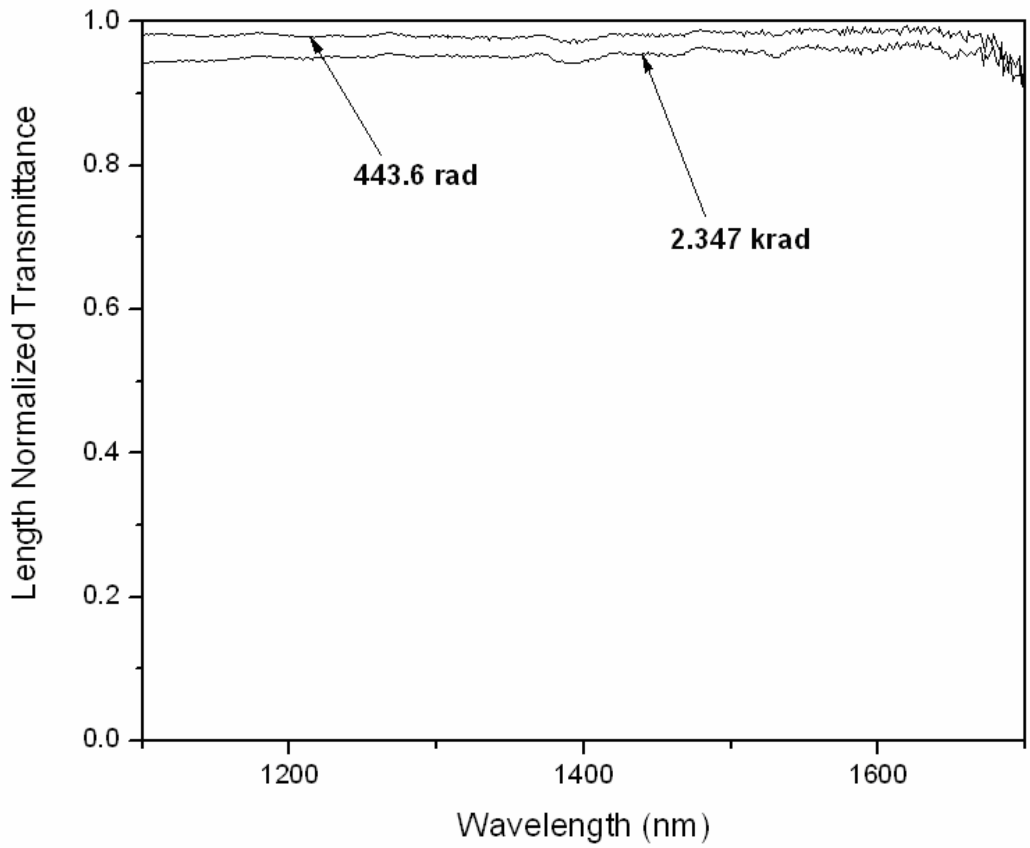

Figure 3: Low total dose data of a Yb1200-4/125 fiber with a dose rate of 14.310 rad/s.

Figure 4 shows the typical spectral response of Yb-doped fibers to gamma radiation for accumulated total doses ranging up to over 100 krad (Si). The spectra are characteristically unstructured, with the presence of variations only in the form of lower transmittances at shorter wavelengths, likely resulting from color center formation in the glass host material[13]. The transmittance is observed to decrease as the dose is increased. At a dose of 6 krad (Si), for example, the transmittance is above 80% for all wavelengths, whereas a total dose of about 100 krad (Si) results in an optical transmittance between 12% and 25% across the measured spectrum. In this figure, transmittances below approximately 10% correspond to complete photodarkening of the fibers. The residual light signal is a result of the noise floor of the instrumentation.

