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GAMMA-RADIATION-INDUCED DEGRADATION OF ACTIVELY PUMPED SINGLE-MODE YTTERBIUM-DOPED OPTICAL LASERS -POSTPRINT

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The integration of optical components into the digital processing units of satellite subsystems has the potential to remove interconnect bottlenecks inherent to the volume, mass, complexity, reliability and crosstalk issues of copper-based interconnects. Assuming on-board high-bandwidth communications will utilize passive optical fibers as a communication channel; this work investigates the impact of gamma irradiation from a Co-60 source on both passive optical fibers and ytterbium-doped single-mode fibers operated as amplifiers for a 1060-nm light source. Standard optical patch cables were evaluated along with active Yb-doped double-clad fibers. Varied exposure times and signal transmission wavelengths were used to investigate the degradation of the fibers exposed to total doses above 100 krad (Si). The effect on the amplified signal gain was studied for the Yb-doped fibers. The increased attenuation in the fibers across a broad wavelength range in response to multiple levels of gamma radiation exposure along with the effect that the increased attenuation has on the actively pumped Yb-doped fiber amplifier performance is discussed.

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Gamma-radiation-induced degradation of actively pumped single-mode ytterbium-doped optical fibers

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ABSTRACT

The integration of optical components into the digital processing units of satellite subsystems has the potential to remove interconnect bottlenecks inherent to the volume, mass, complexity, reliability and crosstalk issues of copper-based interconnects. Assuming on-board high-bandwidth communications will utilize passive optical fibers as a communication channel, this work investigates the impact of gamma irradiation from a Co-60 source on both passive optical fibers and ytterbium-doped single-mode fibers operated as amplifiers for a 1060-nm light source. Standard optical patch cables were evaluated along with active Yb-doped double-clad fibers. Varied exposure times and signal transmission wavelengths were used to investigate the degradation of the fibers exposed to total doses above 100 krad (Si). The effect on the amplified signal gain was studied for the Yb-doped fibers. The increased attenuation in the fibers across a broad wavelength range in response to multiple levels of gamma radiation exposure along with the effect that the increased attenuation has on the actively pumped Yb-doped fiber amplifier performance, is discussed.

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

1. INTRODUCTION

Optical fibers are a desirable replacement to conventional electronic methods of communication given their lighter weight, imperviousness to interference, and wide-bandwidth coverage. Prior studies conducted on the effects of radiation on passive optical fibers have identified that the major mechanism of performance degradation is the creation of absorbing species in the fiber, which in turn inhibit the transmission of light at certain wavelengths[1,2,3,4]. In recent years, the use of rare-earth (RE) doped optical fibers has expanded greatly; nevertheless, their ability to be used in harsh radiation environments has only been the subject of a limited number of studies[1‾5]. These fibers exhibit some of the same decreases in transmission seen in passive optical fibers, but the degree of degradation is significantly higher and the mechanisms responsible for the increase are still not fully identified[5].

Interest in using an all-fiber laser system, possibly one composed of Yb-doped fibers, in defense applications has spurred the need to further study the effects of radiation on Yb-doped fibers (YDFs). The fiber laser presents an extremely lightweight and potentially rugged option for use in multiple platforms, including satellites[6]. Nevertheless, the utility of such a laser for use in radiation-harsh environments will be limited by the damage to the YDFs. Indeed, previous studies have revealed that this is the most radiation-sensitive component in such laser systems[5].

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In this study, single-mode YDFs and passive optical fibers of the type used with YDFs for transmitting amplified signals or laser light were evaluated using the cobalt (Co)-60 gamma irradiation facility at The Ohio State University. A radiation dose rate of 43 krad(Si)/hr was used to expose the fibers to a maximum total dose that ranged from 150-250 krad(Si). The transmission of light through the fibers was measured in-situ and therefore the single-mode YDFs were operated in two modes. Some fibers were actively pumped and seeded (as amplifiers) while others were kept dark (no light) during irradiation, and only pumped/seeded for a short duration (15 sec) at approximately 5 minute intervals for the purpose of conducting measurements. In order to gain further insight into the damage mechanisms, multi-mode YDFs were also irradiated in the same environment while the transmission of a white light source (from 400 to 1100 nm) through the multi-mode YDFs was monitored.

2. EXPERIMENT

2.1 Tested fibers

Three different fiber sample sets were evaluated. These included two types of commercially available double-clad Yb-doped fibers, a single-mode fiber with a core size of 6 µm and a cladding of 125 µm and a multi-mode fiber with a core size of 40 µm, and a passive single-mode fiber of the standard SMF-28 jacketed variety.

The Yb-doped fiber, manufactured by nLight, is a highly doped fiber that provides large signal gain using relatively short lengths[7].

Table 1. Description of the optical fibers used for in-situ analysis of the radiation damage

Optical fiber	*Core Dopant*	*Core/cladding diameters (µm)*
Single-mode-YDF	Yb	6/125
Single-mode-Passive	None	8/125
Multi-mode-YDF	Yb	20/400

2.2 Irradiation source

The Co-60 gamma cell at The Ohio State University is a pool-type gamma irradiation facility using a common cobalt cylindrical rod irradiator submerged 20 feet into a water tank. A mechanical elevator in a 6-in dry tube lowers the sample to the irradiator for measurements, taking approximately 15 seconds to become fully situated. Once in place, the fiber under test is kept at approximately room temperature. The sample location determines the dose rate; in this work the maximum rate available, 43 krad(Si)/hr, was used.

