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

Brian P. Fox and Kelly Simmons-Potter

***Abstract*—Fibers doped with Yb^{3+} serve as optical amplification elements in many high-power amplification systems, and there is an interest in significantly extending the capabilities of rare-earth doped fiber amplifiers to space-based systems. We investigate the effects of gamma-radiation-induced photodarkening on the performance of such fibers, both for passive as well as active configurations. With an emphasis on low total ionizing doses, passive irradiations were found to show increased absorption across the visible and IR spectrum. Furthermore, continuous-pumping of an Yb^{3+}-doped fiber amplifier in a gamma radiation environment was found to exhibit significantly greater degradation than a similar intermittently-pumped irradiated amplifier for low total ionizing doses of under 10 krad(Si) [100 Gy(Si)]. We discuss the implications of the data which provide insight into energy-transfer mechanisms in the fibers and the relationship of gamma-radiation-induced photodarkening and pump-radiation-induced photodarkening associated with the observed fiber degradation.**

***Index Terms*—Aluminosilicate, fiber amplifier, optical fiber, radiation-induced attenuation, rare-earth doped amplifier, rare-earth doped fiber amplifier, Yb-doped fibers, YDFA.**

I. INTRODUCTION

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 [5-13]. 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 [14-24]. 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 annealing.

In the present study, Yb^{3+} doped fibers were subjected to gamma radiation from a ^{60}Co 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.

II. EXPERIMENTAL DETAILS

A. Passive Experimental Setup

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, transmission/absorption spectroscopy was performed on

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pristine, unirradiated sample fibers as well as on passive gamma-irradiated fiber samples, enabling the examination of gamma-induced absorption across visible and NIR wavelength bands. Passive irradiations of Yb^{3+}-doped aluminosilicate fibers (Liekki (now nLight) Yb1200-4/125) were conducted both at radiation test sites and in our labs at the University of Arizona [10,12,24]. As can be seen in the experimental set up (Fig. 1) low-power, broad-spectrum light from a xenon arc lamp was guided through collection/collimating lenses and into a 10x microscope objective, which coupled the light into the core of the sample fiber. The transmitted output of the fiber under test was then measured by a spectrometer. An Ocean Optics HR+ C0073 spectrometer was used to collect data over the visible portion of the spectrum, and an Ocean Optics NIR-512 was utilized to obtain data in the NIR. Spectroscopic measurements made on fibers before exposure to gamma irradiation were compared to those made on post-irradiated fiber samples, allowing for radiation-induced absorbance to be evaluated. Tested fiber lengths were typically ~3 m and the arc lamp was turned on for over 2 hours for each test before any fiber spectra were obtained in order to properly stabilize the lamp spectrum.

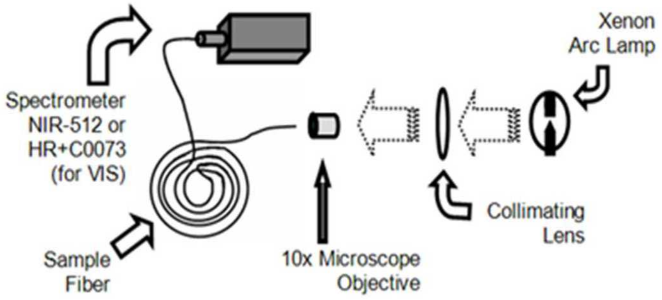


Fig. 1. Test configuration for passive radiation tests on Yb^{3+}-doped fibers.

B. Active Experimental Setup

Active amplifier testing was conducted at the Leach Science Center in Auburn, AL [24]. A schematic of the experimental setup is given in Fig. 2. The amplifier was composed of a length of passive, delivery fiber spliced to a segment of Yb^{3+}doped optical fiber (Yb1200-30/250DC), a probe laser at ~1.06 µm, 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 shielded 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 ~3 m of active Yb^{3+}-doped test fiber. The exit end of the doped fiber spool was fusion spliced to another shielded passive delivery 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 ~1.06 µm. In these experiments fiber amplifiers were tested in either continuous- or intermittent-pumping operational modes in order to examine the effects of pump processes on photodarkening in the fibers.

