Radiation-Resistant Er-Doped Fiber Based on Ge-Ce Co-Doping

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***Abstract*—We investigated the radiation responses of Ge-Ce co-doped erbium-doped fibers (EDFs) under gamma radiation with a dose up to 1000 Gy and a dose rate of 0.2 Gy/s. Three EDFs with low or high concentrations of Ge or Ce were fabricated by modified chemical vapor deposition (MCVD). The absorption spectra and amplification performance of the three Ge-Ce co-doped EDFs before and after radiation were tested and analyzed in detail. The radiation-induced absorption (RIA) can be dramatically weakened by heavily co-doping Ge and Ce, and 0.8 dB radiation-induced gain degradation at 1550 nm was obtained in the erbium-doped fiber amplifier (EDFA) with heavy Ge and Ce doping at a dose of 1000 Gy. Furthermore, the possible mechanism of Ce and Ge effects on radiation tolerance enhancement is discussed. Relevant results indicate that the Ge-Ce co-doped EDF has significant performance improvements in radiation resistance, making it ideal for applications in harsh radiation environments.**

***Index Terms*—Fibers, erbium, radiation hardening, Er-doped fiber amplifier, rare-earth-doped materials.**

I. Introduction

RECENTLY, rare-earth-doped optical fibers and amplifiers have been widely used in space applications, such as satellite telecom [1]–[3], remote sensing [4] and navigation [5] due to their high gain, compactness and light weight. However, the high radiation sensitivity of rare-earth-doped fibers leads to amplification and transmission performance deterioration in fiber amplifiers or lasers under the bombardment of cosmic rays [6]. Currently, the degradation of these properties is believed to derive from the RIA [7], [8]. Traditional rare-earth doped fiber will generate various color center species related to SiO_2, Al or P when exposed to radiation [9]–[11], and the absorption peaks of these color centers are mostly located in the VIS or UV band. As a result, the superabundant absorption arises at the absorption and emission wavelengths of rare-earth-doped fiber. In this case, rare-earth-doped fiber amplifiers such as EDFAs exhibit radiation-induced gain degradation (RIGD) after radiation. Therefore, a crucial topic to be investigated for rare-earth doped fibers is improving the radiation resistance for applications in harsh environments.

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Worldwide researchers have proposed numerous radiation-hardening technologies of rare-earth-doped fibers. One of the most effective approaches is loading hydrogen or deuterium into the fabricated optical fibers [12], [13]. However, a major problem with this kind of method is the high volatility of gas. A hole-assisted carbon-coated (HACC) EDF was developed to effectively solve this problem with less than 10% diffusion of H^2 in the fibers after five months [14]. Another alternative for rad-hard is utilizing the nanoparticle doping process (NDP), which can mitigate the RIA level by limiting the Al content in the EDF [15]. Furthermore, the methods of hardening-by-component in optical fibers or glass materials were extensively studied. The potential of Ce-co-doping for improving the radiation tolerance of bulk optical materials has been proved by Jackson S. Stroud [16]. S. Girard et al. reported an ErYbCe-codoped fiber amplifier with excellent radiation resistance, with 8% gain degradation after a cumulative dose of 900 Gy [17]. In addition, recent studies have shown Ge-doping has a positive impact on radiation hardening in rare-earth-doped fibers [18]–[21]. It has been demonstrated that the introduction of Ge into the rare-earth doped fiber could induce the competition of hole-trapping or electron-trapping between the precursors of Al or P and Ge [19]. To cope with the harsher radiation environment for space missions, we use a Ge-Ce co-doping strategy in EDFs to enhance the radiation resistance. To the best of our knowledge, this is the first time to adopt this doping strategy for radiation hardening in EDFs.

Three radiation-resistant EDFs based on Ge-Ce co-doping were fabricated by MCVD. The dimensions and concentrations of the EDFs are shown in Table I. All EDFs are doped with a similar amount of Al to weaken the clustering effect [22]. The concentrations of Er ions in the three fibers are similar, and the absorption coefficients of the three fibers around 980 nm are almost the same as shown in Fig. 1. The Ge and Ce doping concentrations of the three EDFs are compared as follows: EDF1 and EDF2 have similar Ge concentrations, and the Ce concentration of EDF2 is about three times that of EDF1. EDF3 has a similar Ce concentration as EDF2, and the Ge concentration of EDF3 is about three times that of EDF2. The absorption coefficients of three pristine fibers at 980 nm and 1530 nm are 7.5∼9.0 dB/m and 14.0∼16.0 dB/m which belong to the low absorption type EDFs. Three EDFs have the same core/clad size of 9/125 μm, and the cross section of EDF3 is shown in the illustration of Fig. 1. Currently, the radiation dose range for space missions is about 300-1000 Gy [23]. Three EDFs were exposed to a Co_{60} source under room temperature with accumulative doses of 250 Gy, 500 Gy, 750 Gy and 1000 Gy at an average

