Journal of Non-Crystalline Solids 378 (2013) 79–88

Contents lists available at SciVerse ScienceDirect

Journal of Non-Crystalline Solids

journal homepage: www.elsevier.com/locate/jnoncrysol

Effect of low-earth orbit space on radiation-induced absorption in rare-earth-doped optical fibers

Brian P. Fox [a,*], Kelly Simmons-Potter [a], Dahv A.V. Kliner [b], Sean W. Moore [c]

[a] University of Arizona, Tucson, AZ 85721-0104, United States
[b] nLight, Vancouver, WA 98665, United States
[c] Sandia National Laboratories, Livermore, CA 94551, United States

ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form 1 June 2013
Available online xxxx

Keywords:
Rare-earth;
Optical fiber;
Space radiation;
Color-center;
Ionizing-radiation effects

ABSTRACT

The implementation of optical systems, based on rare-earth doped fibers, in space environments adds a powerful new dimension of functionality to the design of space-based systems, particularly when high power and bandwidth, high fidelity, and low susceptibility to electromagnetic interference are desired. As these specialty fibers are often the most sensitive components of an optical system, extensive use requires considerable insight into the ionizing-radiation-induced changes experienced by the fibers during their operational lifetime. In this research, a suite of aluminosilicate fibers singly or co-doped with erbium and ytterbium ions was deployed into low-Earth orbit for approximately 18 months as part of the Materials International Space Station Experiment (MISSE) 7 mission. Optical spectroscopy performed on the retrieved fibers is compared to control data from pristine, unirradiated fibers, revealing colorcenter generation in the visible portion of the spectrum consistent with silica-related and aluminum-related absorption centers, with band-tailing into the near-infrared. Results suggest that visible to near infra-red (NIR) absorption experienced by the co-doped fiber is less-pronounced than in its singly-doped counterparts, likely a result of the lower aluminum concentration of this fiber. The data were also compared to data from terrestrial ^{60}Co irradiation of the same fiber types and it was found that the overall trends observed in the space-irradiated fibers in the near-infrared were accurately, although not identically, reproduced. The resultant information is important for the design and testing of radiation-hardened optical-fiber-based laser and amplifier systems.

1. Introduction

Rare-earth dopants have become important for numerous modern technologies, due to the distinct and beneficial properties they possess. In optical systems, desirable associated properties include unique, sharp transitions capable of producing stimulated emission, and the ability to incorporate the dopants into a large number of disparate host material types and structures. In comparison with other species, such as the transition-metal ions, rare-earth dopants have the advantage that their integration into different materials only has a relatively minor effect on the location of particular optical transitions in wavelength space [1]. One of the most prolific applications of rare-earth dopants is in optical-fiber laser and amplifier devices. The very long optical path lengths of such fibers mean that even fibers doped with relatively low concentrations of rare-earth constituents are capable of exhibiting gain in such devices [2–6]. Generally, applications based on optical fibers also exhibit a high immunity to electromagnetic interference (EMI) effects, and the fiber geometry, with its associated small volume and light weight, is advantageous for a large number of environments, including space deployment [7].

The current research is focused on rare-earth-doped fiber materials that are primarily designed for fiber amplifier applications (in which the optical fiber segment is used to boost an optical signal), or for fiber laser applications (in which the fiber acts as a light source). Such doped fibers possess high power capabilities, high bandwidths, and high overall efficiency, manifested in low power consumption and low waste-heat generation [2–5]. They also exhibit high reliability due to their monolithic structure, the possibility for alignment-free, fiber-based coupling, and additionally display excellent beam quality. For the present study, fibers doped with erbium (Er) or ytterbium (Yb) ions, as well as fibers co-doped with both of these species, were investigated. While Er^{3+}-doped fibers are primarily used for communication applications [2], Yb^{3+}-doped fibers, with their increased pump-light absorption and minimized excited state absorption arising from their simple energy band structure, are more often associated with high-power applications [3]. Co-doped materials also operate at the communication wavelength of 1.5 μm. In this case, the large absorption efficiency of the Yb ion is utilized to increase the efficiency of the Er^{3+} emission by relying on energy-transfer between the Yb^{3+} and Er^{3+} species [6,8,9].