2.3 Experimental setup

The experimental setup for the single-mode YDF irradiation is detailed in Figure 1. Here five-meter long single-mode fiber patch cables were spliced onto the ends of each Yb-doped fiber sample that was then lowered into the irradiation cell to expose it to the radiation source. The pump and signal laser were combined using a wavelength-division multiplexer (WDM) and input into the fiber under test; the output was subsequently split using a 50/50 splitter between the power meter and the optical spectrum analyzer (OSA). The OSA was used to measure the spectral characteristics of the light transmission and amplification during irradiation. A 99/1 splitter was included on the output of the 1064-nm laser diode after the laser but before the WDM splitter. The 1% output from the splitter was used to monitor signal power fluctuations during the irradiation.

Using this setup, the radiation-induced attenuation (RIA) of the amplified output signal is calculated using Eq 1.

$$\mathrm{RIA}(\lambda,t) = \frac{-10}{l} \times \log\left(\frac{P_{out}(\lambda,t) * P_s(\lambda,t_0)}{P_{out}(\lambda,t_0) * P_s(\lambda,t)}\right) \qquad (1)$$

In (1), *RIA(λ,t)* is the radiation-induced attenuation at a specific time and wavelength measured in dB/m. $P_s(\lambda,t_0)$ is the initial measurement of the signal laser output through the splitter while $P_s(\lambda,t)$ is the measurement at time *t*. The power output from the single-mode YDF before and during irradiation is represented by $P_{out}(\lambda,t_0)$ and $P_{out}(\lambda,t)$, respectively.

The power meter measured the output at 1060 nm and the OSA took spectrum measurements from 970 to 1170 nm. All samples were characterized onsite using the exact same setup prior to lowering them into the irradiation cell.

The multi-mode YDFs were likewise connected to 5-m long 50-µm core passive fibers designed for transmission of 400- to 2400-nm light for the duration of the experiment. The multi-mode YDFs were lowered and exposed while the transmission of a temperature-stabilized white light source was measured through the fibers throughout irradiation and afterwards; this experimental configuration is shown in Figure 2. The transmission spectrum from 500 to 1100 nm was recorded using a CCD spectrometer connected to a laptop. The power spectral density of this light source is not high enough to induce any appreciable amplification, fluorescence, or nonlinear effects in the multi-mode YDFs.

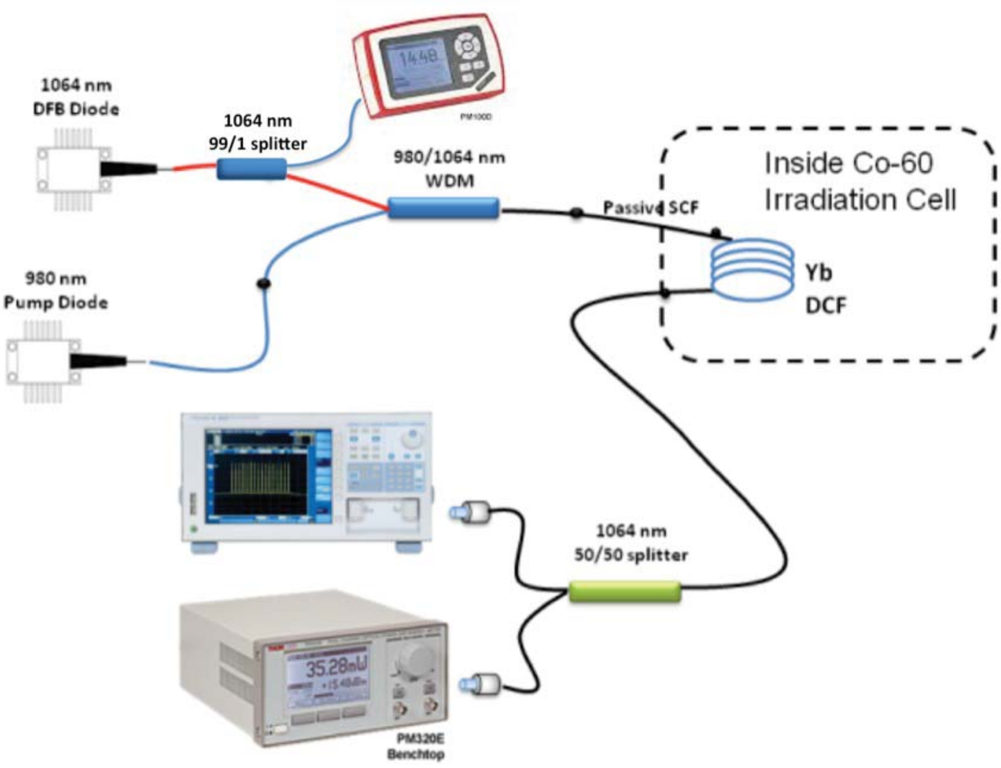

Figure 1. Diagram of the measurement system used for single-mode fiber irradiation.