TABLE I
ER-DOPED FIBERS CHARACTERISTICS

Fiber parameters	EDF1	EDF2	EDF3
Core diameter (μm)	9	9	9
Clad diameter (μm)	125	125	125
Er ($*10^{25}$ Ions/m^3)	0.74	0.85	0.95
Al (mol. %)	2.5~3.0	2.5~3.0	2.5~3.0
Ge (mol. %)	3.7~4.9	4.0~5.1	13.3~14.8
Ce (mol. %))	0.04~0.05	0.13~0.15	0.14~0.15
Abs@980 nm (dB/m)	7.5~9.0	7.5~9.0	7.5~9.0
Abs@1530 nm (dB/m)	14.0~16.0	14.0~16.0	14.0~16.0
MFD@1550 nm (μm)	8.5~9	7.5~8	7~7.5
Number of propagation modes@1550 nm	2	3	4

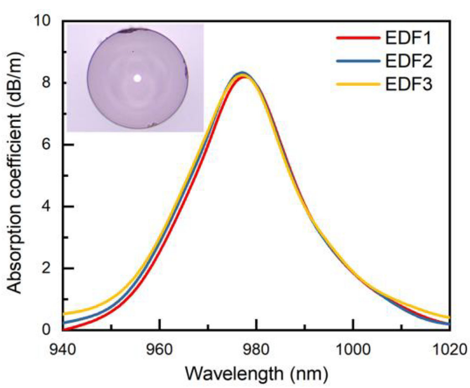

Fig. 1. The spectral absorption coefficient of three pristine fibers around 980 nm. The cross section of EDF3 is shown in illustration.

dose rate of 0.2 Gy/s. We first tested the RIA of three EDFs from 600 nm to 1600 nm, and then the RIGD of the three EDFs at 1550 nm was also tested by a typical EDFA structure. All the tests for RIA and RIGD were performed with 3∼4 hours after irradiation to avoid radiation-induced absorption relaxation.

II. EXPERIMENTAL SETUP FOR RIA AND RIGD TESTING

The absorption spectra of three Ge-Ce co-doping EDFs before and after radiation were measured using the cutback method from 4 m to 0.5 m. The structure diagram of the RIA test system is shown in Fig. 2. The differences in the absorption spectrum between pristine EDF and irradiated EDF were calculated as RIA per 1 m length.

A typical EDFA was built for measuring the gain variation before and after radiation, as shown in Fig. 3. The signal at 1550 nm was generated by a C-band tunable laser source with a power of −20 dBm. The pristine and irradiated of the three EDFs were separately spliced into the amplifier to test the gain. In several

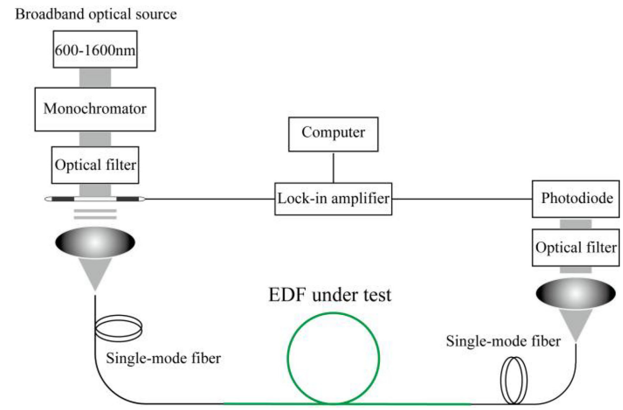

Fig. 2. The structure diagram of RIA test system.

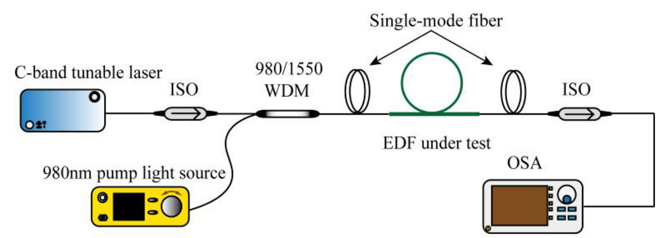

Fig. 3. The RIGD test system diagram. ISO is the optical isolator, WDM is the wavelength division multiplexer, and OSA is the optical spectrum analyzer.

tests, the error due to splicing losses was less than 0.2 dB, which had relatively little effect on the comparison of the RIGD results. The length of all EDFs in the amplifier was 4 m, and the initial gain of pristine versions of three EDFs was 28 dB with 100 mW of pump power at 980 nm.

