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Radiation-resistant cerium co-doped erbium-doped fibers for C- and L-band amplifiers in a high-dose gamma-radiation environment

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Abstract: We experimentally demonstrate a comparative study on the radiation-resistant cerium (Ce) co-doped erbium-doped fiber amplifiers (EDFAs) exposed to a high-dose gamma-radiation environment of 1.8 kGy/h dose rate in the C and L bands. Our results show that Ce is an effective co-dopant in the aluminosilicate EDFs for suppressing radiation-induced attenuation (RIA) of more than an order of magnitude lower than the Ce-free EDF. After exposure to a high-dose gamma-radiation of up to 10 kGy, the Ce co-doped EDF still exhibits good radiation tolerance, providing 41.6 ± 2.9 dB gain and 5 ± 0.8 dB NF from 1535-1560 nm for a -25 dBm input signal. In the L-band, we report, for the first time, the radiation-resistant EDFA with the radiation-induced gain degradation (RIGD) of 3.7 dB under 2.5 kGy irradiation and 4.4 dB under 10 kGy irradiation at 1600 nm. Also, the radiation-dependent gain coefficient and gain saturation were studied in the C and L bands. A comparison of different Ce co-doped EDFs exposed to different total gamma doses reveals the radiation impact on the amplifier performance, indicating the feasibility of using Ce co-doped EDFs for space-based optical communications, requiring robust radiation stability.

1. Introduction

Recently, optical fiber amplifiers, such as erbium-doped fiber amplifiers (EDFAs) have gained significant attention in aerospace communication, benefiting from high gain, wide bandwidth, and good commercial potential. However, in the space radiation environments, EDFs will suffer from radiation-induced attenuation (RIA) due to the formation of the color centers in the glass matrix. The RIA affects the loss at the pump and signal wavelengths of the amplifier, resulting in radiation-induced gain degradation (RIGD) [1]. The RIA is mainly due to the co-dopants used in the doped fibers, such as aluminum (Al) and phosphorus (P), to increase the solubility of rare earth (RE) ions, and suppress clustering in the glass structure. Unfortunately, the Al-related and P-related defects are highly radiation-sensitive, deteriorating the fiber performance under the radiation from X-rays, gamma-rays, solar particles, or protons in the harsh space environment [2,3].

To develop EDFAs with high radiation tolerance, Cerium (Ce) has been studied as a co-dopant to suppress the RIA, by reducing the formation of color centers under radiation [4]. It was reported that Ce co-doping effectively improved the radiation resistance in Er-doped SiO_2-Al_2O_3-CaO glasses [5]. In the C-band, there are some reports on Ce co-doped aluminosilicate fibers to develop the radiation-hardened EDFAs [6] and Er/Yb co-doped fiber amplifiers (EYDFAs) [7,8].

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Germanium (Ge) was also used to develop the radiation tolerant EDFAs in the aluminosilicate host [6,9]. Also, other techniques, such as nanoparticles doping [10,11], H_2 or D_2 loading [7,12], and the hole-assisted carbon-coated (HACC) structure [13], were studied to improve the radiation resistance of C-band EDFAs. The highest gain reported on the radiation-resistant C-band EDFA was ~34 dB at 1550 nm after 1 kGy gamma-radiation by Ce (<0.15mol%) and Ge (>13.3mol%) co-doping [6]. However, to the best of our knowledge, there is no comprehensive study on the radiation-induced effect covering the C-band gain and NF spectrum, gain coefficient, and gain saturation.

Moreover, to the best of our knowledge, there is no report on the radiation-resistant EDFAs in the L-band. To develop additional channels beyond the C-band, L-band EDFA is a good candidate to extend the data transmission capacity for aerospace optical networks. Also, there is significant degradation of optical signals in several parts of the C-band due to the atmospheric molecular absorption lines, requiring the use of L-band EDFA. In addition, it is more challenging to develop L-band radiation-resistant EDFA, which suffers more from the RIA due to a relatively lower population inversion requiring a much longer device length of fiber, compared to the case of C-band EDFA.

In this paper, we demonstrate for the first time, to the best of our knowledge, radiation-resistant EDFAs operating in the C-band (1535-1560 nm) and L-band (1570-1600 nm), respectively. We report the radiation-resistant EDFs using Ce co-doping in the aluminosilicate glass host, without any specific coating, packaging, or additional pre-treatment to EDFs. A series of EDFs with different Ce concentrations were fabricated in-house and exposed to the high-dose gamma-radiation environment using a dose rate of 1.8 kGy/h and up to a total dose of 1, 2.5, and 10 kGy, respectively. Subsequently, the irradiated fibers were characterized in terms of RIA and amplifier performance, including the gain, noise figure (NF), gain coefficient, and saturated output power, to evaluate their radiation tolerance.

