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Investigation of Radiation-Induced Photodarkening in Passive Erbium-, Ytterbium-, and Yb/Er Co-Doped Optical Fibers

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ABSTRACT

The deployment of optical fibers in adverse radiation environments, such as those encountered in a low-Earth-orbit space setting, makes critical the development of an understanding of the effect of large accumulated ionizing-radiation doses on optical components and systems. In particular, gamma radiation is known to considerably affect the performance of optical components by inducing absorbing centers in the materials. Such radiation is present both as primary background radiation and as secondary radiation induced by proton collisions with space-craft material.

This paper examines the effects of gamma radiation on erbium-, ytterbium-, and Yb/Er co-doped optical fibers by exposing a suite of such fibers to radiation from a Co-60 source over long periods of time while monitoring the temporal and spectral decrease in transmittance of a reference signal. For same total doses, results show increased photodarkening in erbium-doped fibers relative to ytterbium-doped fibers, as well as significant radiation resistance of the co-doped fibers over wavelengths of 1.0 - 1.6 microns. All three types of fibers were seen to exhibit dose-rate dependences.

Keywords: Radiation effects, photodarkening, radiation-induced absorption, gamma irradiation, Co-60, rare-earth doped fibers, Yb-doped fibers

1. INTRODUCTION

Rare-earth doped fibers are of central importance to many laser and amplifier systems, due to their high-bandwidth, monolithic structure, high-beam quality, and their potential for high-power applications[1-8]. Specifically, erbium- (Er-) doped fiber amplifiers are ubiquitous in the communication industry because of their ability to amplify signals at the critical 1.5 um wavelength[8-10], while ytterbium- (Yb-) doped fiber amplifiers, operating at 1.06 μm, have the benefit of an overall increased pump absorption efficiency with respect to purely Er-doped fibers[6,7]. The low excited-state absorption cross-secion of Yb-doped silicates, as compared with Er, and the observation of reduced concentration quenching due to ion-ion interactions, also make the Yb-atom a desirable dopant[11,12]. Co-doping the two rare-earth species allows for amplification at telecommunication wavelengths with increased overall absorption via an energy transfer process in which the Yb-atoms act as sensitizing agents and the Er-atoms as the emitting species[6,7,13,14]. Properties such as alignment-free laser/amplifier reliability make rare-earth-doped fibers particularly desirable in harsh radiation environments, and their low weight and small volume are ideal for space-based applications[15,16]. Deployment of such materials and systems in these environments, however, necessitates the development of an understanding of the impact of ionizing-radiation fields on their optical transmission.

It is well known that radiation in low-Earth orbit (LEO) arises from a number of sources including solar events, cosmic rays, and particles trapped in the Van Allen belts[17,18]. For optical materials the radiation sources of primary concern are high energy particles and gamma rays, as these can lead to the formation of color centers (or absorbing centers) in the materials[19-25] which negatively impact fiber performance[23-42]. Determination of the radiation response of these rare-earth doped fibers, therefore, is central to the design of optical systems for use in harsh radiation environments, as these fibers are often the most radiation-sensitive part of an amplifier system[15,32]. Factors affecting the radiation-induced loss observed in doped fibers include the exact type of ionizing radiation, total absorbed dose, dose rate, and fiber characteristics such as core diameter, temperature, rare-earth dopant concentrations, and methods of fabrication[10,26,29,33,36,39,43]. Dopants such as Al, P, and Ge, used to modify the index of refraction in fiber materials and increase doping concentration of the rare-earth ions, have been seen to increase the induced loss by gamma radiation, with the exception of Al co-doped with Er[10,26,33,36,39,43]. The exact concentrations of the rare-earth dopants, however, have been found to only slightly affect radiation sensitivity[43]. Finally, the decrease in optical transmittance of doped fibers with respect to ionizing-radiation dose and dose rate has been described by a power law[6,20-23,25]. The exact nature of radiation-induced changes in the luminescent band structure of such fibers has not been determined.

This paper reports the results of an investigation of the temporal evolution of photodarkening across the infrared (IR) portion of the spectrum (1.0 µm to 1.6 µm) in Yb-doped, Er-doped and Er/Yb co-doped optical fibers subjected to gamma radiation from a Co^{60} source with dose rates of 14.3, 40.1, and 118.7 rad(Si)/s, up to total doses of over 200 krad (Si). All data was obtained under passive (not actively pumped) conditions. The radiation-induced decrease in spectral transmittance was evaluated at a total accumulated dose of 2 krad (Si), approximating reasonable short-term (~2-5 years), real-world, near-Earth-orbit exposure conditions[23], and at >50 krad(Si), corresponding to longer time periods at which substantial optical darkening could be observed.