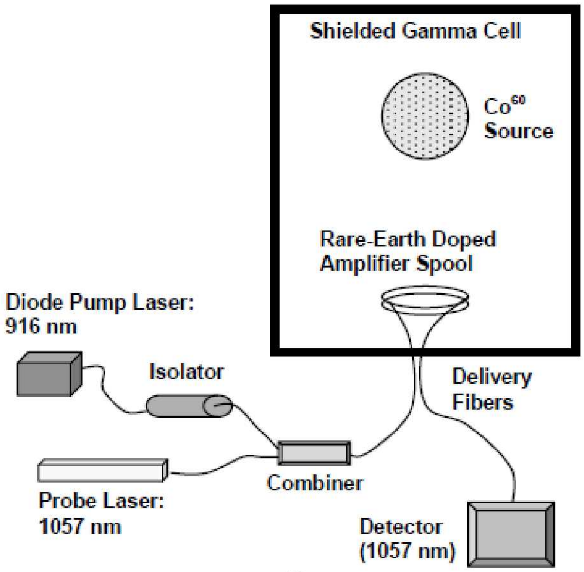


Fig. 2. Test configuration for active fiber amplifier testing.

III. RESULTS

A. Passive Fiber Experimental Results

The general behavior of Yb^{3+}-doped fibers in the NIR portion of the spectrum is radiation-induced darkening (or induced opaqueness) of the fibers with increasing total ionizing dose and a dose rate dependence in which higher dose rates lead to slightly more radiation-induced darkening than lower dose rates per unit dose [9-10,12]. Besides exceptions noted below, the spectral shape of the absorption is generally consistent: Color center absorption in the UV and visible portions of the spectrum with color center tailing into the NIR portion of the spectrum (for further details, especially for general high dose behavior, see [9-10,12]).

Such behavior is seen in Fig. 3 which shows the radiation-induced loss tail across the NIR spectrum for a representative Yb^{3+}-doped fiber following a 16.9 krad [169 Gy(Si)] total dose exposure (dose rate was 16.6 rad(Si)/s [0.166 Gy(Si)/s]). Evident in the figure is the significant decrease in optical transmission of the doped fibers at the signal wavelength of 1.06 µm and beyond. It can clearly be seen that the absorption is more significant at shorter wavelengths within the NIR part of the spectrum, such as the typical 916 nm or 975 nm pump wavelengths of an Yb^{3+}-doped fiber amplifier, while longer wavelengths, such as the typical Yb^{3+}-doped fiber amplifier signal wavelength of 1.06 µm, exhibit lower absorption. The interpretation consistent with this data is that the absorption within this wavelength range is due to band tailing from color-centers formed in the visible portion of the spectrum.

Notably, a spectral behavior has been reported in which longer wavelengths experience a greater radiation-induced absorption than shorter wavelengths [14-16,25]. Such behavior was similarly observed in the fibers under test in the present study, as shown in Fig. 4 which depicts radiation-induced loss in the doped fibers for a select set of NIR wavelengths as a function of accumulated total gamma dose. Interestingly, this behavior was observed only at small initial doses, as can be seen in Fig. 4(a), in which absorbance of the 1401 nm wavelength (dashed line in the figure) is higher than for many of the shorter wavelengths for total ionizing doses of less than 5 krad(Si) [50 Gy(Si)]. Fig. 4(b) zooms in on the region experiencing less than 5 krad(Si) [50 Gy(Si)] of total ionizing dose, further showing the anomalously large absorption at the 1401 nm wavelength at low doses.