It is worth pointing out that the actual space radiation environment varies according to the orbit considered in the space missions. The typical radiation dose level in low earth orbit (LEO) space missions can reach up to 1 kGy [9,13,14], while in the highly irradiated geostationary earth orbit (GEO) satellite mission the total dose can reach up to 3 kGy [15]. The highest total dose of 10 kGy used in our work is extremely high for the current space missions, however such radiation dose is expected for future missions like one of the most severe radiation environments, Jupiter icy moon explorer [13], or other special radiation-environmental applications like large hadron colliders (LHCs) [3]. Another factor influencing the total radiation dose is the duration of the exposure, depending on the life of the space mission. Also, the dose rate of 1.8 kGy/h used in our work far exceeds from the actual dose rate often considered in the space environment [14,16]. Considering the dose rate dependence of the radiation-induced deterioration, the radiation-dependent characteristics reported here can be referenced as an extreme irradiation condition, which needs careful consideration in the real systems with respect to a number of factors such as the actual orbit type, shielding conditions of the component, life of the space mission, etc [1,15,17].

To the best of our knowledge, the radiation tolerance of EDFAs under such harsh radiation conditions, of 1.8 kGy/h dose rate and up to 10 kGy total dose, has not been reported. Also, it has been shown that the radiation-induced effect is insensitive to the nature of radiation, such as X-rays, gamma, protons, and electrons [18]. Thus, the radiation tolerance concluded from the gamma radiation studies can also serve as a proper representation of space radiation [19].

2. Experimental procedure

2.1. C- and L-band amplifiers setup

Figure 1 illustrates the experimental setup for the C- and L-band EDFAs in our work. A tunable laser source (TLS, 8164A, Agilent) was used as the signal source, with an adjustable signal power from −35 to 0 dBm, < 0.2 nm channel bandwidth, and >44 dB optical signal-to-noise ratio (OSNR). Two FBG stabilized pump laser diodes operating at ~980 nm were used as the bi-directional pumps, with a maximum pump power of ~690 mW from each diode (i.e., a maximum total pump power of 1380 mW). An optical spectrum analyzer (OSA, AQ6370, Yokogawa) was used to capture the input and output signal spectra. Three isolators (ISOs, Thorlabs) were used to protect the TLS and LDs. Two wavelength division multiplexers (WDMs, G&H) were used to couple and divide the signal and pump lights. The commercial SMF980 (SD362A-00C, Fibercore) was used to connect the EDF in the setup.

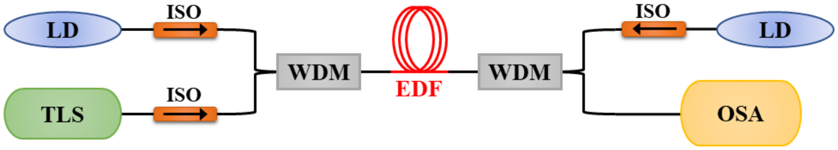

Fig. 1. Schematic of the C/L-band EDFA setup in the experimental work.

2.2. Irradiation tests

The EDFs were placed in a cylindrical ^{60}Co chamber, uniformly irradiated under the gamma dose rate of 1.8 kGy/h. Three sets of EDFs were irradiated up to a total gamma dose of 1, 2.5, and 10 kGy, respectively. Then, the fibers were characterized for radiation-resistant performance after about 5 days of gamma exposure. The radiation-induced attenuation (RIA) was calculated by subtracting the pre-irradiation loss from the post-irradiation loss, both measured using the white light source by the cutback method.

Then, the irradiated fibers were tested in the C-band (1535-1560 nm) and L-band (1570-1600 nm) amplifier setup, respectively. To evaluate the radiation tolerance of the amplifier, the radiation-induced gain degradation (RIGD) was calculated by comparing the gain of the pre-irradiation fiber (pristine) and post-irradiation fibers (for different total gamma doses) using the same device length and pumping conditions.