2. EXPERIMENT

A suite of Yb- and Er-doped aluminosilicate fibers from Liekki and two Er/Yb co-doped fibers from OFS were exposed to gamma radiation from a Co^{60} source in a test cell of the Gamma Irradiation Facility (GIF) at Sandia National Laboratories in Albuquerque, NM. The tested fibers were on the order of 3 m in length, and varied in core and cladding diameter, geometry, numerical aperture, and doping concentrations. The specific Yb fibers used were Yb1200-10/125DC, Yb1200-20/400DC, Yb1200-30/250DC, Yb1200-4/125, and Yb2000-6/125DC, where the first number designates the nominal peak absorption at 976 nm in dB/m, and the second and third numbers denote the core and cladding diameters respectively in µm. The 'DC' specifies the double-clad fibers. The erbium fibers tested were Er16-8/125, Er20-4/125, Er30-4/125, Er40-4/125, Er80-4/125 and Er110-4/125 and the co-doped fibers under test were OFS Er/Yb PM DC. Again for the erbium fibers, the first number in the identifying scheme denotes the nominal peak loss at 1.5 µm in dB/m while the second and third numbers relate to the core and cladding diameters respectively in µm. None of the Er fibers had a double-clad geometry. All fibers were fitted with SMA connectors (Coastal Connections) to facilitate connections to other fibers and test equipment. Double-clad fibers were fusion-spliced to ~1 m long pigtails in order to ensure that the light was confined within the core. SMF-28 pigtails (Corning) were used for the Yb1200 fibers, while HI-1060 pigtails (Corning) were used for the Yb2000 fibers.

The experimental setup in the GIF test cell is shown in Figure 1. The individual array elements making up the Co^{60} source were arranged on a platform, which was raised out of a pool of water into the cell during testing. The Yb-doped test fibers were spooled and placed in plastic boxes, which were vertically suspended from holders facing the source, to provide uniform irradiation. Data from four CaF_2 thermoluminescent devices (TLDs) per spool were averaged to give an indication of the dose rate received by each fiber at the various experiment locations within the test cell, while thermocouples were used to monitor sample temperatures throughout the experiment. Temperatures ranged from 26.3°C to about 30°C, and remained stable, varying only by approximately 2-3°C, during the exposures. The locations of the fiber holders determined the dose rates the fibers experienced. Fibers closest to the source experienced the highest dose rates of 118.7 rad(Si)/s while those further from the source received dose rates of either 40.1 rad(Si)/s or 14.3 rad(Si)/s, depending on their position within the test cell.

Outside of the test cell, broadband reference light from a 75 W xenon arc lamp (Oriel Model 6263) was coupled into a set of delivery fibers by means of collimating optics. The delivery fibers, which carried the optical signal into and out of the test chamber, were SMA connectorized and were standard low-OH silica fibers (Ocean Optics P100-10-VIS/NIR) with a relatively flat transmission spectrum in the near infrared. Special radiation-hard fibers could not be used due to higher OH levels, which introduced unwanted absorption in the wavelength region of interest. Half of the delivery fibers were connected to the ends of spooled, doped test fibers within the test cell. Light coupled into these delivery fibers traveled into the test cell, through the rare-earth-doped test fibers, and then back out of the test cell to the diagnostic equipment. These fiber lines constituted the test channels. The other half of the delivery fibers ran in pairs alongside the test-fiber lines, but the input and output fiber pairs were directly connected to one another inside the test cell (i.e.: the segment of doped, test fiber was absent from the fiber line), constituting background channels. Data collected from the background channels in this way was used to evaluate any changes in the transmission signals of the test-fiber lines which were attributable to losses incurred in the delivery fibers themselves (rather than in the spools of doped fiber). A time-dependent comparison of the spectral signal data with the spectral background data allowed for a direct analysis of gamma-induced losses in the rare-earth-doped fibers under test with the background removed. Segments of pigtail fibers were also included in the background channel configurations for those tests in which pigtails were used to couple light into double-clad test fibers. Data from multiple fiber lines were collected by sampling the fiber outputs sequentially using 1:9 fiber switches (Piezosystems Jena). Transmission spectra were collected on each fiber approximately once per minute and the effect of radiation-induced optical photodarkening was monitored over a 6- to 8-hour period by recording the temporal decrease in the transmittance of the xenon reference light over a broad wavelength window (~1.0 μm to 1.6 μm) using an optical spectrometer (Ocean Optics NIR 512). In addition, as the fiber samples varied in length, all transmission data were normalized to a standardized 1.0 meter fiber length. Results are summarized below.