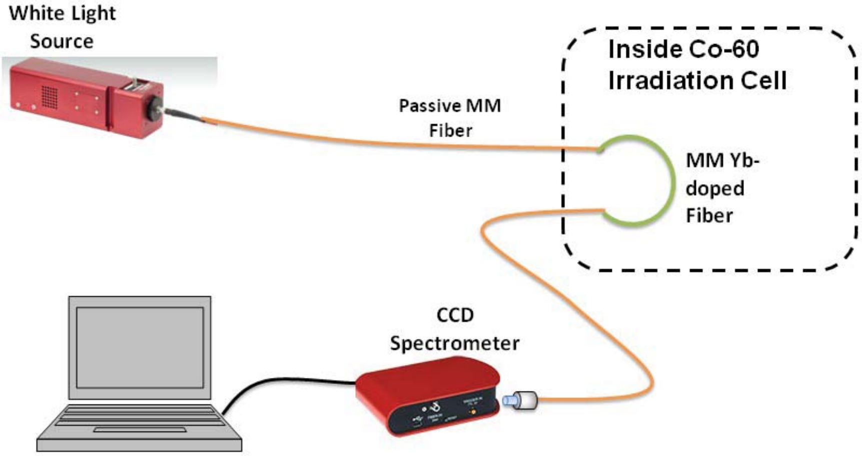

Figure 2. Diagram of measurement system used for multi-mode YDF irradiation

3. RESULTS AND DISCUSSIONS

Degradation of the amplifier output gain was measured to estimate the system-level vulnerability of the Yb-doped fibers. Specifically, spectral RIA measurements were used to analyze the origin of the degradation. The degradation rates of the single-mode and multi-mode fibers were then correlated in order to determine the region of induced absorption that best explains the single-mode YDFA performance degradation.

3.1 Single-mode YDF amplifier performance

During irradiation of both the continuously pumped and intermittently pumped amplifier, the output power decreased nearly monotonically with total dose. This indicates that the degradation during irradiation is a result of the formation of both transient and long-lived defects within the fiber. This also indicates that the degradation is not related to whether the doped fiber is pumped or not, only its overall exposure determines the degradation, an important finding of this work.

For clarity, the data presented in figures 3–7 are from 2 fibers whose data are representative of the performance of the other 6 fibers tested. Both fibers were irradiated in the Co-60 cell at a dose rate of 43 krad(Si)/hr to a total dose of at least 150 krad(Si). The first fiber irradiated was operated as a YDFA during irradiation. Following irradiation, it was left outside the irradiation cell to recover overnight (unpumped) and the amplification was measured again the following day, 20 hours later. The fiber was then lowered back into the Co-60 cell and again exposed to 150 krad(Si). The second fiber was unpumped (except during measurements) and the pump and signal lasers were turned on at regular intervals to measure its amplified signal output. The set of fibers irradiated demonstrate a loss of amplified signal output of 5.3±0.3 dB/m after 150 krad(Si) irradiation regardless of whether they were pumped or un-pumped during their exposure to the radiation source, **Figure 3**.

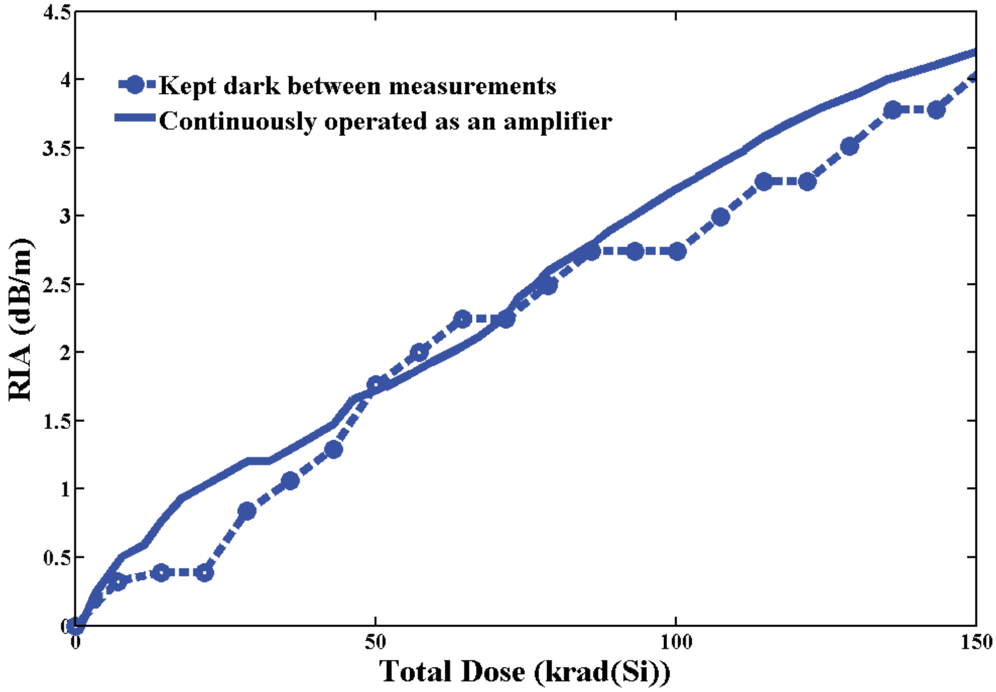

Figure 3. RIA as a function of total dose for fiber irradiated while operated as an amplifier and for those that are kept dark between measurements. There is no significant difference in the magnitude of the RIA between either scenarios.