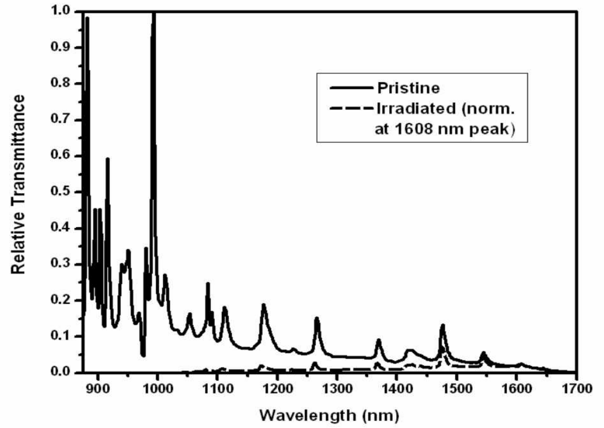
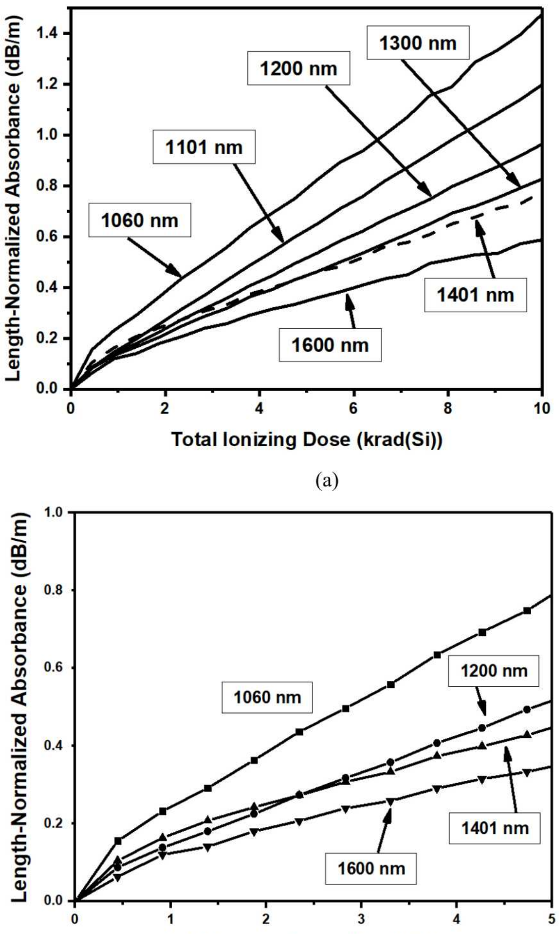


Fig. 3. Transmittance of pristine and gamma-irradiated Liekki (now nLight) Yb1200-4/125 fiber samples in the near infrared plotted in units of relative transmittance (normalized to large peak at 1.6 µm). The sample was irradiated to a total dose of 16.9 krad (Si) [169 Gy(Si)].

Fig. 5 shows total ionizing dose–normalized loss in units of dB/(m*krad(Si)) [0.1 dB/(m*Gy(Si))] over part of the NIR portion of the spectrum for different total ionizing doses. Whereas a stable normalized loss, consistent with the interpretation of color center tailing from the UV and visible portion of the spectrum, is realized around 10-30 krad(Si) [100-300 Gy(Si)], it is evident that small doses lead to larger dose-normalized losses, especially at the wavelength near 1400 nm. An increase of absorption at such wavelengths (at room temperature) is consistent with what has been found in pure silica core F-doped clad fibers, with different types of self-trapped holes identified as possible culprits [17].

The results of the visible spectroscopy on a Liekki Yb1200-4/125 fiber, representative of the sample suite tested, are shown in Fig. 6, with Fig. 6(a) showing the irradiated and pristine samples in terms of relative transmittance. In this figure, the shape of the lamp spectrum is clearly evident. Fig. 6(b) shows the logarithm of the pristine sample counts divided by the irradiated sample counts taking into account any instrumental offsets and arbitrarily normalized to a prominent lamp spectrum peak at 824 nm, resulting in a plot of excess, gamma-induced absorbance of the irradiated fiber relative to the pristine fiber. From the shape of the trace in this figure, 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.



(a)

(b)

Fig. 4. For a Liekki Yb1200-4/125 fiber at a dose rate of 14.3 rad(Si)/s [0.143 Gy(Si)/s], the figures depict length-normalized absorbance over a (a) 10 krad(Si) [100 Gy(Si)] and a (b) 5 krad(Si) [50 Gy(Si)] total ionizing dose scale for selected wavelengths.

