

Effect of Ionizing Radiation on Optical Transmission of Actively Pumped Yb-Doped Fiber Amplifiers

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Abstract: Fibers doped with Yb³⁺ serve as optical amplification elements in many ground-based and space-based systems. We instigate the effects of gamma-radiation-induced photodarkening on the performance of such fibers.

Summary: Fibers doped with rare-earth constituents are of particular interest for many applications, since they often serve as critical components of fiber optic systems due to their compact size, light weight, and high-power amplification capabilities. Ytterbium-doped fibers, in particular, have a simple band structure, which can be used to amplify signals in the ~ 1.06 μm region, useful for many data applications.¹⁻⁴ However, such elements are often the most sensitive part of a system. When optical fibers are exposed to gamma radiation, a photodarkening process takes place in which the optical transmittance of the fiber decreases with increasing accumulated dose.⁵⁻⁹ Understanding this process is critical for determining the system performance of fiber amplifiers in space-based applications, for example. The physical origin of the darkening is understood to arise from the presence of trap states, which are filled as a consequence of ionizing radiation, leading to an unwanted increase of absorption of light at relevant wavelengths, such as the signal and pump wavelengths of an amplifier. The amount of radiation-induced absorption observed is contingent upon a number of factors, ranging from the fiber geometry, fabrication methods, and type of glass, to specific type and amounts of dopants, as well as type of radiation, dose rate, total accumulated dose, and effects of annealing¹⁰⁻¹¹.

In the present study, Yb³⁺ doped fibers were subjected to gamma radiation from a Co⁶⁰ source in either a passive (unpumped) mode or an active (pumped) mode. Optical transmission of the former was monitored to determine the effect of gamma radiation on the fiber materials. In the latter, the optical transmission of actively-pumped fiber amplifiers was monitored, in-situ, during radiation exposure to determine the effects on device performance.

Passive fiber irradiation was conducted at the Gamma Irradiation Facility (GIF) at Sandia National Laboratories (SNL) in Albuquerque, NM. As can be seen in the experimental set up (Figure 1) tested fibers (length ~ 3 m) were spooled and placed at different locations within the test cell in order to study the impact of varying dose rate on their optical behavior. Fibers closest to the source experienced the higher dose rate of 40.1 rad(Si)/s, while fibers further from the source received 14.3 rad(Si)/s. 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, standard, low-OH silica fibers (Ocean Optics P100-10-VIS/NIR) with a relatively flat transmission spectrum in the near-IR. 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 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. 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 doped fibers under test with the background removed.

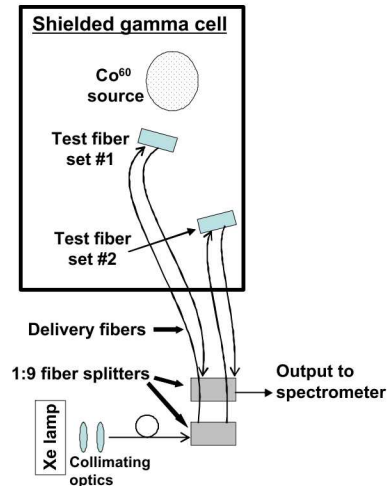


Figure 1: Test configuration for passive radiation tests on doped fibers.

Active amplifier testing was conducted at the Leach Science Center in Auburn, AL. A schematic of the experimental setup is given in Figure 2. The amplifier was composed of passive fiber, a Yb^{3+} -doped optical fiber, a probe laser at $\sim 1.06 \mu\text{m}$, and a pump laser diode radiating at 916 nm and operating near 2 V. The pump light was coupled into an optical isolator, and the two laser beams were then unified into a single delivery fiber using a combiner. The delivery fiber propagated the signal and pump beams from the experiment area, outside the radiation cell, through a conduit into the gamma irradiation cell where it was fusion spliced to $\sim 3 \text{ m}$ of active Yb^{3+} -doped test fiber. The exit end of the doped spool was fusion spliced to another passive fiber, which guided the output of the amplifier out of the test cell and onto a detector, configured to monitor the amplifier signal output at the probe wavelength of $\sim 1.06 \mu\text{m}$.