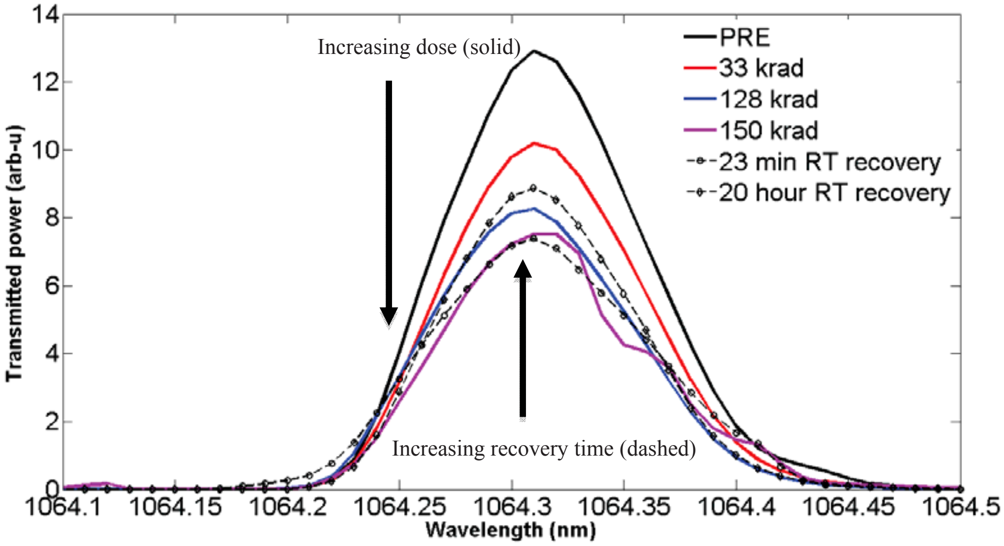

Figure 4. Transmitted power of the amplified signal before, during and after irradiation for a continuously pumped single-mode YDF. During irradiation, the output spectrum decreases with increasing dose. After irradiation, the output power recovers somewhat , yet not to the pre-irradiation level.

Figure 4 provides the spectral output at the amplified signal wavelength before, during and after irradiation. Analysis of the signal indicates that the primary transmitted signal wavelength is invariant during and following irradiation (within the variation expected from the 1064 nm laser source). The total intensity (integrated transmitted power), however, declines and appears to be near saturation at the total gamma dose. The recovery time constant is long and following a 20-hour room temperature recovery the output of the YDFA has only recovered to 78% of the total initial signal output power. It is anticipated that heating of the fibers could speed up recovery but this was not explored in this work. Fox *et al* found that heating of the fibers to 170°C did not produce any annealing in completely darkened YDFs[8]. However, Mady *et al.*, conducted experiments of Yb-doped optical fiber preforms and reported that thermal detrapping with temperatures up to 500°C corresponded to a recovery of light transmission[9]. In their work, it is noted that recovery above 50% transmission did not occur until the temperature was raised to 350°C. Therefore it is speculated that in order to have a significant effect on recovery, the fibers would have to be heated above 350°C.

As expected, the RIA for the single-mode YDFs follows a power-law dependence an with increasing dose as defined in (2).

$$\mathrm{RIA}(D) = a \times D^b \tag{2}$$

Here *D* is the dose and *a* and *b* are fiber-specific parameters. The dose versus RIA curves for all of the single-mode YDFs were fit using expression (2). The fit for both the fibers that were continuously pumped and those that were unpumped during irradiation returned the same average value, *b*, of 0.83±0.05. In addition, there is no measurable indication that the presence of the pump and signal laser lights has an effect on the degradation of the performance of the fiber amplifier system when exposed to gamma irradiation up to 150 krad(Si).

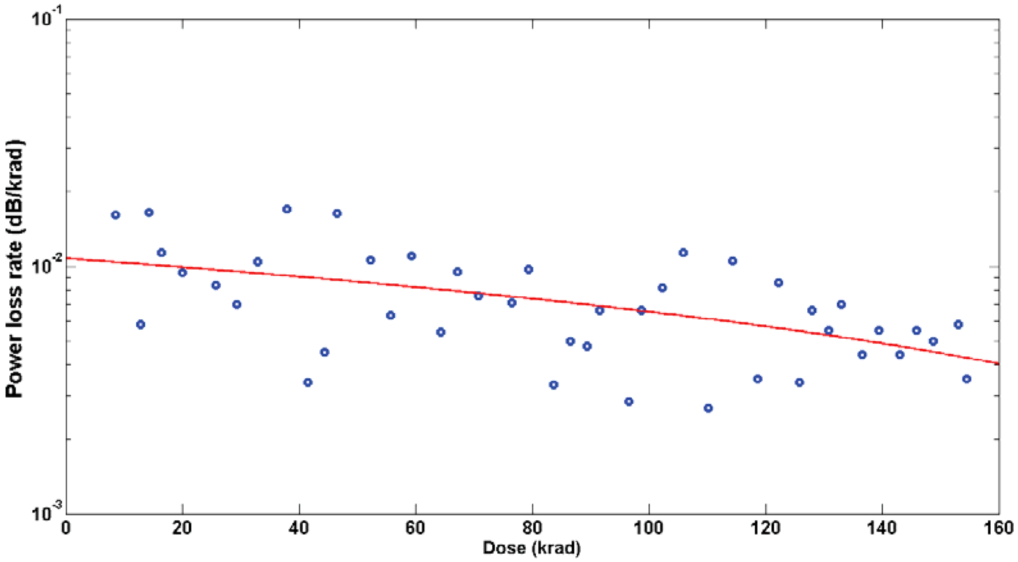

Figure 5. Power loss rate (dB-krad^{-1}(Si)) as a function of total dose for a fiber irradiated up to 150 krad. The downward trending rate is an indication of RIA saturation.

The derivative of the RIA with respect to dose, here referred to as the power loss rate, is plotted as a function of the total dose for the continuously pumped fiber irradiated up to 150 krad(Si) in Figure 5. The power loss rate decreases nearly monotonically with increasing dose. Although no saturation (power loss rate ≈ 0) was observed during the irradiation experiment, the rate declines at the higher total dose, suggesting a trend towards saturation. Saturation of the RIA occurs when either the potential defect sites become completely populated and/or when the rate of defect creation matches that of defect annealing.