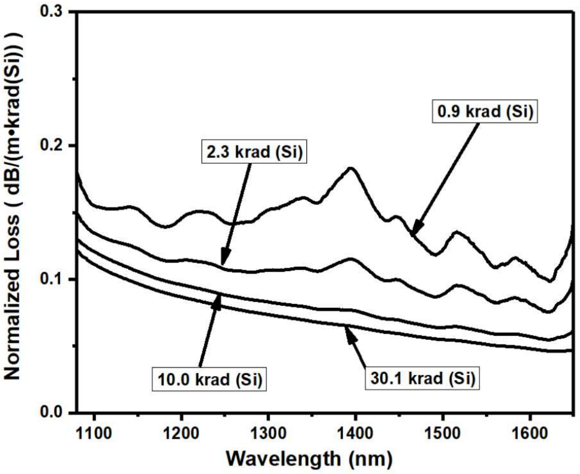
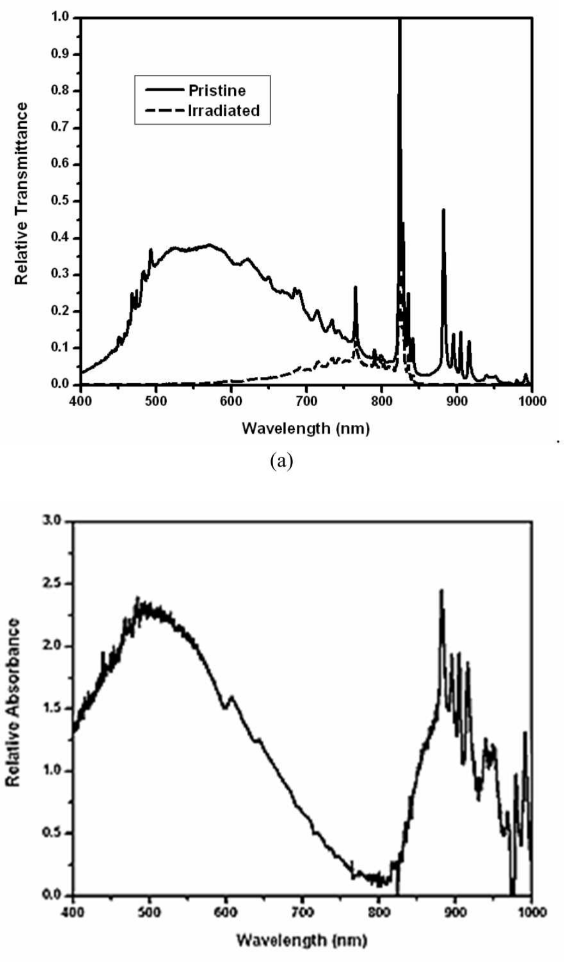


Fig. 5. For a Liekki Yb1200-4/125 fiber at a dose rate of 14.3 rad(Si)/s [0.143 Gy(Si)/s], the figure shows dose-normalized loss in the NIR portion of the spectrum for different total ionizing doses

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 nm [19-21]. It may also be noted that the general shape of the absorption is very similar to that obtained in similar experiments concerning Er^{3+}-doped fibers, and the radiation-induced absorption of such fibers has also been linked to various aluminum-related color-centers [15,26].



(a)

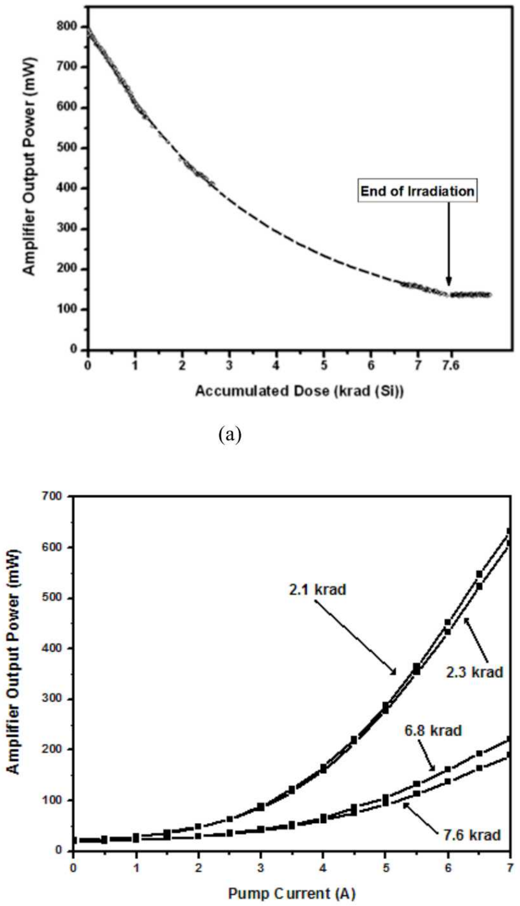
(b)

Fig. 6. Spectroscopy of gamma-irradiated and pristine doped fiber samples across the visible spectrum plotted (a) individually in units of relative transmittance (normalized to large peak at 824 nm) and (b) in terms of relative absorbance. The fiber depicted (a Liekki Yb1200-4/125 type fiber) was irradiated to a total ionizing dose of 16.9 krad(Si) [169 Gy(Si)].