* Corresponding author. Tel.: +1 5203272068.
E-mail address: bpf@email.arizona.edu (B.P. Fox).

0022-3093/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.jnoncrysol.2013.06.009

The beneficial properties discussed above highlight the desirability of rare-earth-doped fibers for use in ionizing-radiation environments, such as space [10–12]. Implementation of these materials, however, requires that survivability of the materials in the harsh space environment be sufficiently addressed. It is well-documented that irradiation of optical materials by gamma radiation leads to electron ionization and to the subsequent formation of absorption centers [13–22]. Such induced absorption generally leads to a reduction in the optical transmission of materials in some region of the optical spectrum. The shape and location of the induced absorption, along with known parameters such as the composition of the material, can lead to a determination of possible origins of, and associated mechanisms responsible for, the radiation-induced degradation. While properties of the rare-earth-ions do not seem to be greatly affected, by ionizing radiation, possibly due to the formation of an aluminum-based solvation shell around the ions [18], the transmittance of rare-earth doped optical fibers is known to be prone to ionizing radiation damage [13–22] and generally represents the most sensitive component of a fiber-based optical system [13]. With regard to space-based applications, therefore, it is of principal interest to determine the effects of radiation in this environment on the transmission behavior of the rare-earth-doped fibers in question.

The present study examines a suite of rare-earth-doped aluminosilicate optical fibers that resided for approximately 18 months in low-Earth orbit in the MISSE-7 apparatus. Optical spectroscopy of both the space-irradiated fibers and of a set of pristine fibers provides information regarding radiation-induced color center generation in the fibers. Further, a comparison of the data to terrestrial ^{60}Co tests of the same fiber types enables an interpretation of the validity of such ground-based testing. Overall, this work is aimed at both extending the scope of previous investigations into the behavior of rare-earth doped fibers under irradiation [20–23], and at providing novel data on the effects of a true space-radiation environment on the optical performance of these fibers. The latter goal will provide insight reaching beyond the field of fiber-based optics, as outcomes of terrestrial ^{60}Co irradiations, which are often used for accelerated space qualification of materials, can be evaluated for their effectiveness.

2. Experiment

The current investigation represents a small part of a larger research effort denoted the Materials International Space Station Experiment 7 (MISSE-7), which is an experimental test bed designed to study the space-environment-related degradation of a wide variety of materials [24,25]. This test bed consists of two Passive Experimental Containers (PECs), which can be described as holders for a large number of materials, among these the rare-earth doped fibers that are the focus of the current investigation. The MISSE-7 experiment was delivered to the International Space Station (ISS), situated in Low-Earth Orbit (LEO) at an altitude of just under 400 km, by the space shuttle Atlantis, mission STS-129, launched in November of 2009. Once the shuttle was docked at the ISS, the MISSE-7 PECs, stored in the cargo bay during flight, were removed from the orbiter and deployed atop the Express Logistics Carrier-2 (ELC2), a platform affixed to the S3 truss of the ISS. During installation, one of the two PECs, PECb, was positioned in the "ram/wake" position with respect to the space station's orbit, and PECa, which included the rare-earth doped fiber samples, was situated at a 90° angle to PECb, in the "zenith/nadir" position (facing Earth/space). Fig. 1 shows photographs of the fibers within PECa, taken in the laboratory prior to deployment and in LEO following deployment. The large arrows in the figures point to the rare-earth fiber samples. MISSE-7 was exposed to space radiation for 18 months (~8500 orbits of the space station), before returning to Earth aboard the space shuttle Endeavor during the STS-134 mission conducted in May 2011.

