OE Optical Engineering

RESEARCH PAPER

Influence of co-dopants on the reduction of radiation-induced gain degradation in erbium-doped fiber

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ABSTRACT. The gain degradation behavior of erbium-doped fiber amplifiers (EDFA) in a master oscillator power amplifier (MOPA) configuration was characterized using the fibers irradiated with varying irradiation dosages from our in-house ^{60}Co-ray source. The results indicate that power degradation and photo-anneal recovery processes simultaneously exist for erbium-doped fibers with relatively low concentrations of the co-dopants cerium and germanium added. For fibers with relatively high concentrations of germanium and comparable levels of cerium co-dopants, highly effective radiation hard behavior is exhibited, which is attributed to germanium alone. A fiber optimized for efficiency also provides a radiation-hard EDFA where after a 100-kRad (1000 Gy) exposure, the degradation in signal gain was 5 dB at a MOPA pump power of 315 mW.

Keywords: erbium erbium-doped fiber amplifier; radiation harden

Paper 20240754G received Jul. 24, 2024; revised Oct. 2, 2024; accepted Oct. 3, 2024; published Oct. 29, 2024.

1 Introduction

In radiation-rich environments such as in space, erbium-doped fibers (EDF) are well suited for broadband amplifiers for lasercomm, broadband superluminescent sources for fiberoptic gyroscopes, light detection and ranging (LIDAR) systems, and optical fiber sensors.[1,2] However, it is well known that radiation damage occurs in these fibers, where it may be due to a number of different species such as protons, electrons, and heavy ions.[3] Unlike quartz, where the ideal SiO_2 structure is preserved throughout the crystal, silica glass has configurational disorder. This disorder includes dangling bonds, where unbound oxygen radicals are present, and unexpected bonds, where oxygen deficiency (ODC) sites occur in the lattice.[4] These "intrinsic" defects are present due to the processing of silica glass, such as during fiber draw.[5]

Upon radiation exposure, new defects are then created from the existing processing/draw defects. These new defects for SiO_2 glass include electron and hole pair generation where covalent bonds are broken, and trapping of electrons or holes by atoms (more covalent bond breaking) and ions. Even residual chlorine from the fiber processing can form a defect within the glass.[5] Extrinsic defects are also created by the co-dopants used to create both active and passive fibers. The introduction of germanium in the core of passive fibers for the creation of a waveguide creates a "germanium lone pair center" during the drawing process.[6,7] After irradiation, this can become an electron trapping center called a germanium electron center. For fibers doped with

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aluminum, which is added to solubilize rare earth ions and to flatten the gain bandwidth, aluminum oxygen hole centers (ALOHC) are created, where holes are trapped.[5] This has traditionally been thought to be the most abundant defect in silica fibers, and great efforts have been used to try to minimize this defect.[8,9] Co-doping of optical fiber with phosphorous (P) is also common, especially for erbium-ytterbium fibers, where it increases the efficiency of signal transfer between the ions. But for this case, P-associated defects are known to exist at both pump and signal wavelengths, and therefore, P is generally not used for Er-doped fibers.[1] Finally, we note that the Er^{3+} ions themselves in fact may trap both negative and positive charges, causing them to become a "recombination center." This is perhaps the most important process for both degradation of gain and recovery.[5,10–12]

These defects create changes in the fiber absorption spectrum, where new and stronger absorption peaks are exhibited, leading to radiation-induced absorption (RIA).[1] This is also often postulated to be the reason for radiation-induced gain degradation and an increase in the noise figure.[3,12]

Current methods used to impart radiation hardness to EDFs include hydrogen loading, where it has been postulated to passivate dangling bonds, also known as non-bridging oxygen hole centers (NBOHCs). Unfortunately, hydrogen incorporation creates OH groups that absorb in the IR,[1] thereby reducing the gain. In addition, irradiation leads to the formation of NBOHCs and hydrogen outgassing, thereby reducing the performance of the fiber.[1] Cerium (Ce) co-doping is well known to be an effective method to increase radiation hardness in glasses.[13] Industry has effectively used Ce co-doping for RIA reduction, where Ce co-doped EDF is commercially available.[14,15] While Ce co-doping does not alter the spectroscopic properties of the EDF, there is no indication that it may help reduce erbium ion clustering unlike other co-dopants, a process that is detrimental to amplifier performance. Furthermore, Ce clustering itself occurs in the fiber and therefore creates scattering centers. It is because of this that there is a limit to the amount of Ce that can be added as a gain degradation reducer.