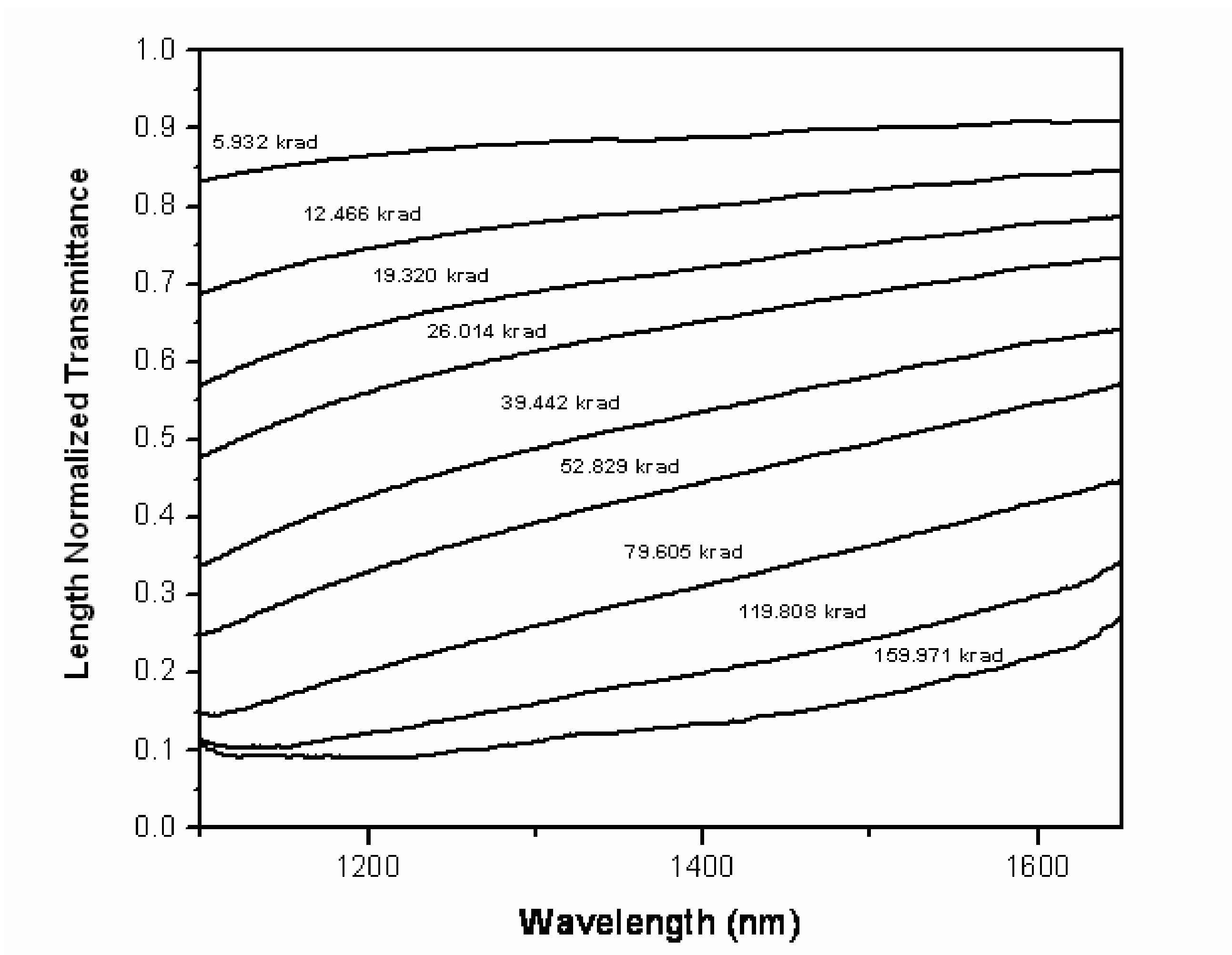

Figure 4: Transmittance of Yb1200-4/125, Yb-doped fibers exposed to γ-radiation at near infrared wavelengths.

A series of post-radiation thermal anneals was attempted on the fiber samples. These investigations were performed in order to ascertain whether some portion of the permanent photodarkening could be removed through heating. The tests were performed by coupling light from the xenon arc lamp into and out of gamma-irradiated doped fibers and then placing the fibers in direct contact with a heated alumina tray or, alternatively, by heating the fibers directly in an ambient-atmosphere, standard box furnace. The optical transmission of the test fiber was monitored, using the Ocean Optics NIR 512 spectrometer, as the fiber was heated. The potential for thermally induced recovery of the optical transmittance was evaluated. Samples were heated to temperatures as high as 120°C for up to 30 minutes. No recovery in the transmittance of the samples was observed. All samples remained permanently photodarkened following all thermal treatments. Reports in the literature support the use of thermal annealing during radiation exposure in order to aid in recovery of the optical transmittance[7]. Such a possibility remains a subject of future investigations.

4. CONCLUSION

This paper reports, for the first time, the temporal evolution of photodarkening in Yb-doped fibers across the near-infrared spectrum as a result of gamma radiation exposures at the dose rates 14 rad/s (Si) and 40 rad/s (Si). The acquired

Yb-doped fiber spectra clearly show a decrease in the transmittance across the spectrum, with a higher loss at shorter wavelengths. At large doses over 100 krad a low point was reached, and the residual noise floor was attributed to the limitations of the instrumentation. No saturation due to self-annealing processes during the experiment was observed and no recovery of the transmittance by means of post-experimental anneals was achieved, indicating that the color centers represent deep trap states.

The behavior of the Yb-doped fiber at total doses representative of the environment over 2-5 of years in low-Earth orbit confirms the relative radiation hardness of Yb-based fibers. As speculated previously, this radiation resistance might be the result of the DND technology, which typically produces more uniform profiles, thus effectively dissipating energy faster and preventing the formation of color centers[17]. A further possible cause might be the presence of a Yb^{2+}/Yb^{3+} conversion process, which could act as an absorbing agent, thereby shielding the rest of the fiber structure from photodarkening[18]. The present results do not favor either model, but do substantiate the strong performance of these fibers in low-dose gamma environments. To better understand the formation of gamma-induced color centers in Yb-doped silica fibers, other methods of analysis, such as spectroscopy and microscopy should be performed. These experiments would provide insight into the microscopic structure of the doped fibers and complement the existing data, which deals mainly with the observation of radiation-induced loss by means of transmittance measurements. A better understanding of radiation induced processes in the microstructure of rare-earth-doped fibers can potentially improve the design of Yb-doped fibers.

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