Following a 24-hour room temperature recovery during which no light source was transmitted through the fiber, the fiber was irradiated for an additional 150 krad under the same conditions (Figure 6). Fitting the curves in Figure 6 to a line results in a slope of 0.052 dB-m^{-1}-krad(Si) for the first irradiation and 0.041 dB/m*krad(Si) for the second irradiation. These slopes represent the fiber radiation sensitivity. This lower sensitivity measured during the second irradiation is likely a continuation towards saturation that was measured in the previous irradiation.

The amplified spontaneous emission (ASE) spectrum of the single-mode YDFs was measured by transmitting only 975 nm pump light through the fiber without the 1064 nm signal present. The ASE is the limiting factor for an unsaturated amplifier or laser system's maximum achievable gain. In addition, it is the dominant source of noise[10]. Figure 7 shows the effect of irradiation on the ASE of a fiber irradiated while being continuously pumped. As the radiation dose increases, the ASE power decreases and the peak of the curve shifts to longer wavelengths. Comparing the RIA for the peak versus dose for the ASE and that of the amplified signal shows that the ASE intensity decreases more slowly with respect to dose than that of the amplified signal. This lack of correspondence between two RIA values indicates that the signal-to-noise ratio may not correlate well to the reduction in amplified signal output. This would in turn increase the degradation of a YDFA system performance beyond what would be expected when only considering the loss at the signal wavelength.

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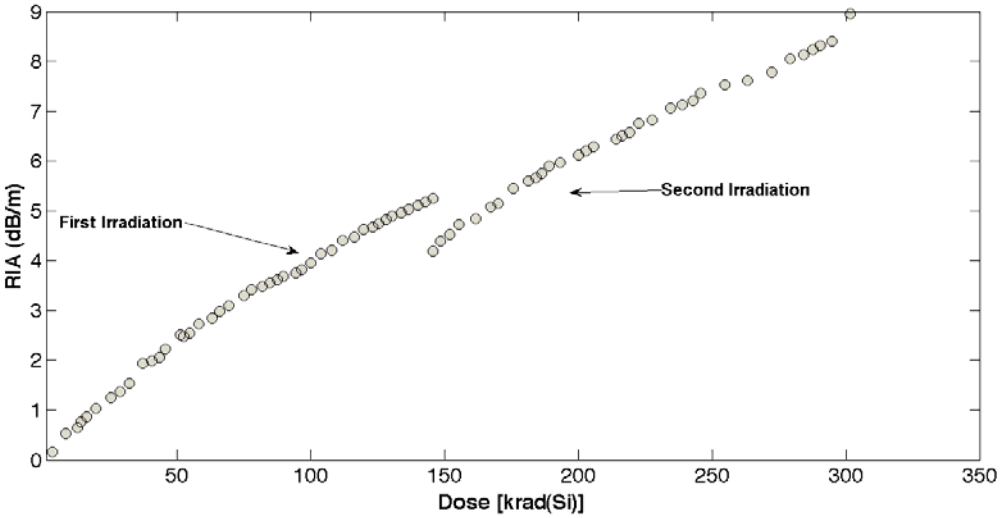

Figure 6. Radiation induced attenuation of the amplified signal output for a fiber that was irradiated twice. Fitting of the curves shows that the RIA does not increase as rapidly during the second irradiation, suggesting a saturation of damage.

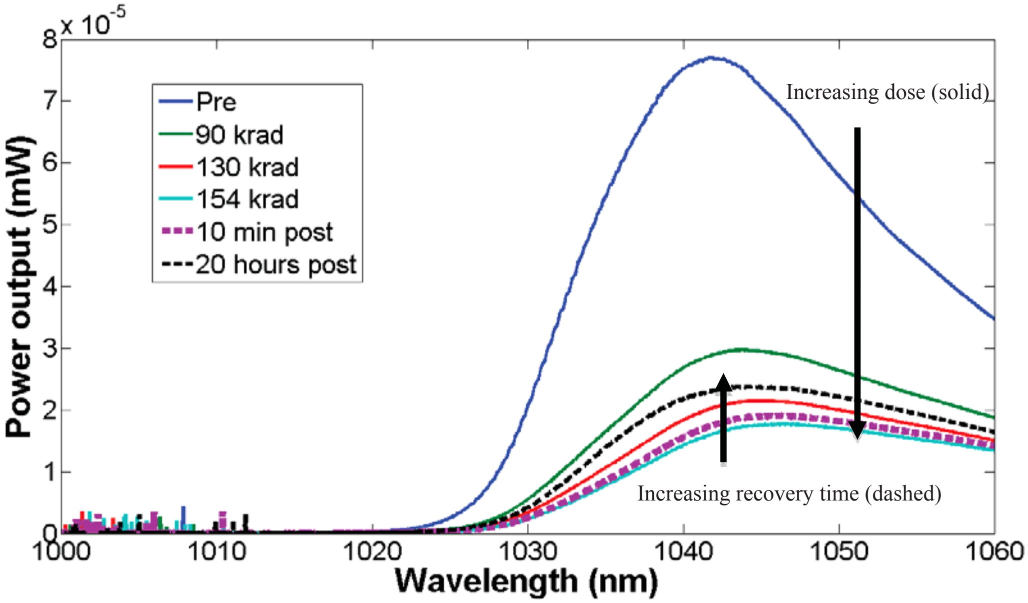

Figure 7. Amplified spontaneous emission transmission through single-mode YDF before, during and after irradiation generated using the same pump power. As dose increases, the spectrum decreases and the peak shifts to longer wavelengths.