Previously, we used rare earth co-dopants such as lanthanum to increase the efficiency of resonantly pumped Er-fiber lasers and demonstrated a benefit for moderate radiation hardness based on this method.[16,17] Cao et al. used cerium and germanium co-doping to show excellent radiation-resistant EDF.[18] In this case, radiation hardness was exhibited using very high concentrations of germanium and cerium. These dopants are well known to increase the core refractive index. Because of this, their fibers had as many as four propagation modes at 1550 nm, due to the high refractive index of both dopants.[18] In this study, we report on the use of cerium along with germanium co-doping, both together and separately, and its impact on the performance of an EDFA in a radiation-rich environment, where we have expanded on our previous work.[19] In this case, our goal is to obtain even better performance in a radiation-rich environment while maintaining a lower fiber numerical aperture to near single-mode behavior. Near single-mode behavior may be desirable for future power scale-up purposes in the case where large core, double-clad fibers would be used in applications where good beam quality is needed. This presents a significant challenge because, as noted above, the incorporation of both Ge and Ce dopants in the fiber core significantly increases the fiber numerical aperture, therefore raising the fiber V-number. Our results indicate excellent radiation hard behavior where we ascertain the impact of Ge and Ce doping.

2 Experimental

EDFs prepared using preforms fabricated by the modified chemical vapor deposition (MCVD) were investigated in this study. The parameters for these fibers are given in Table 1. The Er content for the fibers was determined with electron microprobe analysis (EPMA) and compared with small signal core absorption results from an optical spectrum analyzer. The core absorptions here were similar with values ranging from 12 to 20 dB/m at 1532 nm. For reference, an Er core absorption of 12 dB/m corresponds to $\sim 1 \times 10^{25}$ Er ions/m^3 in a single-mode fiber. It is important to note here that the core diameters for our fibers are larger than commercially available rad hard fibers, where they oversleeve; therefore, they have high NA but the diameters allow them to be single mode. The fibers in this study were co-doped with either germanium or cerium, resulting in the formation of GeO_2 and Ce_2O_3 in the core after processing. The GeO_2 concentrations in

Table 1 Parameters for the fibers in this study.

Fiber	Er core Abs. 1530 nm (dB/m)	NA	MFDa (μm)	Modes	GeO_2 mol. %	Ce_2O_3 mol. %	Gain degrad. 10 kRad (dB)	Gain degrad. 50 kRad (dB)
EDF1	12	0.11	11.2	1	Low	0.027	12	Dark
EDF2	12	0.12	10.3	1	Low	0.120	6	Dark
EDF3	15	0.21	7.6	2	Highest	0.028	0	2.15
EDF4	20	0.18	7.9	2	High	—	0	3.77

[a]LP01 mode.

this work have been varied and will be referred to in terms of "low" to "highest" for proprietary reasons. The Ce_2O_3 mole concentrations are also listed. In the table, the value for gain degradation at 10 kRad and 50 kRad are listed. Fibers that show no gain after irradiation are listed as "dark."

A master oscillator power amplifier (MOPA) was used to measure gain for the fibers. For the measurements, we utilized a 10-μW (−20 dBm) small signal produced with a 1560-nm laser diode combined with >300-mW pump laser at 976 nm to core-pump the EDFs. Gain measurements were performed on pristine fibers before and after radiation exposure to compare gain degradation. The post-irradiation gain on these fibers was performed within 2 h after being removed from the Co pool. Gain degradation is defined as gain after exposure subtracted from gain before exposure. The lengths of the fibers used were determined by the concentration of Er in them, in accordance with a standard equation for gain. This was done to achieve ∼30 dB gain on the pristine fibers for pump powers near 300 mW. For the fibers in this study, because they all had similar concentrations, the lengths were approximately the same. Each of the EDFs was wound into a 5-cm diameter sample coil. We note that this coil diameter does not result in measurable bend loss to the fiber. The EDF coil was inserted into a sealed sample can, which was lowered into the ^{60}Co γ-ray pool source. Because the γ irradiation is fixed at a rate depending on the proximity of the fiber to the ^{60}Co, the total accumulated dose is determined by the time of exposure. Radiation exposures were varied from 10 kRad (100 Gy) up to 100 kRad (1000 Gy) at a dose rate of ∼0.4 Gy/s. A cutback measurement was performed before and after the tests to measure the pump and signal powers injected in the EDF.