III. RESULTS AND DISCUSSIONS

The absorption spectra of the three pristine EDFs and the absorption spectra of the EDFs under different radiation doses are shown in Fig. 4. Irradiation causes an increase in the absorption coefficient of the EDFs, and the absorption coefficient increases with increasing irradiation dose (note the different vertical coordinates in the figures). In addition, the absorption coefficient of the short wavelength band is higher than that of the long wavelength band. A detailed comparison of the RIA of the three EDFs at different doses is shown in Fig. 5. EDF3 exhibits the best radiation resistance at the same exposure level. By comparing the RIA of EDF1 and EDF2, we discover that heavily Ce doping can significantly improve the radiation tolerance of EDF in high-dose or low-dose environments. In addition, we found a relatively clear absorption band of erbium ions in the RIA spectra, this may be due to the fact that a portion of Er^{3+} traps electrons and produces Er^{2+} when exposed to radiation [18]. The experimental results of EDF2 and EDF3 show that the radiation resistance can be further improved through heavily co-doping Ge and Ce. Moreover, from Fig. 5(c) and (d) we can see that EDF3 (heavily doped cerium and germanium) has

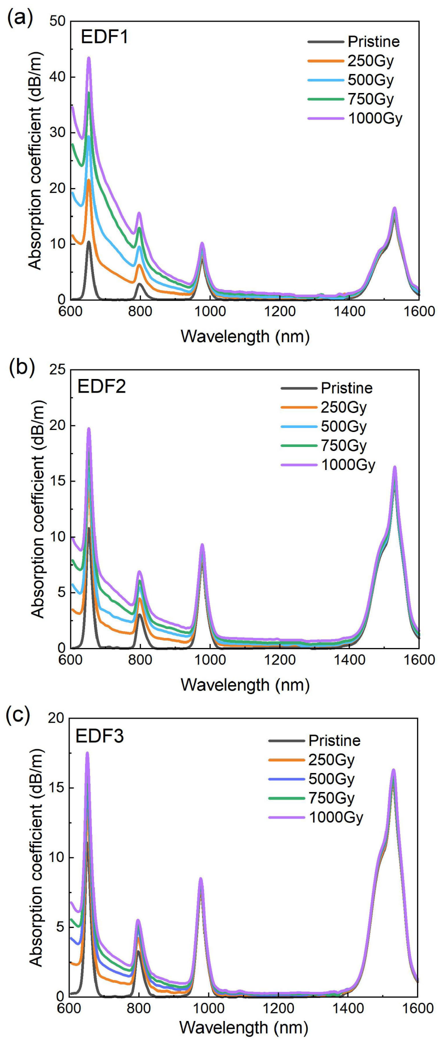

Fig. 4. The absorption spectra of EDF1, EDF2 and EDF3 under different radiation doses.

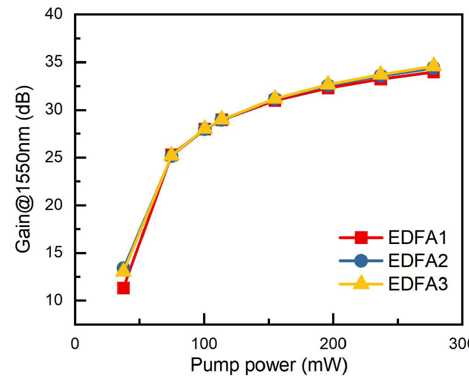

Fig. 6. The gain curves of EDFA1, EDFA2 and EDFA3 based on EDF1, EDF2 and EDF3, respectively. The results were tested before the three EDFs were irradiated.