a

b

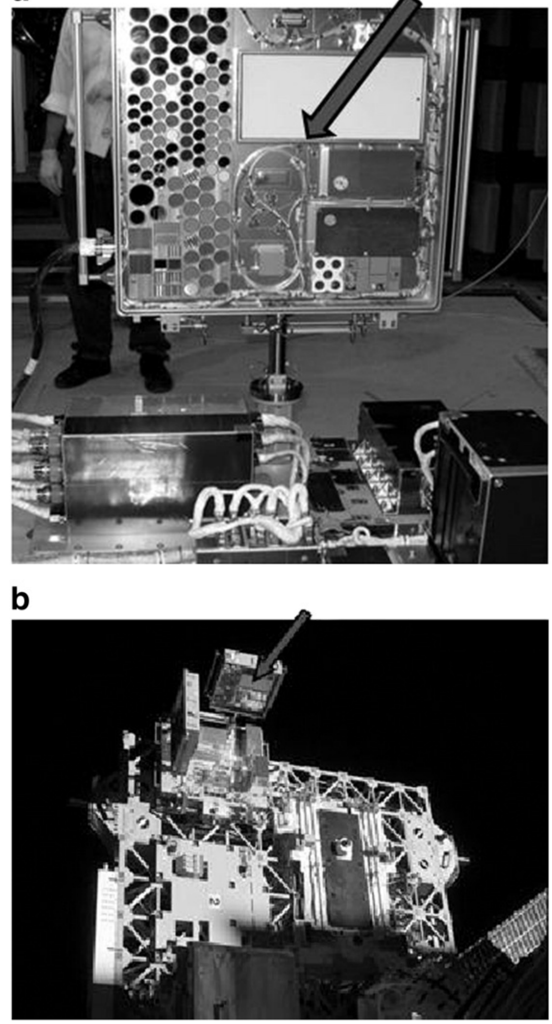

Fig. 1. (a) MISSE-7 PECa on Earth, containing the rare-earth doped sample fibers (indicated by the large arrow; courtesy of the Naval Research Laboratory). (b) MISSE-7 aboard the ELC-2 on the ISS with PECb on the left, oriented in the "ram/wake" direction and PECa on the right containing the rare-earth doped fibers and oriented in the "zenith/nadir" (Earth/space) direction (credit: National Aeronautics and Space Administration, ISS021-E-031746).

The sample suite aboard the MISSE-7 project PECa contained a total of six compositions from the two manufacturers Nufern and Liekki (currently nLight). The sample suite consisted of three Er^{3+}-doped (Liekki Er16-8/125, Er30-4/125, Er80-4/125), two Yb^{3+}-doped (Liekki Yb1200-30/250DC, Nufern LMA-YDF-15/130), and one Er^{3+}/Yb^{3+} co-doped samples (Nufern MM-EYDF-12/130). For the Liekki fiber designations listed above, the ion is stated first, followed by the peak absorption in dB/m, given at a wavelength of 1530 nm for the Er^{3+}-doped fibers and at a wavelength of 976 nm, in the case of Yb^{3+}-doped fibers. For the fiber designations of both Liekki as well as Nufern, the last two numbers signify the core and cladding diameter in μm, respectively. Regarding the number of samples, a redundancy of six was chosen for each fiber type, yielding a total of 36 fibers sent into space. The fibers were divided into two groups of 18 fibers and each group was bundled and inserted into one of two Tefzel® tubes (an ETFE tube from DuPont™). The two tubes containing the samples were then sent to the Naval Research Laboratory (NRL) for integration into MISSE-7 and eventual deployment into space.

An estimation of the total accumulated space radiation dose within the fibers during the MISSE-7 mission was made via a standard model (SHIELDOSE), as outlined in the ISS document "SSP 30512 Revision C" [26]. The model allows for the estimation of a dose rate, and by extrapolation over 18 months, also of a total accumulated ionizing dose of a