3 Results and Discussion

We begin by noting that the Er fibers in this study without either cerium or germanium co-dopants did not exhibit any gain after being irradiated in the Co pool even after the lowest dose of 10 kRad (100 Gy). In Fig. 1(a), we have plotted gain curves for two Er-doped fibers before (solid line with symbols) and after (dashed line with symbols) being irradiated in the Co pool at 10 kRad. Here, the gain is plotted as a function of MOPA pump power. Before radiation exposure, the fibers have ∼30 dB of gain when reaching 275 to 315 mW of pump power. Each fiber has differences in gain because its length has not been completely optimized for the erbium concentration. We first note that after radiation exposure the two fibers have their gain curves shifted dramatically, where transparency (transition from absorption to gain) in the fibers is not reached until near 150 mW of pump power for the fiber EDF1 designated by squares, and for the fiber designated by triangles, EDF2, it occurs near 100 mW of pump power. This is an example of photodarkening in the fibers. Here, a significant portion of the Er^{3+} ions are not available to create gain until large pump powers are reached, and then, the gain increases more rapidly without the typical "knee" in the curve that pristine gain curves exhibit. This behavior may be analogous to a fiber that is heavily Er-doped, and very large pump powers are required to reach transparency and much longer fibers would be needed to achieve a comparable gain. The radiation damage has rendered many of the Er^{3+} ions inactive in the amplifier, and no fiber reaches the same gain as their pristine version. Both fibers have the same GeO_2 concentration, which is very low, and they both have a relatively low concentration of Ce_2O_3. However, EDF2 has

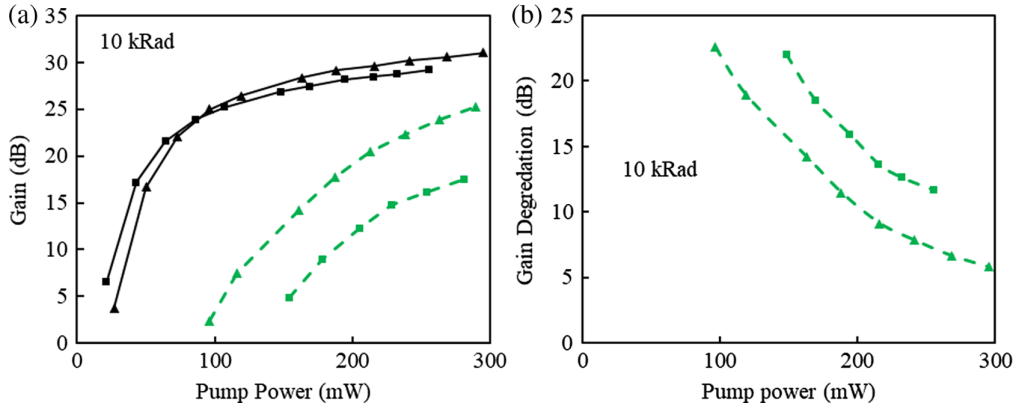

Fig. 1 (a) Gain curves for EDF1 (squares) and EDF2 (triangles) before (solid lines) and after (dashed lines) a 10-kRad (100 Gy) dose. (b) Degradation in gain for the same two fibers.

~4.5 times the concentration of cerium than EDF1. The recovery of the fibers during pumping is the result of the photoanneal process that occurs as the fibers are being pumped in the MOPA. Here, the curves show the rapid increase without the knee and saturation discussed previously. In Fig. 1(b), the degradation in gain for the two fibers is plotted. Here, it is noted that EDF1 has a gain degradation of ~12 dB after a 10-kRad exposure, whereas for EDF2, the degradation is 6 dB. For radiation doses above 10 kRad, the fibers showed no gain and are listed as "dark" in Table 1 for the 50-kRad column. This behavior is to be expected, as radiation hardening by Ce and Ge co-doping has been established. However, we will see that the addition of substantially more germanium as a co-dopant significantly changes the gain behavior after radiation exposure.