3. Results and discussion

3.1. In-house fabricated fibers

A series of Er-Ce co-doped aluminosilicate preforms were fabricated using the modified chemical vapor deposition (MCVD) and solution doping method. Er, Al, and Ce were incorporated in the SiO_2 soot by immersing the porous soot layer in a methanolic solution for a sufficient solution doping period. After drying, the glassware was reassembled to the lathe and a solid preform was obtained by oxidation, sintering, collapsing, and sealing processes. Maintaining the same fabrication conditions with the only difference in the Ce concentrations, three preforms were selected to study with different Ce concentrations of 0 (EDF-a, Ce free), 2.6 wt% (EDF-b), and 4.8 wt% (EDF-c). The preforms were drawn into the fiber with a core/clad diameter of ~6/100 µm for EDF-a, ~3.8/150 µm for EDF-b, and ~3.2/150 µm for EDF-c. The basic parameters of the three EDFs are presented in Table 1.

The refractive index difference (Δn) was measured using the optical fiber refractive index profiler (IFA-100, Interfiber Analysis). Figure 2(a) shows the Δn and LP01 mode field intensity profiles at the pump wavelength of 980 nm and one signal wavelength of 1600 nm of EDF-c. The core compositions were measured and analyzed using the electron probe micro analyzer (EPMA). The doping element distribution profiles of EDF-c are illustrated in Fig. 2(b), with the Ce concentration of 4.8 wt%, Al concentration of 3.1 wt%, and Er concentration of 0.2 wt%. The absorption coefficient was measured using a white light source (IL1, Bentham) and

Table 1. Basic parameters of EDFs used in this work

	EDF-a	EDF-b	EDF-c
Ce mass (wt%)	0	2.6	4.8
Δn	0.007	0.015	0.022
Core diameter (μm)	6	3.8	3.2
Clad diameter (μm)	100	150	150
LP11 cutoff (nm)	1070	1030	1040
Absorption at 980 nm (dB/m)	12	12	11
Background loss at 1200 nm (dB/m)	0.02	0.04	0.10

an OSA (AQ6370, Yokogawa) by the cutback method. At the 980 nm pump wavelength, the absorption coefficient was 12 dB/m for EDF-a and EDF-b, and 11 dB/m for EDF-c. Also, the background loss at 1200 nm was measured to be 0.02 dB/m for EDF-a, 0.04 dB/m for EDF-b, and 0.10 dB/m for EDF-c. To characterize the amplifier performance, the average splice loss between the SMF980 and the EDF at the signal wavelengths was measured to be 0.51 dB for EDF-a, 0.43 dB for EDF-b, and 0.16 dB for EDF-c. The splice loss was taken into consideration when calculating the gain and NF.

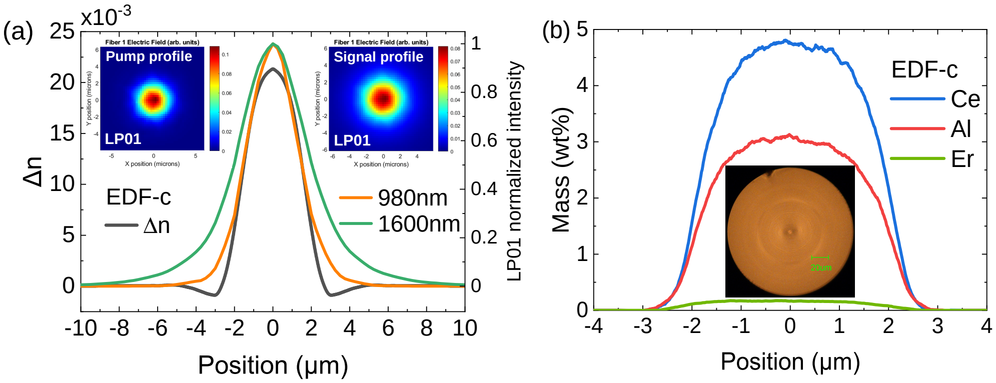

Fig. 2. (a) For EDF-c, the distribution profiles of the refractive index difference (Δn) and the LP01 normalized intensity at 980 nm pump and 1600 nm signal wavelengths. The insets show the 2D profiles of LP01; (b) For EDF-c, the distribution profiles of the core element (Ce, Al, Er) measured by EPMA. The inset shows a microscope image of the fiber end face.