3.2 Passive fiber degradation

The radiation-induced attenuation in the passive fiber was measured using both the pump and signal lasers. A pristine 2-meter long passive patch cable with ceramic ferrules was characterized using a variety of pump and signal powers, and then placed in the Co-60 cell at a location providing 21.5 krad(Si)-hr^{-1}. The fiber remained in the chamber for approximately 26 hours resulting in a total dose of 560 krad(Si). At the pump wavelength, the attenuation measured is 0.25 dB/m while an attenuation of 0.17 dB/m was measured at the signal wavelength, Figure 8. This is only a fraction of the loss measured in signal and pump light output during irradiation of the YDF fibers and therefore is concluded to contribute minimally to the error of the measuring the single-mode YDF amplifier output.

Henschel *et al*. studied the effects of Co-60 irradiation on ceramic single-mode fiber connectors. They estimated that the upper limit of attenuation due to damage to the fiber optic connectors to be 0.15 dB following exposures to 1 Mrad(Si) at a dose rate 62.6 krad(Si)hr[11]. To examine this effect in the passive fiber tested, a post-irradiation measurement was conducted in which it was cut in half and one end spliced to an un-radiated fiber. Taking fusion splicing losses into account, the degradation in the light transmission through the un-radiated fiber with the irradiated coupler was .07 dB and .04 dB for 1064-nm light and 975-nm light respectively. It was deduced that the majority of RIA attributable to the passive fiber was due to the darkening of the single-mode passive fiber rather than that from the connectors.

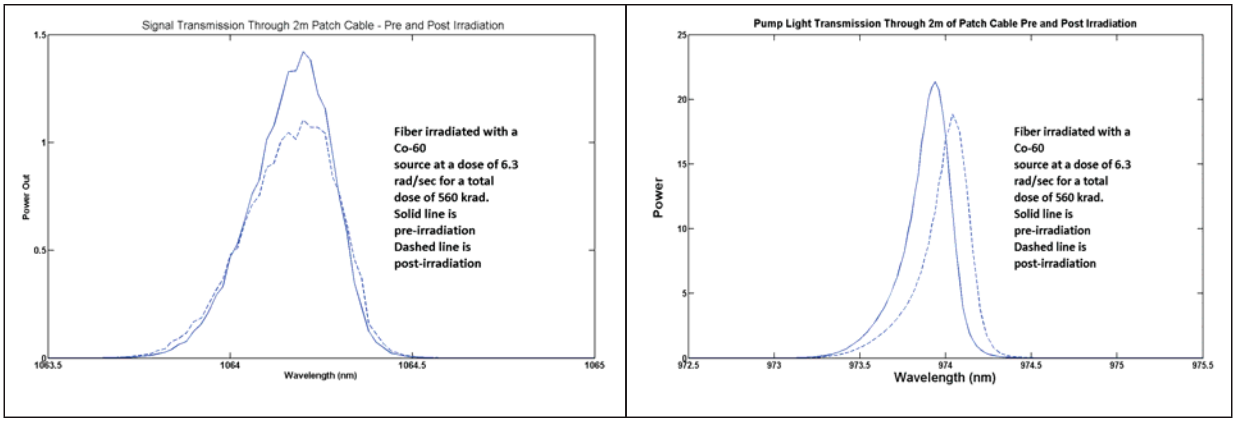

Figure 8. Transmission of 975 nm and 1064 nm light through passive fiber before (solid line) and after (dashed line) 560 krad(Si) of exposure. Arbitrary units are used to plot the y-axes.

3.3 Multimode fiber transmission

Once again, for the sake of brevity, only one example of results of the irradiation of four multi-mode YDFs will be presented. Figure 9 is typical of the induced attenuation for the irradiated multi-mode YDFs. The largest magnitude of RIA rate occurs at wavelengths below 980 nm and after that, above 1000 nm. Figure 10 presents the RIA at 975 nm and 1064 nm as a function of dose. It clearly indicates an increased RIA at the 1064-nm wavelength. Therefore, these effects compound one another since, not only is the single-mode YDFA experiencing an increased absorption of light at the pump wavelength (which reduces the fiber's inversion), but any signal, which is amplified by the doped fiber, is now also exposed to an increased absorption in the fiber.

Examining the radiation-induced absorption of the white light measured through the multi-mode fiber indicates that the greatest absorption is located at regions outside of the Yb-doped fiber's active absorption and emission spectral regions (900 to 1100 nm). This gamma-irradiation induced absorption behavior is comparable to the result obtained by Deschamps *et al*. on Yb-doped fiber preforms, irradiated with Co-60 up to 180 krad(Si) total dose[12]. In their work, along with that of Arai *et al*, the primary source of increased absorption is attributed to defects arising from the Al doping of the fibers. The additional absorption spectra from Figure 9 can be decomposed into a set of Gaussians by using predetermined locations of Al-OHC absorption in amorphous silica detailed in Table 2[13,14]. Figure 11 demonstrates that the heights of the three well-defined Al-based defect centers' Gaussians were adjusted to provide a good fit (dashed line) at wavelengths below 1000 nm.