In Fig. 2, we plot the gain curve for one relatively highly germanium co-doped EDF. This fiber, designated as EDF3, has a nearly identical concentration of cerium as EDF1 presented in Fig. 1, the fiber with the greatest gain degradation, but it has the highest Ge concentration in this work. The pristine EDF3 had a final gain of 32.4 dB at 315 mW of pump power. In this case, we see a drastic difference in the post-irradiation gain behavior for this fiber. We began with a 10-kRad dose which resulted in absolutely no degradation in the gain of the fiber and is not plotted here. The fiber was then irradiated with 25 kRad (250 Gy), 50 kRad (500 Gy), and 100 kRad (1000 Gy) doses as shown in the figure. The shape of the irradiated gain curves follows the pristine curves far more closely than the fibers in Fig. 1. This can be seen by the knee in the curves similar to a typical gain curve for a pristine fiber, and the curves subsequently begin to flatten, where saturation begins to appear. This implies that the fiber has not been photodarkened or has been to a very small degree. In this case, only a small degree of photoanneal is occurring as well, and the fiber has radiation-hard behavior by design. In Fig. 2(b), the gain degradation for this fiber is plotted for the three levels of irradiation. After a 25-kRad dose, the fiber quickly

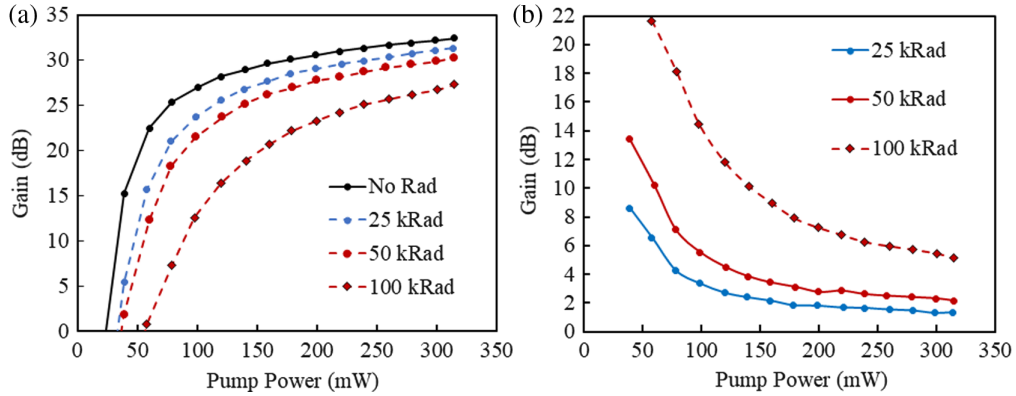

Fig. 2 (a) Gain curves for EDF3 before (solid black) and after various exposures (dashed). (b) Gain degradation curves for the same fiber after various exposures.

reaches its final gain degradation value of 1.36 dB. After a 50-kRad dose, the fiber exhibits a 2.15-dB gain degradation value. Here, we can see that the photoanneal recovery is finished by ~150 mW of pump power. Finally, the fiber exhibits a 5.14-dB gain degradation value after a 100-kRad dose. So for this fiber, its degradation is lower for a 100-kRad dose than the best fiber in Fig. 1 for a 10-kRad dose. It is clear that the larger increase in Ge concentration has made a very large difference, and the Ce seems to have no effect on its performance. We note that the numerical aperture for this fiber has increased such that it has two modes at 1550 nm.

To further demonstrate the benefits of germanium doping to increase the radiation hardness of EDF, in Fig. 3, we present the gain degradation for EDF3 along with a fiber that has no cerium in it, EDF4. This fiber has a lower GeO_2 concentration than EDF3, but the value is still far higher than EDF1 and EDF2 (see Table 1) and is presented to further illustrate the benefit of relatively rich concentrations of germanium in EDF. We note that this fiber had no gain degradation at a dose of 10 kRad (not presented). Here, both fibers were irradiated to 50 kRad. We can see that EDF4 exhibits radiation-hard properties with a degradation of ~3.7 dB. This is not as good as EDF3, but the difference is attributed to a relatively lower GeO_2 concentration, and its rad hard properties are not due to cerium, and still far exceed the fibers given in Fig. 1.