3.2. Radiation-induced attenuation

We first present the radiation-induced attenuation (RIA) spectrum for the three EDFs, as shown in Fig. 3. Without any Ce in the core, EDF-a exhibited an extremely high RIA due to the radiation-sensitive Al-related color centers in the glass matrix [19]. The RIA at 1350 nm of EDF-a was measured to be 7.6, 15.5, and 37.6 dB/m under the total dose of 1, 2.5, and 10 kGy, respectively. By adding Ce, EDF-b and EDF-c exhibited a suppressed RIA, and EDF-c, with a higher Ce of 4.8 wt%, was more radiation-tolerant. The RIA at 1350 nm of EDF-c was reduced to 0.3, 0.7, and 1.6 dB/m under the total dose of 1, 2.5, and 10 kGy, respectively.

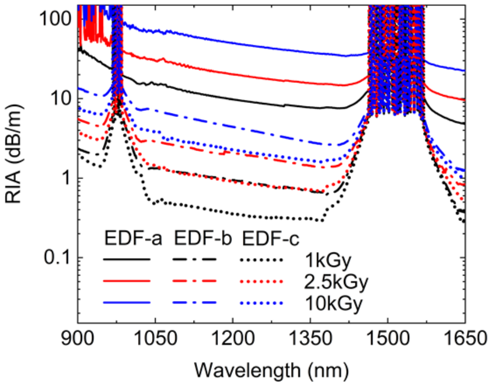

Fig. 3. The radiation-induced attenuation (RIA) spectra of EDF-a, EDF-b, and EDF-c under the gamma dose of 1, 2.5, and 10 kGy, respectively.

3.3. Radiation-induced gain degradation in the C-band

Then, we measured the small-signal gain using an input signal power of -25 dBm and the total pump power of 1380 mW. In the C-band, using 7 m of pre-irradiation EDF-a (pristine), we achieved a high and flat gain of 46.1 ± 2.3 dB with 5.8 ± 1.0 dB NF from 1535-1560 nm. However, after the irradiation with a total dose of 2.5 kGy, this fiber was showing only <4 dB gain with >4.5 dB NF when using 0.5 m of fiber. Figure 4(a) shows the gain and NF spectra of the pristine EDF-a (7 m) and 2.5 kGy irradiated EDF-a (0.5 m). The gain is presented by the solid lines and the NF is presented by the dashed lines. Figure 4(b) shows the gain and NF variations at 1550 nm with the pump power for 0.5 m of the irradiated EDF-a. Using the same device length of 7 m as the pristine fiber, the irradiated EDF-a was completely darkened without showing any positive gain with the available pump power in our work.

Then, the 2.5 kGy and 10 kGy irradiated EDF-b and EDF-c were tested in the C-band, respectively. Figure 4(c) shows the gain and NF spectra of EDF-b and EDF-c under different irradiation conditions (i.e., pristine, 2.5 kGy total dose, and 10 kGy total dose). The corresponding gain and NF ranges are presented in Table 2. After irradiation, the device length was maintained the same as the pristine fiber, which was 7 m for EDF-b and 8 m for EDF-c. With 2.6 wt% Ce, EDF-b had the RIGD of <3.7 dB after 2.5 kGy irradiation and <5.1 dB after 10 kGy irradiation. With 4.8 wt% Ce, EDF-c was more radiation-resistant, only suffering <1.5 dB RIGD after 2.5 kGy irradiation and <3.3 dB RIGD after 10 kGy irradiation. For 10 kGy irradiation, EDF-c still exhibited 41.6 ± 2.9 dB gain with 5 ± 0.8 dB NF. To the best of our knowledge, the highest post-irradiation gain of the C-band EDFA reported to date is ~34 dB at 1550 nm, provided by the Ge-Ce co-doped EDF after 1 kGy irradiation with a 720 Gy/h dose rate [6]. Our EDF-c outperforms even under heavier exposure of 10 kGy irradiation.

Table 2. Gain and NF in the C-band (1535-1560 nm)

	EDF-b		EDF-c	
	Gain (dB)	NF (dB)	Gain (dB)	NF (dB)
Pristine	44.3 ± 2.6	5.6 ± 0.8	43.9 ± 2.7	5.1 ± 0.6
2.5 kGy dose	43 ± 3	5.4 ± 0.8	42.8 ± 2.9	5.8 ± 0.8
10 kGy dose	40.6 ± 2.7	5 ± 0.6	41.6 ± 2.9	5 ± 0.8