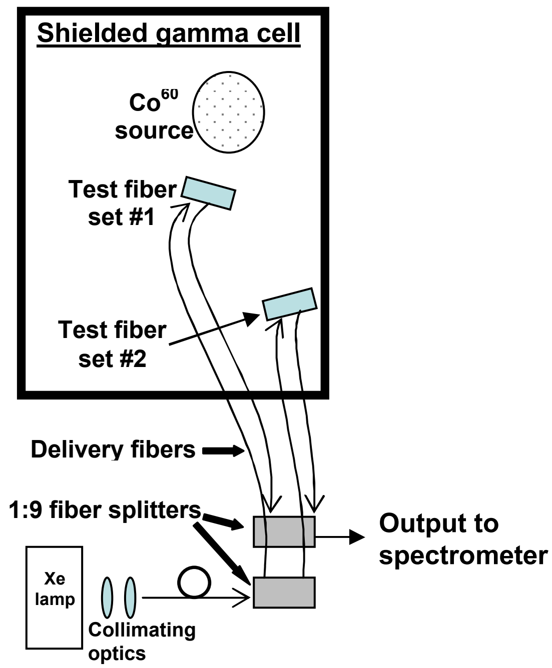
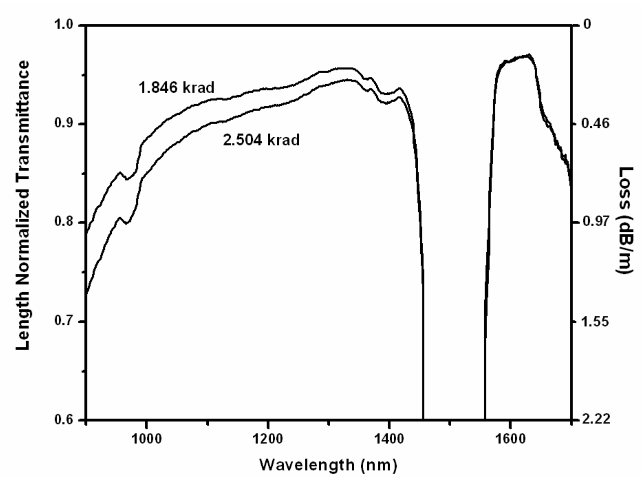


Figure 1: Experimental configuration for test fibers located in gamma test chamber (GIF-A) at Sandia National Laboratories, NM, for radiation exposure studies. Broadband optical radiation from a xenon arc lamp, located outside the test chamber, was coupled into a set of standard SiO_2 delivery (background) fibers. Delivery fibers entered the test chamber through access ports and coupled light into the test fibers located inside the gamma test chamber. The transmission spectrum over the wavelength range of 1000 nm to 1600 nm, was monitored at 1 min. intervals throughout the 6 - 8 hour gamma exposure for each test and/or background fiber. An Ocean Optic NIR 512 spectrometer was used to monitor spectral data.

3. RESULTS AND DISCUSSION

Transmittance data for the suite of tested fibers was examined as a function of both dose rate and total dose. Figure 2 shows examples of the data from the Er20-4/125 fiber after processing. The figure show the spectral response of the test fiber after receiving a dose of approximately 2 krad (Si), the estimated total dose received in a short deployment scenario in low-Earth orbit[23], with the left figure at a dose rate of 14.3 rad(Si)/s and the right at 40.1 rad(Si)/s. The large dip in the figures centered at 1.5 μm corresponds to strong absorption at this wavelength by the Er-constituent of the material. Total radiation-induced losses of 10-30% can be observed in the spectra. Similar data has been seen for Yb-doped fibers[25], except that the decrease in transmittance was more uniform with respect to wavelength and reached a maximum loss of approximately 8% for both dose rates at these total doses, indicating a reasonably high radiation resistance for the Yb-doped fibers as compared to the Er-doped materials.

Gamma-radiation-induced loss in optical transmittance in Er/Yb co-doped fiber is shown in Figure 3 for comparison. Loss bands attributable to the Yb constituent are evident at wavelengths below 1.1 µm and the large absorption band arising from the Er-dopant is seen centered at 1.5 µm as expected. It is quite interesting to note that the co-doped fiber appears to exhibit the strongest resistance to gamma-radiation-induced optical photodarkening at these total doses. Total accumulated losses of as little as 2-3% are observed in these fibers as compare to the much larger losses of 8% to 30% for the Yb- and Er-doped fibers respectively.



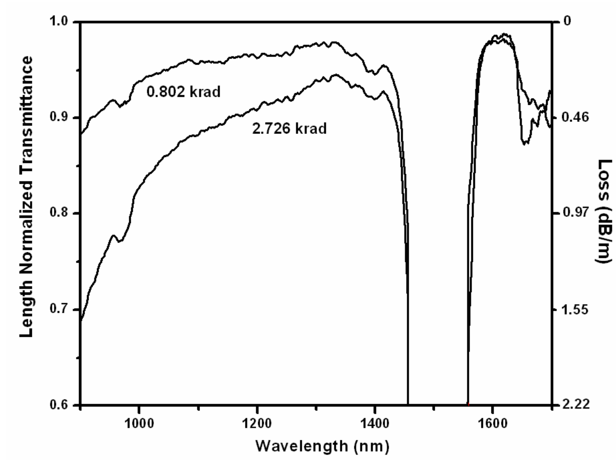


Figure 2: Gamma-radiation-induced decreases in optical transmittance at total doses commensurate with 2-5 years in a low-Earth-orbit. Data are taken from processed spectrometer data of an Er20-4/125 fiber. Dose rates of 14.3 rad(Si)/s and 40.1 rad(Si)/s are for the left and right plots, respectively.