Whereas radiation-induced absorption in the NIR spectral region can often be attributed to color center formation in the UV and visible portions of the spectrum tailing into the NIR, it has been pointed out [27-28] that other absorptions in the NIR may contribute as well, such as the P1 center in P-doped materials [11,29] and, more recently, a self-trapped hole center [30]. Although the data in Fig. 6(b) is difficult to interpret due to such factors as low signal-to-noise in the NIR region (partly from strong absorption of the Yb^{3+} ion in this region [21,31]), and perhaps proximity to the spectral edge of the detector, other reports of absorption in this region (800-1200 nm) have found absorption in this spectral region as well [27] and data in Fig. 3 similarly shows strong absorption at these wavelengths. It has been suggested [27,32] that interstitial molecular O_2 derived from within the glass matrix due to radiation may contribute to absorption near 1064 nm.

B. Active Fiber Experimental Results

For the actively-pumped fiber amplifiers (both continuously pumped and intermittently pumped), the decrease of the amplifier output signal (with the 916 nm pump laser current operating at 6 A, 1.9 V) was monitored during gamma irradiation. The data for the continuously-pumped, irradiated, fiber amplifier is shown in Fig. 7. Fig. 7(a) shows the decrease of the amplifier output signal power at 1057 nm as a function of accumulated total gamma dose, which is seen to be exponential in nature up to a dose of 7.6 krad(Si) [76 Gy(Si)], at which point the signal had decayed to ~17% of its original value and the irradiation was stopped. The data in Fig. 7(a) is closely fit with an exponential curve (dashed line) with a decrease of about 0.33 dB/(m*krad(Si)) [0.033 dB/(m*Gy(Si))].



(a)

(b)

Figure 7: (a) Decrease of amplifier output in continuously-pumped fiber due to increasing accumulated gamma-radiation dose up to 7.6 krad(Si) [76 Gy(Si)] [11-12], with a dose rate of 117 mrad(Si)/s [1.17 mGy(Si)/s], after which the irradiation was stopped (the dashed line is an exponential trend line, small diamonds indicate data points). Data are also shown for 2 hours after the irradiation. (b) Decrease of amplifier output power vs. amount of pumping for various total accumulated gamma-radiation doses (doses are in krad(Si) [10 Gy(Si)]). Squares indicate data points.

It should be noted that data were not collected continually throughout the irradiation which is evident in the gaps between data points in Fig. 7(a). Further, data were collected for 2 hours following sample irradiation in order to examine any effect of room-temperature annealing of the induced loss. The absence of annealing, which would be evidenced by time-dependent signal recovery, is seen in Fig. 7(a). Finally, the passive amplifier performance was measured after the completion of the irradiation sequence by coupling only signal light into the test fiber (no pump). Under these conditions, it was observed that the fiber transmission at the signal wavelength had decreased by ~10% compared to the pristine (unirradiated) fiber following the 7.6 krad(Si) [76 Gy(Si)] exposure.

The decay in amplifier efficiency for the continuously-pumped Yb^{3+}-doped fiber can also be seen in Fig. 7(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. Although photobleaching is possible with non-ionizing radiation [33], in general the damage responsible for the decreased amplifier performance in this research appears to be permanent, as no recovery was seen in Fig. 7(a) following the irradiation (neither thermal recovery from the room temperature anneal nor recovery from pump radiation–induced photobleaching).