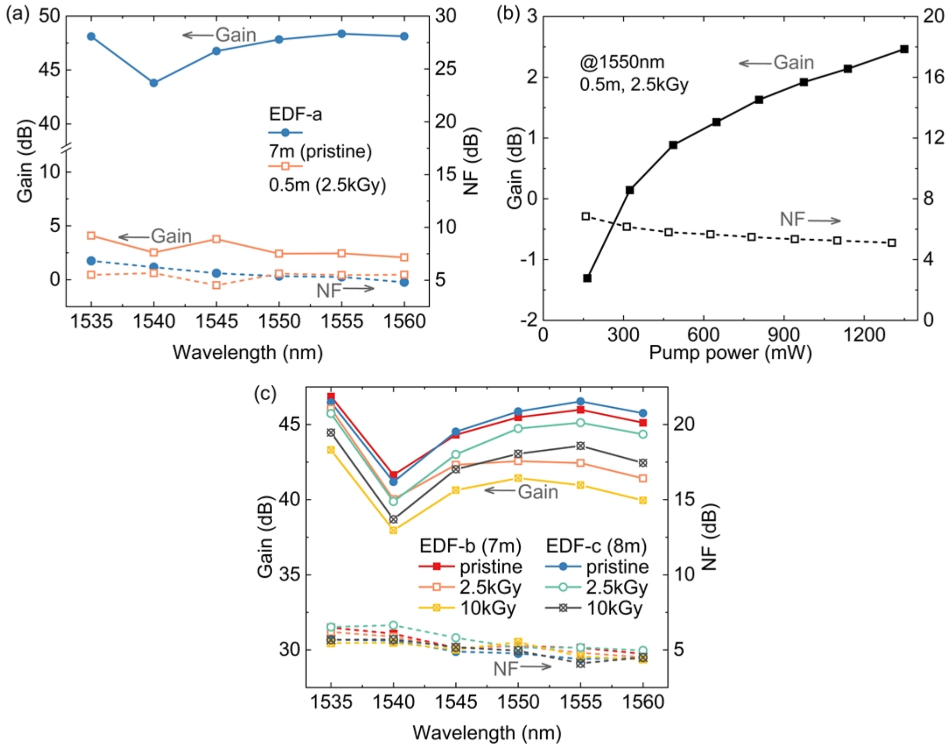

Fig. 4. (a) The C-band gain and NF spectra of the pristine and 2.5 kGy irradiated EDF-a; (b) The gain and NF variations at 1550 nm with the pump power of the 2.5 kGy irradiated EDF-a; (c) The C-band gain and NF spectra of EDF-b and EDF-c, using the pristine, 2.5 kGy irradiated, and 10 kGy irradiated fibers, respectively.

3.4. *Radiation-induced gain degradation in the L-band*

In the L-band EDFA, we required a longer device length to achieve the desired population inversion, resulting in higher amplifier deterioration from the RIA. Also, the pre-irradiation optimal device length was not suitable after irradiation. The highly degraded EDF-a was completely darkened in the L-band, which means the available pump power in our work was not sufficient to overcome the threshold of any length of irradiated EDF-a. For EDF-b and EDF-c, the post-irradiation device length was optimized with respect to the highest overall gain from 1570-1600 nm, under 2.5 kGy and 10 kGy irradiation conditions, respectively. It was observed that the optimal device length was decreased as fibers were irradiated with a higher dose, as shown in Fig. 5. In the following discussions on the irradiated fibers, the gain and NF of the pristine fiber using the same device length were compared as a benchmark to evaluate the radiation-induced amplifier degradation.

Figure 6(a) and (b) show the L-band gain and NF spectra of pristine, 2.5 kGy and 10 kGy irradiated EDF-b and EDF-c. The gain and NF at 1600 nm, and the device length are presented in Table 3. Here the fiber lengths for pristine EDF-b and EDF-c were selected based on the optimal amplifier performance in the L-band of the respective irradiated fibers. The pristine EDF-b and EDF-c all provided >18 dB gain and <5.3 dB NF from 1570-1600 nm. After 2.5 kGy irradiation, 13 m of EDF-b had a 12.6 dB gain with 6.9 dB NF at 1600 nm, while 12.6 m of EDF-c exhibited a 16.2 dB gain with 5.6 dB NF. The RIGD at 1600 nm was 7.2 dB for EDF-b and 3.7 dB for EDF-c. After 10 kGy irradiation, the RIGD increased to 9.7 dB for EDF-b and