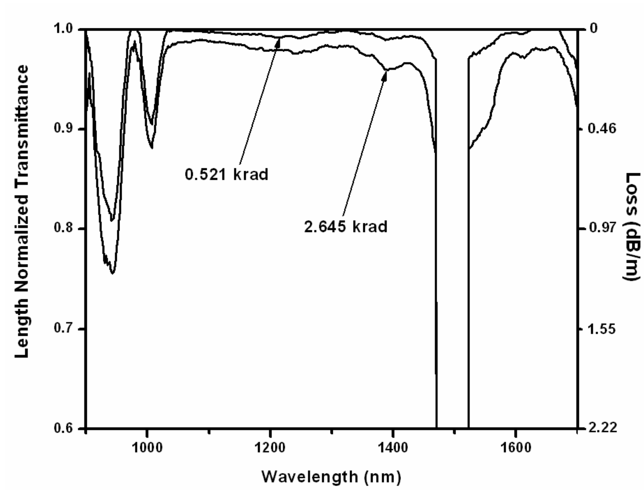


Figure 3: Gamma-radiation-induced decreases in optical transmittance at total doses commensurate with 2-5 years in a low-Earth-orbit. Data are taken from processed spectrometer data of an OFS Er/Yb PM DC fiber. The dose rate was 40.1 rad(Si)/s for this test sample.

Similar spectral trends can be observed in the samples exposed at both low and high dose rates with large accumulated total doses (upwards of 50 krad (Si)). These data are shown for Yb-doped fiber, Er-doped fiber, and for co-doped fiber in Figure 4 below. Significant photodarkening is seen in all of the samples following large total doses of gamma irradiation with eventual complete photodarkening observed for typical total doses of 100 krad (Si) or greater. Specifically, it can be seen that the fibers exhibited a relatively rapid decrease in the transmission spectrum over the 1.0 – 1.6 µm window reaching substantial levels of darkening (<40% transmittance at all wavelengths) at total accumulated doses of >50 krad. While these total dose levels clearly exceed the anticipated near-Earth space environment, it is instructive to examine these data taken under passive fiber-amplifier operation.