In contrast to the amplifier depicted in Fig. 7, amplifier operation was also monitored in-situ during the gamma radiation exposure for an amplifier fiber that was only pumped intermittently for extremely brief periods of time to obtain periodic amplifier data. Data from the intermittently-pumped fiber amplifier is shown in Fig. 8. The bottom curve of this figure shows the amplifier output as a function of total accumulated dose when both the pump and signal beams are propagated through the fiber. It can be seen that the amplifier output power at the signal wavelength decreased almost linearly when pumping throughout the exposure was minimized. This decrease is seen to be significantly smaller than that of the continuously-pumped amplifier of Fig. 7. Specifically, a signal decrease to ~66% of the pre-irradiation value (with a total decrease of about 0.06 dB/(m*krad(Si)) or 0.006 dB/(m*Gy(Si))) is observed in the intermittently-pumped fiber experiments as compared with a decrease in amplifier output to ~17% of its pre-irradiation value for the continuously-pumped case after ~7.6 krad (Si)). The upper curve in Fig. 8 depicts the behavior of the intermittently-pumped amplifier with only the signal beam coupled into the test fiber, thus providing an evaluation of passive, gamma-induced loss in the fiber at the signal wavelength. A total radiation-induced transmittance loss of just under 10% is observed in the figure after 7-8 krad(Si) of exposure.

Clearly the difference in shape between the curves in Fig. 7 and Fig. 8 points to a difference in mechanisms in these two experiments. In particular, the larger signal decrease of the continuously-pumped amplifier in comparison with the intermittently-pumped amplifier, combined with the difference in shape of these decreases, demonstrates that the presence of pump radiation leads to a change in the mechanism of radiation-induced loss in the materials that strongly influences the dynamics of color-center formation in the Yb^{3+}-doped fiber amplifier material. A look at the passive (unpumped) transmittance loss of the signal wavelength following irradiation revealed similar values for the two configurations of around 10%. These percentages correspond to the amount of power loss attributable to absorption at the signal wavelength and may be ascribed to low-energy (long wavelength) color-center formation in the materials (i.e., aluminum-associated color-center band tailing). The origin of the more substantial remainder of the decrease of amplifier efficiency (total losses of 34% for intermittent pumping and 83% for continuous pumping after 7.6 krad (Si) [76 Gy(Si)]) can, thus, be ascribed to processes related to the pump state.

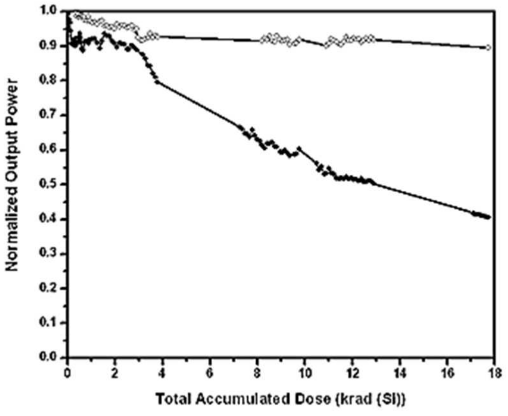


Figure 8: Power output of Yb^{3+}-doped fiber amplifier normalized to initial measured power (~800 mW, prior to irradiation) vs. total accumulated gamma-dose for an intermittently-pumped fiber amplifier at 1.06 mm with no external pump applied (open circles) and for the same amplifier operated with both pump and signal wavelengths applied (solid circles) at 6 A, ~1.9 V. Dose rate 117 mrad(Si)/s [1.17 mGy(Si)/s].

IV. DISCUSSION

When evaluating the response of the fiber amplifier, the degradation can have a number of origins, including direct absorption at the pump and signal wavelengths, both of which can impact amplifier behavior. Besides color center tailing from the UV/visible into the NIR portion of the spectrum and causing absorption there, often sufficient in describing degradations in certain rare-earth-doped fiber amplifiers [6,34], interference with the amplification mechanism (e.g. energy transfer) can be viewed as a further degradation process [24,28,29,32]. It is valuable to examine both the passive, radiation-induced absorption data and the pumped fiber amplifier data in order to evaluate the impact of such processes on the observed fiber responses.

Studies have suggested a number of color centers responsible for observed ionizing-radiation-induced loss in Yb^{3+}-doped optical fiber, including those mentioned previously as well as interstitial molecular O_2 derived from within the glass matrix (evidenced by strong absorption at the signal wavelength and a local absorption maximum in the NIR) in response to radiation [31,32]. Absorption shapes in the visible portion of the spectrum of Fig. 6(b) of this research are consistent with aluminum-based color centers [19,21] being present following irradiation, and the unusual (NIR local maximum) absorption at wavelengths greater than 800 nm is also observed. Whereas the amplifier described in this research implemented slightly different signal and pump wavelengths from those in [27] (in particular, the pump wavelength did not fall on an absorption minimum for the amplifier data depicted in Fig. 7 and Fig. 8), the strong absorption in the region of 800 nm to 1100 nm is still expected to impact operation. A further consideration for the direct absorption seen in the optical fiber is the presence of pump radiation, which has, in some cases, been found to cause further absorption from the UV/visible tailing into the NIR while pump radiation is present [35].