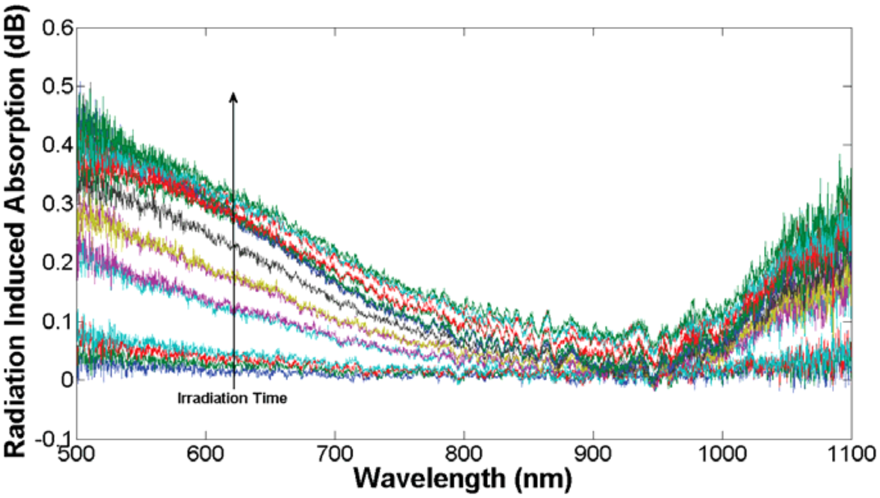

Figure 9. Radiation induced absorption in multi-mode YDF as a function of irradiation time (total dose).

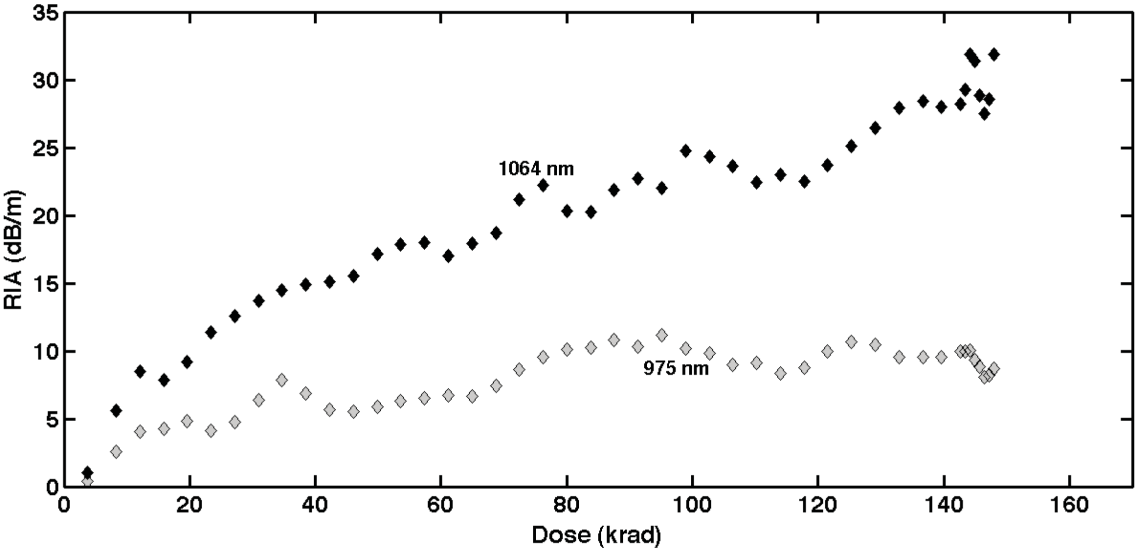

Figure 10. RIA at 975 nm and 1064 nm transmitted from a white-light source through a multi-mode YDF during irradiation. The RIA at 1064 nm is more sensitive to dose than the RIA at 975 nm.

Table 2. Known Al defect absorption centers and the corresponding full width at half-maximum of the absorption curves.

Absorption Peak Maximum (nm)	FWHM (nm)	Reference
388	200	[14]
539	230	[14]
564	472	[4]

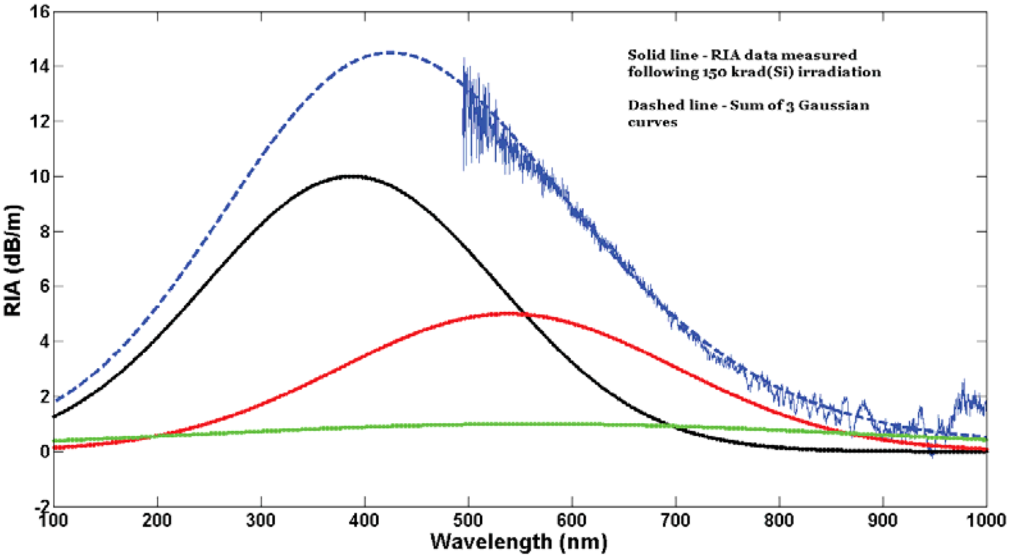

Figure 11. Fit of the RIA of light through the multi-mode fiber following 150 krad(Si) irradiation. The heights of the three well-defined Al-based defect centers' Gaussians were adjusted to provide a good fit (dashed line) at wavelengths below 1000 nm.