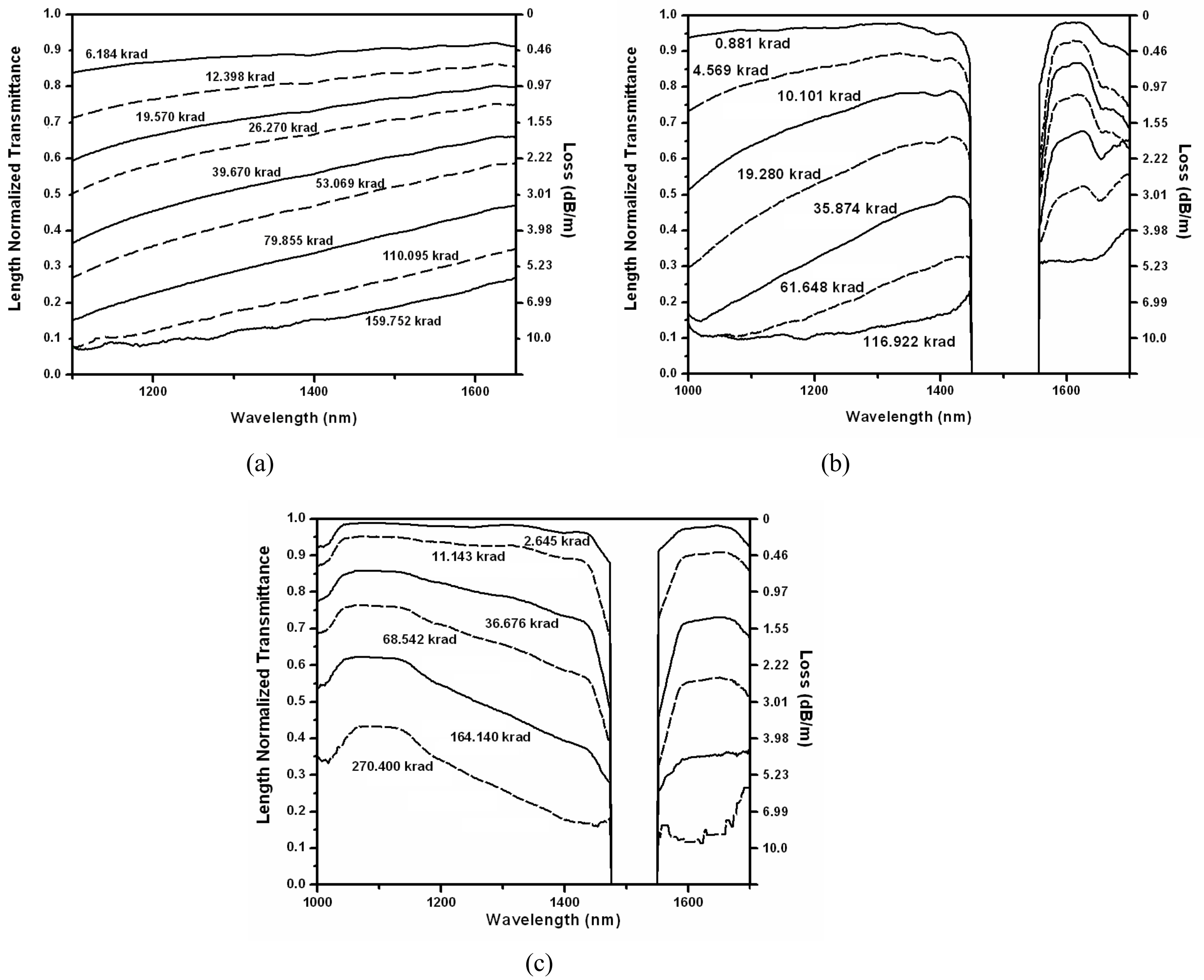


Figure 4: Effect of large total-dose gamma irradiation on the optical transmittance of (a) Yb-doped (Yb1200-4/125), (b) Er-doped (Er20-4/125) and (c) Yb/Er co-doped fibers. All samples were exposed at a dose rate of 40.1 rad(Si)/s.

To emphasize the dose-rate dependence of the transmittance, Figure 5 shows transmittance spectra obtained at different dose rates plotted together. A slight dose rate dependence is evident, which becomes more prominent at larger total accumulated gamma doses. The dose rate does not appear to affect the spectral shape of the absorption feature. Such an effect may be observed at all accumulated total dose values for both the Yb-doped and the Er-doped fibers. The difference between samples exposed at a rate of approximately 14.3 rad(Si)/s versus 40.1 rad(Si)/s was on the order of 3-10% across the observed spectrum. Such a dose-rate dependence warrants further investigation.

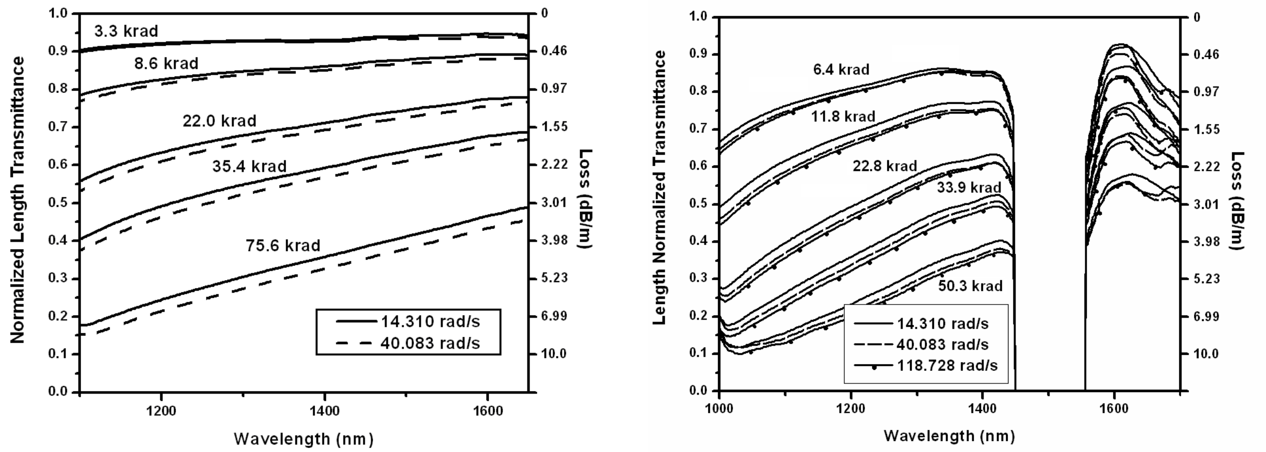


Figure 5: The effect of gamma dose rate on induced optical loss in Yb1200-4/125 (left) and Er20-4/125 (right).

In addition to the gamma radiation studies reported above, a series of post-radiation, thermal anneals were also attempted on the fiber samples. These investigations were performed in order to ascertain whether or not some portion of the permanent photodarkening, observed in all of the doped fibers following >100 krad (Si) gamma radiation exposure, 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 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 function was evaluated. Samples were heated to temperatures as high as 120°C for up to 30 minutes. In these experiments, no recovery in the transmittance of any of the samples was observed. All samples remained permanently photodarkened following all thermal treatments. Reports in the literature[13] do support the use of thermal anneals during radiation exposure in order to aid in recovery of the optical transmittance. Such a possibility remains a subject of future investigations.