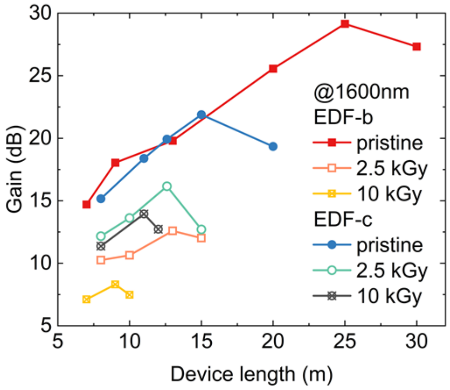

Fig. 5. The gain variations at 1600 nm with the device length of EDF-b and EDF-c, using the pristine, 2.5 kGy irradiated, and 10 kGy irradiated fibers, respectively.

slightly increased to 4.4 dB for EDF-c. The comparison between the two EDFs at two dose levels suggests that Ce co-doping significantly improves the RIGD of the amplifier in the L-band. Even in the extremely high irradiation level of 10 kGy, EDF-c still achieved a 14 dB gain with 6.2 dB NF. Also, the RIGD per dose was much lower for the 10 kGy irradiated fibers than in the case of 2.5 kGy irradiation. It indicated that the RIGD starts to saturate with the accumulative dose [1,6]. It is worth mentioning that the RIGD at a lower total dose (<1 kGy) is not a simple interpolation from the high-dose results due to the progressively saturating trend with an increasing total dose.

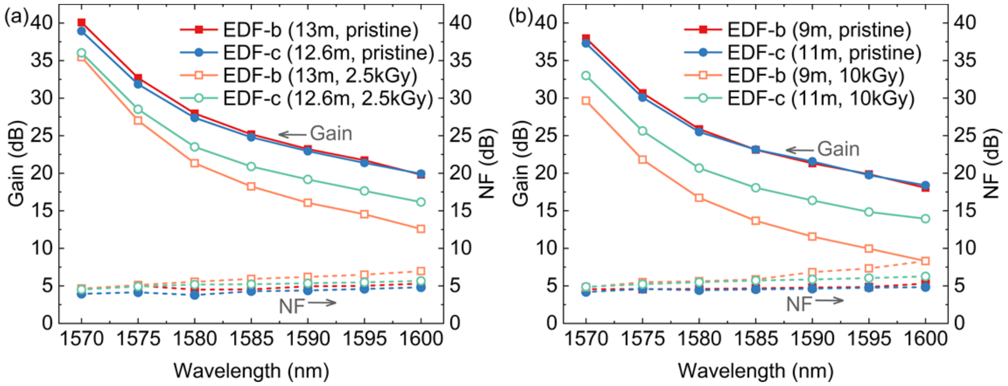

Fig. 6. The L-band gain and NF spectra of EDF-b and EDF-c using (a) the pristine and 2.5 kGy irradiated fibers (b) the pristine and 10 kGy irradiated fibers.

Table 3. Gain, NF, and device length in the L-band (@1600 nm)

	EDF-b			EDF-c		
	Gain (dB)	NF (dB)	Length (m)	Gain (dB)	NF (dB)	Length (m)
Pristine	19.8	5.3	13	19.9	4.8	12.6
2.5 kGy dose	12.6	6.9	13	16.2	5.6	12.6
Pristine	18	5.3	9	18.4	4.8	11
10 kGy dose	8.3	8.2	9	14	6.2	11

3.5. Gain coefficient and gain saturation in the C-band

Furthermore, we studied the gain and NF variations with the pump power at 1550 nm in the C-band, as shown in Fig. 7(a) and (b). The gain coefficient was calculated to be the maximum ratio of the gain to the pump power. After irradiation, the gain coefficient of EDF-b decreased from 0.32 dB/mW (pristine) to 0.15 dB/mW (2.5 kGy) and 0.10 dB/mW (10 kGy), together with a higher pump threshold. The results indicated that to achieve a similar gain of 41.5 dB at 1550 nm at different irradiation conditions, the EDFA could be operated by increasing the pump power from ~400 mW (pristine) to ~1000 mW (2.5 kGy) and ~1380 mW (10 kGy). Similarly, the gain coefficient of EDF-c decreased from 0.16 dB/mW (pristine) to 0.11 dB/mW (2.5 kGy) and 0.09 dB/mW (10 kGy). Targeting a 43 dB gain at 1550 nm, the EDFA could be operated by increasing the pump power from ~700 mW (pristine) to ~1000 mW (2.5 kGy) and ~1380 mW (10 kGy).