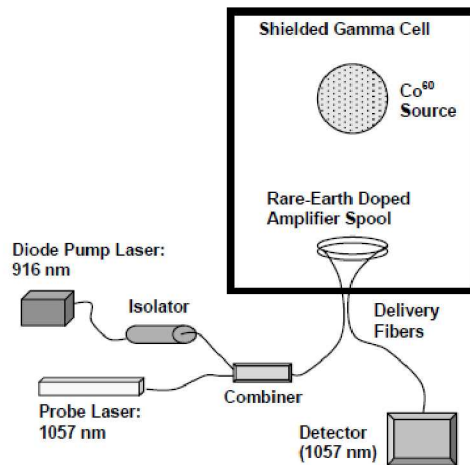


Figure 2: Test configuration for active fiber amplifier testing.

In order to foster an understanding of the behavior of the Yb^{3+} -doped fiber material to gamma radiation, a spectroscopic investigation was essential. To this end, spectroscopy was performed on the passive gamma-irradiated fiber samples as well as on pristine, unirradiated sample fibers enabling the examination of gamma-induced absorption across visible and NIR wavelength bands. The results of the visible spectroscopy are shown in Fig. 3, with the left figure (a) showing the irradiated and pristine samples in terms of relative transmittance. In this figure, the shape of the lamp spectrum is clearly

evident. Figure 3(b) on the right, shows the logarithm of the pristine sample counts divided by the irradiated sample counts, resulting in a plot of excess, gamma-induced absorbance of the irradiated fiber relative to the pristine fiber. A large absorption can clearly be seen ranging from below 400 nm to about 700 nm, with an absorption maximum around 500 nm, indicating color-center production in this part of the spectrum. This absorption is consistent with certain aluminum-related radiation-induced color-centers, such as the aluminum-oxygen-hole-center absorptions at 388 nm and 539 nm¹².

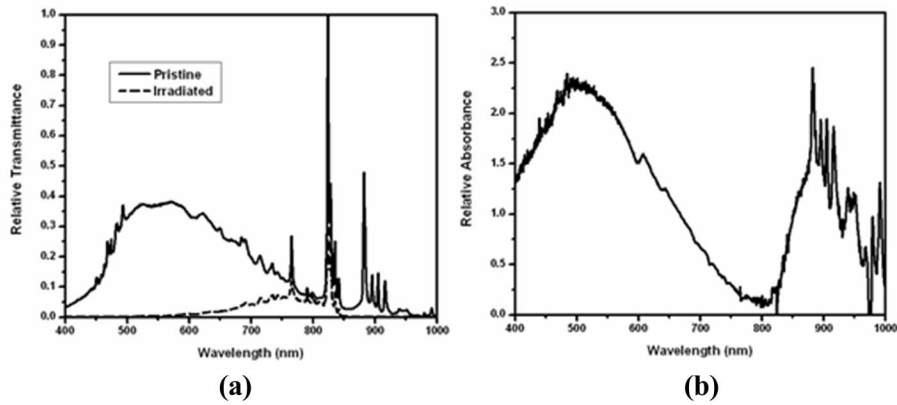


Figure 3: Absorption spectroscopy of gamma-irradiated and pristine doped fiber samples in the visible part of the spectrum plotted (a) individually in units of relative transmittance (normalized to large peak at 824 nm) and (b) in terms of relative absorbance.

For the actively-pumped fiber amplifiers, the decrease of the amplifier output signal (with the 916 nm pump laser current operating at 6 A, 1.9 V) was monitored during the irradiation and is shown in Fig. 4. The left side of this figure, (a), shows the decrease of the amplifier output signal power at 1057 nm, which is seen to be exponential in nature up to a dose of 7.6 krad (Si), at which point the signal had decayed to ~17% of its original value and the irradiation was stopped. The data in Fig. 4(a) is closely fit with an exponential curve with a decrease of about 1 dB/krad(Si).