4. CONCLUSIONS

The degradation of a number of YDFs was measured in-situ during exposure to gamma irradiation from a Co-60 source. The single-mode YDFs were operated as amplifiers to examine the effect on the amplified signal output during irradiation. Transmission of a white light source was measured through the multi-mode YDFs in order to illuminate the damage effects in the single-mode YDFs. Passive fiber of a type typically used with the single-mode YDFs was irradiated in order to gauge the magnitude of its contribution to the observed degradation of the system.

The Power Law fit for both the single-mode fibers that were continuously pumped and those that were kept dark during irradiation returned the same average value, *b*, of 0.83±0.05. In addition, there is no measurable indication that the presence of the pump and signal laser lights has an effect on the degradation or the performance of the fiber amplifier system when exposed to gamma irradiation up to 150 krad(Si).

The single-mode YDFs experience a degradation of the output along with a decrease in ASE that does not neatly correlate with the signal output decrease. The experiments conducted with the multi-mode YDFs demonstrated the absorption at the signal wavelength (1064nm) increases more rapidly than the absorption of light at the pump wavelength (975 nm). In addition to the pump light being diverted away from exciting Yb^{3+} ions, the amplification that occurs at the 1064 nm signal wavelength is subjected to stronger losses in the fiber. The multi-mode YDF transmission spectra also indicate that absorption centers created primarily in the NIR region (attributed to Al based defects) have the most intense effect on the single-mode YDFA performance.

The magnitude of the passive fiber transmission degradation and that of the ceramic optical fiber connectors compared to that of the YDF is small enough to be excluded when considering the damage to YDFAs operating in harsh radiation environments.

Additional experiments have been conducted in which the Yb-doped fibers were exposed to a mixed gamma/neutron environment (pulsed and continuous). The results of those experiments indicate that the damage to the YDFAs from high-dose-rate transient irradiation recovers significantly faster than the damage done under low-dose-rate continuous irradiations. These results will be presented in a future publication.

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REFERENCES

[1] D. L. Griscom, M. E. Gingerich, and E. J. Friebele, "Radiation-Induced Defects in Glasses: Origin of Power-Law Dependence of Concentration on Dose", Physical Review Letters, 71(7), 1019-1022 (1993).

[2] E.J. Friebele, P.C. Schultz, and M. E.Gingerich, "Compositional effects on the radiation response of Ge-doped silica-core optical fiber waveguides", Applied Optics, 19(17), 2910-2916 (1980).

[3] C.E.Barnes. J.J.Wiczer, "Radiation Effects in Optoelectronic Devices", SAND84-0771,1984.

[4] S. Girard, J. Kuhnhenn, A. Gusarov, B. Brichard, M. Van Uffelen, Y. Ouerdane, A. Boukenter, and C. Marcandella, "Radiation Effects on Silica-Based Optical Fibers: Recent Advances and Future Challenges", IEEE Transactions on Nuclear Science, 60(3), 2015-2036 (2013).

[5] Lezius M. Lezius, K. Predehl, W. Stöwer, A. Türler, M. Greiter, Ch. Hoeschen, P. Thirolf, W. Assmann, D. Habs, A. Prokofiev, C. Ekström, T. W. Hänsch, and R. Holzwarth, "Radiation Induced Absorption in Rare Earth Doped Fibers", IEEE Transactions on Nuclear Science, 59(2), 425-433 (2012)

[6] Sean W. Moore, Daniel B.S. Soh, Scott E. Bisson, Brian D. Patterson, and Wen L. Hsu, "400 µJ 79 ns amplified pulses from a Q-switched fiber laser using an Yb3+-doped fiber saturable absorber," Optics Express 20(21), 23778-23789 (2012).

[7] S.K. Tammel, M.J. Söderlund, J. J. Koponen, V. Philippov, P. Stenius, "The Potential of Direct Nanoparticle Deposition for the Next Generation of Optical Fibers," *SPIE Photonics West '06 OPTO Symposium* (2006)

[8] Brian P. Fox, Zachary V. Schneider, Kelly Simmons-Potter, William J. Thomes, Jr., Dorothy C. Meister, Ray P. Bambha, and Dahv A. V. Kliner, "Spectrally Resolved Transmission Loss in Gamma Irradiated Yb-Doped Optical Fibers", IEEE Journal of Quantum Electronics, 44(6), 581-586 (2008).

[9] Franck Mady, Mourad Benabdesselam, Yasmine Mebrouk and Bernard Dussardier, "Radiation effects in ytterbium-doped silica optical fibers: traps and color centers related to the radiation-induced optical losses", Proc. RADECS 2010, LN2, 25Jan 2011.

[10] Paschotta, Rüdiger, Johan Nilsson, Anne C. Tropper, and David C. Hanna. "Ytterbium-doped fiber amplifiers." *IEEE Journal of Quantum Electronics* 33, no. 7 (July 1997): 1049-1046.

[11] H. Henschel, Kohn, O., and H.U. Schmidt. "Radiation sensitivity of passive fibre optic components." Proc. SPIE 1973, Passive Fiber Optic Components and Their Reliability, 250 (November 18, 1993).

[12] Thierry Deschamps, Hervé Vezin, Cédric Gonnet, and Nadège Ollier, "Evidence of AlOHC responsible for the radiation-induced darkening in Yb doped fiber", Optics Express 21(7), 8382-8392 (2013).

[13] H. Hosono, et al., "Radiation-Induced Coloring and Paramagnetic Centers in Synthetic SiO_2: Al Glasses", Nuclear Instruments and Methods in Physics Research, **B91**, 395-399 (1994).

[14] T. Arai, K. Ichii, S. Tanigawa and M. Fujimaki, "Photodarkening Phenomenon in Yb-doped Fibers", Fujikara Technical Review, 6-11, 2009.