4. CONCLUSION

It is clear that the application of optical materials and components in space-based technologies presents a significant challenge due to the adverse operational radiation environment. The presence of high energy gamma photons can lead to significant transmission loss in optical materials through the formation of radiation-induced color centers and subsequent optical photodarkening. In the present study, a representative space environment, of 2-5 years at low-Earth orbit, was approximated and evaluated. Reasonable estimates of the radiation exposure that optical fibers might be subjected to under those conditions were made and gamma radiation tests were conducted on doped optical fibers. The current report evaluates, for the first time, the temporal and spectral evolution of gamma-radiation-induced photodarkening in a suite of rare-earth-doped optical fibers across the near IR spectrum. Radiation-induced optical photodarkening was observed and evaluated for fibers exposed to ~ 2 krad (Si), representing the short-term LEO environment, and for fibers exposed to much larger doses of gamma radiation ranging above 50 krad (Si). The acquired doped-fiber spectra clearly show a decrease in the transmittance of the irradiated fibers across the spectrum, with generally a higher loss at shorter wavelengths, which is consistent with the notion of radiation-induced color center formation in the fibers[20-23]. At large doses over 100 krad (Si) 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 formed during gamma irradiation represent deep trap states.

It was observed that while all of the doped fibers exhibited radiation-induced optical transmission loss, the Yb-doped and the Er/Yb co-doped fibers showed a greater resistance to radiation damage than did the Er-doped fibers. In fact, the behavior of the Yb-doped and co-doped fibers at total doses representative of the environment over 2-5 years in LEO confirms the relative radiation hardness of these fibers. As speculated previously, this radiation resistance might be the result of the DND technology used to produce the fibers, which typically produces more uniform profiles, thus effectively dissipating energy faster and preventing the formation of color centers[44], however this would only explain the general radiation response of all of the Liekki fibers under test (as all were fabricated using similar processing). The difference in the radiation response of the different dopants, thus, is more likely explained by the presence of valence-state conversion processes (specifically the Yb^{2+}/Yb^{3+} conversion). It is reasonable to suppose that the ability of Yb to both accept and donate electrons enables it to act as an absorbing agent, thereby shielding the rest of the fiber structure from photodarkening[24, 25, ,45].

In addition to the observed photodarkening, the data did suggest some non-linearity in the dose-rate dependence of the photo-response of the fibers. This effect clearly requires further study in order to understand the potential impact of solar excursions and abnormal radiation flux on the performance of the doped-fiber devices.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. R. L. Farrow, D. A. V. Kliner, P. Schrader, A. A. Hoops, S. W. Moore, G. R. Hadley, R. L. Schmitt, “High-Peak-Power (>1.2 MW) Pulsed Fiber Amplifier,” *Proc. SPIE* 6102, 61020L (2006).
2. K. Sumimura, H. Yoshida, H. Fujita, M. Nakatsuka, “Yb Fiber Mode-Locked Laser with a Wide Tuning Range for Chirped Pulse Amplification System,” *IEICE Electronics Express* 3 (11), 233-237 (2006).
3. Y. Jeong, J. K. Sahu, D. N. Payne, J. Nilsson, “Ytterbium-Doped Large-Core Fiber Laser with 1.36 kW Continuous Wave Output Power,” *Opt. Exp.* 12 (25), 6088-6092 (2004).
4. C. D. Brooks, F. Di Teodoro, “1-mJ Energy, 1-MW Peak-Power, 10-W Average-Power, Spectrally Narrow, Diffraction-Limited Pulses From a Photonic-Crystal Fiber Amplifier,” *Opt. Exp.* 13 (22), 8999-9002 (2005).
5. M. Laroche, H. Gilles, S. Girard, N. Passilly, K. Aït-Ameur, “Nanosecond Pulse Generation in a Passively Q-Switched Yb-Doped Fiber Laser by Cr^{4+}:YAG Saturable Absorber,” *IEEE Photonics Technology Letters* 18 (6), 764-766 (2006).
6. J. Nilsson, S.-U. Alam, J. A. Alvarez-Chavez, P. W. Turner, W. A. Clarkson, A. B. Grudinin, “High-Power and Tunable Operation of Erbium-Ytterbium Co-Doped Cladding-Pumped Fiber Lasers,” *IEEE J. of Quantum Electron.* 39 (8), 987-994 (2003).
7. J. E. Townsend, W. L. Barnes, K. P. Jedrzejewski, S. G. Grubb, “Yb^{3+} Sensitised Er^{3+} Doped Silica Optical Fibre with Ultrahigh Transfer Efficiency and Gain,” *Electron. Lett.* 27 (21), 1958-1959 (1991).
8. J. L. Zyskind, “Erbium-Doped Fiber Amplifiers,” *Proc. SPIE* 158, 14-23 (1991).
9. W. J. Miniscalco, “Erbium-Doped Glasses for Fiber Amplifiers at 1500 nm,” *J. Lightwave Technology* 9 (2), 234-250 (1991).
10. G. M. Williams, M. A. Putnam, C. G. Askins, M. E. Gingerich, E. J. Friebele, “Radiation Effects in Erbium-Doped Optical Fibres,” *Electron. Lett.* 28 (19), 1816-1818 (1992).
11. R. Paschotta, J. Nilsson, A. C. Tropper, D. C. Hanna, "Ytterbium-Doped Fiber Amplifiers," *IEEE J. Quantum Electron.* 33 (7), 1049-1056 (1997).
12. H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, J. M. Dawes, “Ytterbium-Doped Silica Fiber Lasers: Versatile Sources for the 1-1.2 µm Region,” *IEEE Journal of Selected Topics in Quantum Electronics* 1 (1), 2-13 (1995).
13. R. G. Ahrens, J. J. Jaques, M. J. LuValle, D. J. DiGiovanni, R. S. Windeler, "Radiation Effects on Optical Fibers and Amplifiers," *Proc. SPIE*, 4285, 217-225 (2001).
14. R. G. Ahrens, J.A. Abate, J. J. Jaques, H. M. Presby, A. B. Fields, D. J. DiGiovanni, R. S. Windeler, S. Kannan, M. J. LuValle, “Radiation Reliability of Rare Earth Doped Optical Fibers for Laser Communication Systems,” *Proc. MILCOM ‘99, IEEE* (1), 694-697 (1999).