Pump-radiation-induced photodarkening with no ionizing radiation present is also known to cause amplifier degradation in high-powered amplifiers [31], which may be the result of processes involving excited state absorption of NIR photons into centers associated with Yb-Al complexes, possibly involving charge transfer processes, and absorbing at or near the UV [31,35-38].

Color center signatures of Yb-doped fiber amplifier materials degraded by gamma irradiation and pump-radiation are similar and, in the case of Yb^{3+}-doped fibers, appear to involve the same aluminum co-dopant [21]. [27] conducted a similar experiment as noted within this research involving both continuously- and intermittently-pumped amplifiers of similar materials and found that continuously-pumped amplifiers of [27] degrade smoothly in the same fashion as the continuously-pumped amplifier data depicted in Fig. 7, whereas the intermittently-pumped amplifier degradation is less smooth and is typically a bit lower than the continuously-pumped amplifier degradation for the same total ionizing dose. Although this trend may not be apparent (statistically significant) over longer irradiations, it is apparent at low total ionizing doses below about 20 krad(Si) [200 Gy(Si)], and is consistent with the intermittently-pumped amplifier data discussed in this research (Fig. 8), which showed a smaller sensitivity to radiation compared to its continuously-pumped counterpart from Fig. 7.

A possible explanation for this behavior is that high energy (short wavelength) color-center formation leads to depopulation of the amplifier pump-energy state resulting in a dramatic decrease in the fiber amplifier output (or efficiency). One likely scenario to describe the performance decrease of the amplifiers involves the absorption of multiple pump photons to access and populate higher energy levels in the visible that are attributable to color-center trap states that have been formed through the gamma irradiation of the materials. This explanation is consistent with the presence of multiple photons of high energy relative to the signal photons, the increased induced loss seen in the continuously pumped case in comparison to the intermittently pumped case, as well as the spectroscopy consistent with aluminum-related color-centers in the visible part of the spectrum. The data, therefore, support a model in which an energy transfer from the pump level to gamma-induced trap states leads to a depopulation of the pump state, resulting in less energy available for the lasing transition, in turn which constitutes the decrease in amplifier efficiency. Especially for low total ionizing doses, degradation may not be fully established due to a lack of pump (possibly also signal) photons in the intermittently-pumped amplifier, and, therefore, the degradation of the amplifier is temporarily lowered until more pumping has taken place.

It should be noted that radiation-hardened fiber amplifiers using the Yb-dopant have been made with additional co-dopants such as P and Ce, which yield yet additional insights into photodarkening mechanisms [39-40].

V. CONCLUSION

In Yb^{3+}-doped fibers and fiber amplifiers, complex dynamics appear to be present at low total ionizing doses. In passive fibers, strong visible absorption is observed which tails into the NIR, and unusual absorption is seen around 1400 nm at such doses. Actively-pumped Yb^{3+}-doped fibers were seen to exhibit differences in behavior between continual and intermittent pumping for the conditions tested. Overall, for continuous pumping of the amplifier, a large, exponential decrease in output power was seen, while a roughly linear decrease was observed in the case of intermittent pumping, yielding total losses of 34% for intermittent pumping and 83% for continuous pumping after 7.6 krad (Si) [76 Gy(Si)]. A small percentage of the decrease of amplifier output power at the signal wavelength (~10%) was attributed to the formation of low-energy/long-wavelength absorbing states formed as a result of the interaction of gamma-radiation with the fiber material. The remainder was attributed to color-center formation in the visible portion of the spectrum by means of multiple pump-photon absorption. Thus, depletion of the pump by radiation-induced color centers may be a likely explanation for the performance decrease in active operation of the Yb^{3+}–doped fiber amplifier in a gamma-radiation environment. To provide further clarity to the effect of ionizing radiation on the degradation of an Yb^{3+}-doped fiber amplifier, more investigation is necessary in multiple areas, including, but not limited to, absorption mechanisms taking place in the NIR and mechanisms of Yb^{3+} de-excitation and possible charge transfer mechanisms.

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