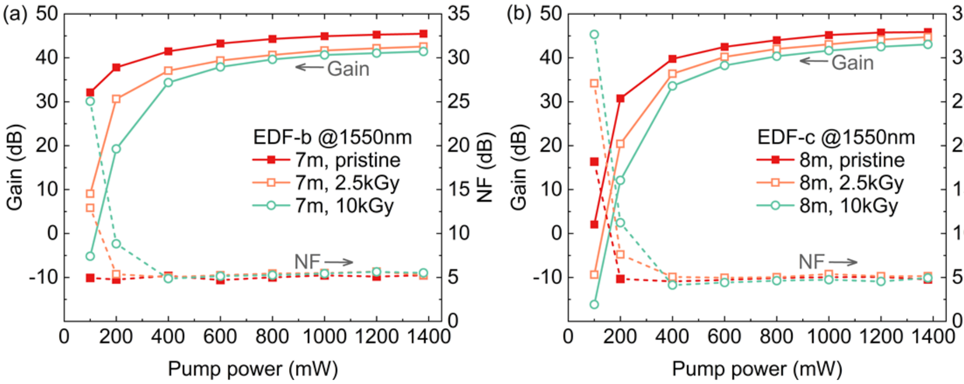

Fig. 7. The gain and NF variations at 1550 nm with the pump power of (a) EDF-b and (b) EDF-c, using the pristine, 2.5 kGy irradiated, and 10 kGy irradiated fibers, respectively.

On the other hand, we studied the gain and NF variations with the input signal power at 1550 nm in the C-band, as shown in Fig. 8(a) and (b). With an increasing signal power from -35 to 0 dBm, the gain saturated when reaching the 3 dB drop compared to the small-signal gain value. The saturated output power was 24 dBm (pristine), 21 dBm (2.5 kGy), and 20 dBm (10 kGy) for EDF-b. For EDF-c, the saturated output power was 22.5 dBm (pristine), 21 dBm (2.5 kGy), and 20 dBm (10 kGy). The above results exhibit the good radiation tolerance of the C-band EDFA using EDF-b and EDF-c.

3.6. Gain coefficient and gain saturation in the L-band

Similarly, we studied the gain and NF variations with the pump power at 1600 nm in the L-band, as shown in Fig. 9(a) and (b). Compared to the C-band results, the drop in gain coefficient and increment of pump threshold were more obvious after irradiation. For EDF-b, the gain coefficient at 1600 nm decreased from 0.09 dB/mW to 0.013 dB/mW after 2.5 kGy irradiation, and from 0.146 dB/mW to 0.013 dB/mW after 10 kGy irradiation. For EDF-c, the gain coefficient at 1600 nm decreased from 0.048 dB/mW to 0.019 dB/mW after 2.5 kGy irradiation, and from 0.054 dB/mW to 0.017 dB/mW after 10 kGy irradiation. Figure 10(a) and (b) show the gain and NF variations with the input signal power at 1600 nm, exhibiting negligible gain and NF variations for both EDF-b and EDF-c, both pre- and post-irradiation.

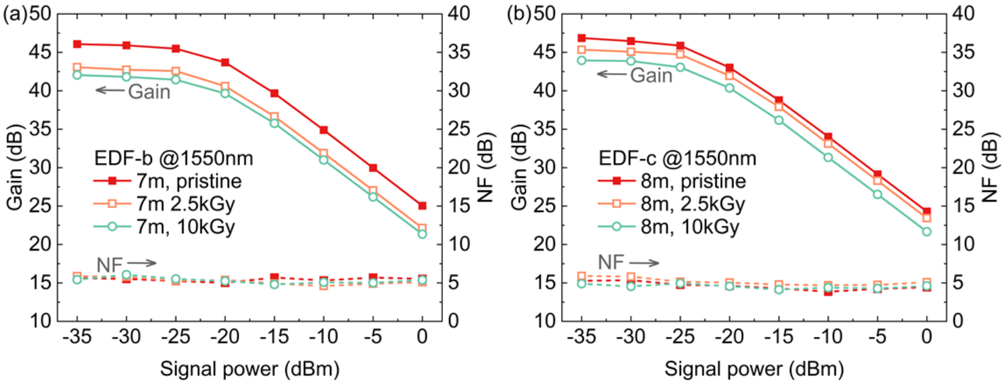

Fig. 8. The gain and NF variations at 1550 nm with the input signal power of (a) EDF-b and (b) EDF-c, using the pristine, 2.5 kGy irradiated, and 10 kGy irradiated fibers, respectively.