In the work by Cao et al., both Ce in relatively low concentrations, such as our highest Ce concentration fiber, and Ge in substantial concentrations were used to impart radiation hardness to the fibers; however, they did not look at the two species independently.[18] So in that case, we believe that the rad-hard properties are primarily due to germanium co-doping and not cerium.

For greater increases of cerium to be used in EDF, careful doping procedures are required to reduce detrimental clustering and therefore scattering of the signal. Indeed, for highly cerium-doped fibers created in our work with equivalent concentrations of erbium and fiber length, the values for gain are far lower at ~300 mW pump power (not presented). This may be due to the clustering of the Ce ions, causing a large degree of scattering of the signal light. Here, the light may not propagate in the fiber core for long lengths of fiber and will be lost in the cladding. We also note that the presence of both Ge and Ce in the fiber core does not affect the Er absorption or emission cross-section or fluorescence lifetime.

The success of the Ge doping method may be attributed to a couple of factors. Mebrouk et al. have reported that during irradiation Er^{3+} is reduced to Er^{2+}, resulting in gain degradation.[12] The addition of germanium into the fibers may be responsible for reducing this process because Ge co-doping introduces Ge (I) and Ge (II) electron traps that compete with Er^{3+} traps, as has been postulated by others.[12,20] We feel that this is the case for our results, where it is obvious that the signal degradation is far less severe and even eliminated for the relatively heavily Ge co-doped fiber even without the addition of Ce. It is also widely established that upon γ-radiation exposure the ALOHC that are created induce attenuation at the pump wavelength, although the magnitude of these effects may be in question.[1,21] It is also claimed that the attenuation can be reduced by co-doping with cerium and germanium because both of those dopants can capture the holes to compensate for the process.[18] Previous results have indicated that cerium can also serve to sensitize the germanium in the fiber giving it an oxidation change from Ce^{3+} to Ce^{4+}.[18] So here, electrons

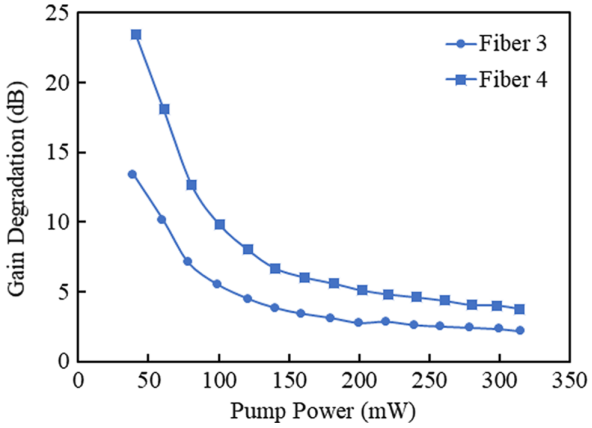

Fig. 3 Gain degradation for EDF3 (circles) and EDF4 (squares) after a 50-kRad (500 Gy) dose.

may be released to combine with the holes created during the radiation process with the result that the two co-dopants working in conjunction are highly beneficial. We feel that this may be the case for low concentrations of both dopants as in EDF1 and EDF2, where EDF2 did show an improvement due to its much greater, albeit still low Ce concentration. But for EDF3 and EDF4, where the fibers were exposed to much greater radiation doses, the cerium most likely provides no benefits for rad-hard behavior, and the benefits come from large Ge concentration alone. In fact, the action of Ge alone has been shown to provide this same mechanism for rad-hard behavior in other work.[22] So we believe that is the case here; germanium co-doping is both effective for reducing the Er^{3+} recombination and compensating for ALOHC creation.

In summary, we have presented a strategy for reducing gain degradation in EDFs after heavy radiation doses by co-doping with cerium and germanium. We have presented four EDFs that received doses of as much as 100 kRad (1000 Gy) γ radiation in the 60 Co pool. We have shown that the introduction of relatively small amounts of cerium and germanium may work together to show only a minimal improvement in radiation hardness, whereas large concentrations of germanium significantly improve the radiation hardness of these fibers.

Code and Data Availability

The data that support the observations of this work will be made available by the corresponding author upon reasonable request.

Acknowledgments

The authors have no relevant financial interests in the paper and no other potential conflicts of interest.

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