15. R. J. Bussjager, M. J. Hayduk, S. T. Johns, E. W. Taylor, "Comparison of Radiation-Induced Passive and Dynamic Responses in Two Erbium-Doped Fiber Lasers," *IEEE Aerospace Conf. Proc.* 3, 1369-1379 (2002).
16. M. Caussanel, O. Gilard, M. Sotom, P. Signoret, J. Gasiot, "Extrapolation of Radiation-Induced EDFA Gain Degradation at Space Dose Rate," *Electron. Lett.* 41 (4), 168-170 (2005).
17. E. R. Benton, E. V. Benton, "Space Radiation Dosimetry in Low-Earth Orbit and Beyond," *Nuclear Instruments and Methods in Physics Research B* 184 (1-2), 255-294 (2001).
18. P. S. Haskins, J. E, McKisson, A. G. Weisenberger, D. W. Ely, T. A. Ballard, C. S. Dyer, P. R. Truscott, R. B. Piercey, A. V. Ramayya, "Gamma-ray measurements from the space shuttle during a solar flare," *Adv. Space Res.* 12 (2-3), 331-334 (1992).
19. L. B. Glebov, "Linear and Nonlinear Photoionization of Silicate Glasses", *Glass Science and Technology* 75, C2 (2002).
20. D. L. Griscom, "Nature of Defects and Defect Generation in Optical Glasses," *Proc. Soc. Photo-Opt. Instrum. Eng.* 541, (1985).
21. D. L. Griscom, M. E. Gingerich, E. J. Friebele, "Radiation Induced Defects in Glasses: Origin of Power-Law Dependence of Concentration on Dose," *Phys. Rev. Lett.* 71 (7), 1019-1022 (1993).
22. G. M. Williams, B. M. Wright, W. D. Mack, E. J. Friebele, "Projecting the Performance of Erbium-Doped Fiber Devices in a Space Radiation Environment," *Proc. SPIE* 3848, 271-280 (1999).
23. O. Berné, M. Caussanel, O. Gilard, "A Model for the Prediction of EDFA Gain in a Space Radiation Environment," *Photonics Technology Letters, IEEE,* 16 (10), 2227–2229 (2004).
24. B. P. Fox, Z. V. Schneider, K. Simmons-Potter, W. J. Thomes, D. C. Meister, R. P. Bambha, D. A. V. Kliner, M. J. Söderlund, "Gamma Radiation Effects in Yb-Doped Optical Fiber," *Proc. SPIE* 6453, (2007).
25. B. P. Fox, Z. V. Schneider, K. Simmons-Potter, W. J. Thomes, D. C. Meister, R. P. Bambha, D. A. V. Kliner, "Spectrally-Resolved Transmission Loss in Gamma Irradiated Yb-Doped Optical Fibers," *IEEE J. of Quantum. Electron.*, submitted (2007).
26. R. B. J. Lewis, E. S. R. Sikora, J. V. Wright, R. H. West, S. Dowling, "Investigation of Effects of Gamma Radiation on Erbium-Doped Fibre Amplifiers," *Electron. Lett.* 28 (17), 1589-1591 (1992).
27. M. M. Broer, D. M. Krol, and D. J. DiGiovanni, "Highly Nonlinear Near-Resonant Photodarkening in a Thulium-Doped Aluminosilicate Glass Fiber," *Opt. Lett.* 18 (10), 799 (1993).
28. C. Fukuda, Y. Chigusa, T. Kashiwada, M. Onishi, H. Kanamori, S. Okamoto, "γ-Ray Irradiation Durability of Erbium-Doped Fibres," *Electron. Lett.* 30 (16), 1342-1344 (1994).
29. J. D. O. McFadden, R. Greenwell, J. Hatch, C. Barnes, D. Pentrack, D. Scott, "Measurements and Results of Gamma Radiation Induced Attenuation at 980 nm of Single Mode Fiber," *Proc. SPIE*, 2811, 77-86 (1996).
30. G. M. Williams, M. A. Putnam, E. J. Friebele, "Space Radiation Effects on Erbium Doped Fibers," *Proc. SPIE* 2811, 30-37 (1996).
31. E. W. Taylor, S. J. McKinney, A. D. Sanchez, J. E. Winter, D. M. Craig, A. H. Paxton, R. Ewart, K. Miller, T. O'Connor, R. Kaliski, "Gamma-Ray Induced Effects in Erbium-Doped Fiber Optic Amplifiers," *Proc. SPIE*, 3440, 16-23 (1998).
32. R. J. Bussjager, M. J. Hayduk, et al., "Gamma-Ray Induced Responses in an Erbium Doped Fiber Laser," *Aerospace Conference, 2001, IEEE Proceedings* 3, 1473-1479 (2001).
33. B. Brichard, A. F. Fernandez, H. Ooms, M. Van Uffelen, F. Berghmans, "Study of the Radiation-Induced Optical Sensitivity of Erbium and Aluminum-Doped Fibres," *Proceedings of the 7th European Conference on Radiation and its Effects on Components and Systems, RADECS 2003, IEEE*, (2003).
34. S. T. Johns, M. J. Hayduk, R. J. Bussjager, C. M. Gerhardstein, E. K. Vettese, M.L. Fanto, E. W. Taylor, "Temporal Responses of Actively Mode-Locked Erbium-Doped Fiber Lasers Irradiated by Gamma-Rays," *Electron. Lett.* 39 (18), 1310-1312 (2003).
35. M. Van Uffelen, S. Girard, et al., "Gamma Radiation Effects in Er-Doped Silica Fibers," *IEEE Trans. Nucl. Sci.* 51 (5), 2763-2769 (2004).
36. M. N. Ott, "Radiation Effects Expected for Fiber Laser/Amplifier Rare Earth Doped Optical Fiber," Sigma Research and Engineering / NASA GSFC, Parts, Packaging and Assembly Technologies Office Survey Report, (2004).
37. T. S. Rose, D. Gunn, G. C. Valley, "Gamma and Proton Radiation Effects in Erbium-Doped Fiber Amplifiers: Active and Passive Measurements," *J. Lightwave Technology* 19 (12), 1918-1923 (2001).
38. J. J. Koponen, M. J. Söderlund, S. K. Tammela, "Photodarkening in Yb-Doped Silica Fibers," H. Po Liekki Oy - *Proc. SPIE* 5990, 599008 (2005).