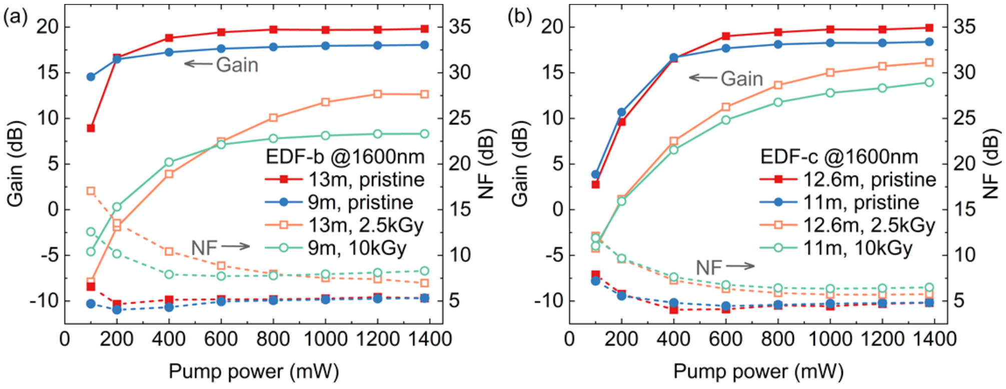

Fig. 9. The gain and NF variations at 1600 nm with the pump power of (a) EDF-b and (b) EDF-c, using the pristine, 2.5 kGy irradiated, and 10 kGy irradiated fibers, respectively.

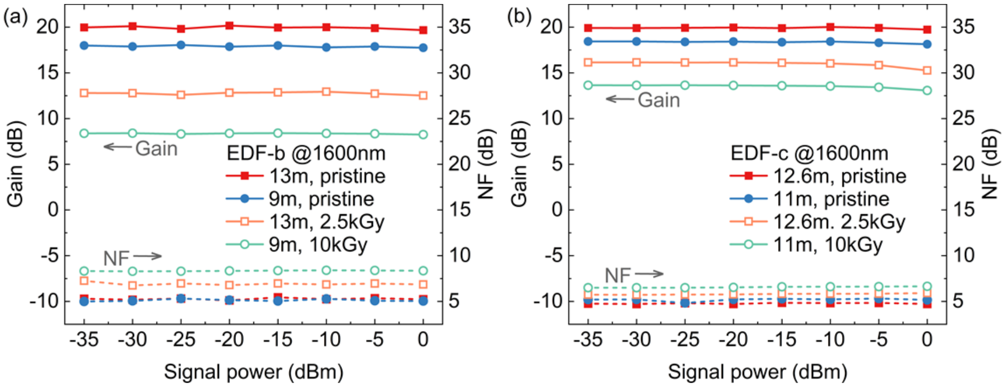

Fig. 10. The gain and NF variations at 1600 nm with the input signal power of (a) EDF-b and (b) EDF-c, using the pristine, 2.5 kGy irradiated, and 10 kGy irradiated fibers, respectively.

4. Conclusions

We have demonstrated, to the best of our knowledge, the first comparative investigation on the performance of C- and L-band radiation-resistant EDFAs under elevated doses of gamma-radiation. The radiation resistance of erbium-doped aluminosilicate fiber was significantly improved by co-doping with Ce, fabricated using the MCVD and solution doping technique. The EDFA has reached >41 dB gain in the C-band (1535-1560 nm) and >18 dB gain in the L-band (1570-1600 nm) for Ce co-doped EDFs. While the pure Al co-doped EDF became almost darkened after irradiation due to the Al-related defects, the addition of Ce in the core significantly reduced the RIA of EDFs by more than an order of magnitude. In the C-band, EDF-c, with 4.8 wt% of Ce, is still fully operational with 41.6 ± 2.9 dB gain and 5 ± 0.8 dB NF even under 10 kGy irradiation. It is, to the best of our knowledge, the highest post-irradiation gain reported to date in the radiation-resistant C-band EDFAs. In the L-band, we report, for the first time, that the RIGD at 1600 nm of EDF-c was 3.7 dB under 2.5 kGy irradiation and 4.4 dB under 10 kGy irradiation. Under 10 kGy irradiation, a gain of 14 dB with a NF of 6.2 dB was achieved at 1600 nm. Also, the gain coefficient and saturated output power for the irradiated fibers have been reported. We believe that our findings of improved RIA in EDFs co-doped with Ce are highly significant for optical fiber amplifiers in space telecommunication systems, especially for long-term, harsh radiation, and high-dose rate space missions.

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Disclosures. The authors declare no conflicts of interest.

Data Availability. The data for this work is accessible through the University of Southampton Institutional Research Repository [20].

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