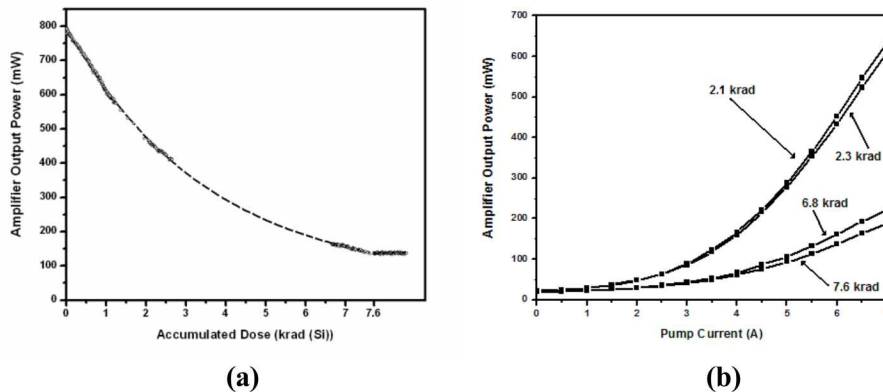


Figure 4: (a) Decrease of amplifier output due to increasing accumulated gamma-radiation dose up to 7.6 krad (Si), with a dose rate of 419 rad(Si)/hr, after which the irradiation was stopped (the dashed line is an exponential trend line). (b) Decrease of amplifier output power vs. amount of pumping for various total accumulated gamma-radiation doses (doses are in krad (Si)).

The decay in amplifier efficiency can also be seen in Fig. 4(b), which depicts several curves of amplifier output power vs. pump laser current for increasing total accumulated gamma-radiation doses. Evident in the figure is the similarity of the fiber output, regardless of total accumulated gamma-radiation dose, at low pump laser currents. As the pump laser current is increased, the substantial effect of gamma radiation

on the amplifier operation can clearly be seen as the amplifier output suffers from significant radiation-induced loss with increasing total accumulated radiation dose.

Further results of both passive and active radiation testing of these doped fibers will be discussed and results will be placed in the context of both induced defects in the materials and overall amplifier performance.

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References:

- 1) R. L. Farrow, D. A. V. Kliner, P. Schrader, A. A. Hoops, S. W. Moore, G. R. Hadley and R. L. Schmitt, "High-Peak-Power (>1.2 MW) Pulsed Fiber Amplifier," Proc. SPIE 6102, 61020L (2006).
- 2) K. Sumimura, H. Yoshida, H. Fujita, and 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) R. Paschotta, J. Nilsson, A. C. Tropper, and D. C. Hanna, "Ytterbium-Doped Fiber Amplifiers," IEEE J. Quantum Electron. 33(7), 1049-1056 (1997).
- 4) H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, and 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).
- 5) R. G. Ahrens, J. A. Abate, J. J. Jaques, H. M. Presby, A. B. Fields, D. J. DiGiovanni, R. S. Windeler, S. Kannan, and M. J. LuValle, "Radiation Reliability of Rare Earth Doped Optical Fibers for Laser Communication Systems," Proc. MILCOM '99, IEEE 1, 694-697 (1999).
- 6) O. Berné, M. Caussanel, and O. Gilard, "A Model for the Prediction of EDFA Gain in a Space Radiation Environment," Photonics Technology Letters, IEEE 16(10), 2227-2229 (2004).
- 7) J. D. O. McFadden, R. Greenwell, J. Hatch, C. Barnes, D. Pentrack, and D. Scott, "Measurements and Results of Gamma Radiation Induced Attenuation at 980 nm of Single Mode Fiber," Proc. SPIE 2811, 77-86 (1996).
- 8) B. P. Fox, Z. V. Schneider, K. Simmons-Potter, W. J. Thomes, D. C. Meister, R. P. Bambha, D. A. V. Kliner, and M. J. Söderlund, "Gamma Radiation Effects in Yb-Doped Optical Fiber," Proc. SPIE 6453, 645328 (2007).
- 9) B. P. Fox, Z. V. Schneider, K. Simmons-Potter, W. J. Thomes, D. C. Meister, R. P. Bambha, and D. A. V. Kliner, "Spectrally-Resolved Transmission Loss in Gamma Irradiated Yb-Doped Optical Fibers," IEEE J. of Quantum. Electron. 44(6), 581-586 (2008).
- 10) T. S. Rose, D. Gunn, and C. G. Valley, "Gamma and Proton Radiation Effects in Erbium-Doped Fiber Amplifiers: Active and Passive Measurements," J. Lightwave Technology 19(12), 1918-1923 (2001).
- 11) B. Tortech, Y. Ouerdane, S. Girard, J.-P. Meunier, A. Boukenter, T. Robin, B. Cadier, and P. Crochet, "Radiation Effects on Yb- and Er/Yb-Doped Optical Fibers: A Micro Luminescence Study," J. Non-Cryst. Solids 355(18-21), 1085-1088 (2009).
- 12) T. Arai, K. Ichii, S. Tanigawa, and M. Fujimaki, "Defect Analysis of Photodarkened and Gamma-Ray Irradiated Ytterbium-Doped Silica Glasses," Optical Fiber Communication Conference, OSA Technical Digest, paper OWT2, (2009).