39. E. W. Taylor, J. Liu, "Ytterbium-Doped Fiber Laser Behavior in Gamma-Ray Environment," *Proc. SPIE 5897*, 58970E (2005).
40. J. J. Koponen, M. J. Söderlund, H. J. Hoffman, S. K. T. Tammela, "Measuring Photodarkening from Single-Mode Ytterbium Doped Silica Fibers," *Opt. Exp.* 14 (24), 11539-11544 (2006).
41. J. J. Koponen, M. J. Söderlund, H. J. Hoffman, D. A. V. Kliner, J. Koplow, "Photodarkening Measurements in Large-Mode-Area Fibers," *Proc. SPIE* 6453, 64531E (2007).
42. I. Manek-Hönninger, J. Boullet, T. Cardinal, F. Guillen, S. Ermeneux, M. Podgorski, R. Bello Doua, F. Salin, "Photodarkening and Photobleaching of an Ytterbium-Doped Silica Double-Clad LMA Fiber," *Opt. Exp.* 15 (4), 1606-1611 (2007).
43. H. Henschel, O. Köhn, H. U. Schmidt, J. Kirchhof, S. Unger, "Radiation-Induced Loss in Rare Earth Doped Silica Fibres," *IEEE Trans. Nucl. Sci.* 45 (3), 1552-1557 (1998).
44. S. K. Tammela, M. J. Söderlund, J. J. Koponen, V. Philippov, P. Stenius, "The Potential of Direct Nanoparticle Deposition for the Next Generation of Optical Fibers," *Proc. SPIE* 6116, 61160G (2006).
45. S. M. Kaczmarek, T. Tsuboi, M. Ito, G. Boulon, G. Leniec, "Optical Study of Yb^{3+}/Yb^{2+} Conversion in CaF_2 Crystals," *J. Phys.: Condens. Matter* (17), 3771-3786 (2005).