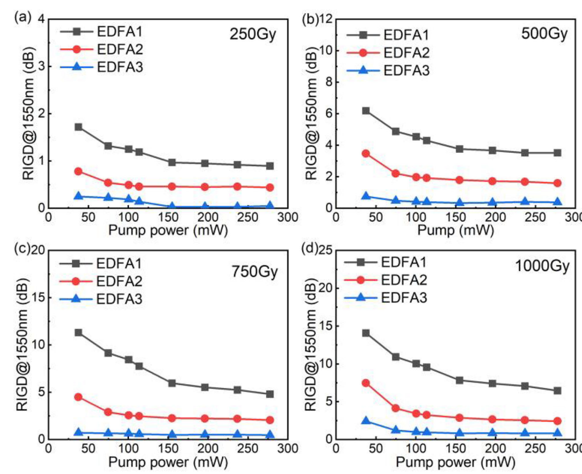

Fig. 7. Evolution of RIGD with pump powers for EDFA1, EDFA2 and EDFA3 under different radiation doses. (a) 250 Gy, (b) 500 Gy, (c) 750 Gy and (d) 1000 Gy. Each gain test at different pump powers was recorded after pumping the irradiated erbium-doped fiber for two minutes, with a test time of about 16 minutes per fiber.

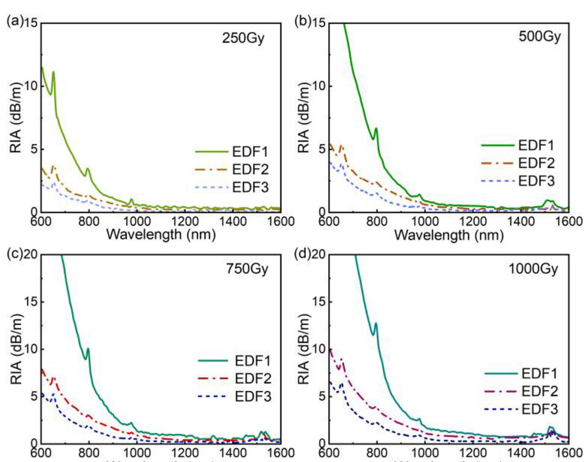

Fig. 5. Evolution of RIA with dose from 600 nm to 1600 nm for EDF1, EDF2 and EDF3. (a) under 250 Gy, (b) under 500 Gy, (c) under 750 Gy and (d) under 1000 Gy.

better radiation tolerance especially at high doses (750 Gy and 1000 Gy).

RIA is suitable for describing the additional absorption of optical fiber in the spectral domain for the appointed radiation environments, and it is a universal parameter to measure the anti-radiation capability of optical fiber. In practical applications such as EDFA, the color centers around the pump and signal wavelengths will be generated after radiation and degrade the gain of the amplifier. Fig. 6 shows the variation of gain at 1550 nm with pump power for the three EDFAs based on three pristine EDFs. In our experimental evaluations, the gain curves of the three EDFAs are quite close, which indicates that the highly doped germanium and cerium do not degrade the amplification performance of the fabricated EDFs. The variation of RIGD with pump power for the three EDFAs at the four doses is shown in Fig. 7. RIGD is obtained by subtracting the gain of the EDFAs after each irradiation from that measured before irradiation. To investigate the influence of the photo-bleaching

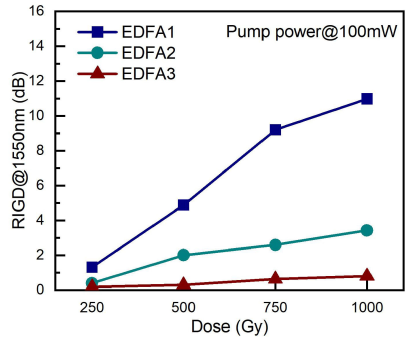

Fig. 8. Comparison of the RIGD of EDFA1, EDFA2 and EDFA3 at 100 mW pump power at doses of 250 Gy, 500 Gy, 750 Gy and 1000 Gy.

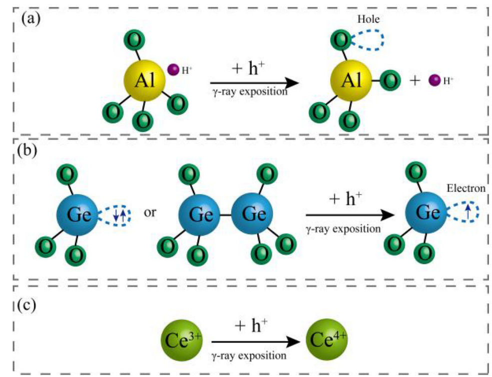

Fig. 9. Models for the formation of Al-OHC, GeE' and Ce^{4+} under gamma radiation. (a) Al-OHC, (b) GeE' and (c) Ce^{4+}.

on the tests, each gain test at different pump powers was recorded after two minutes of pumping the irradiated erbium-doped fibers. From Fig. 7 we can see that as the pump power increases, an obvious photo-bleaching phenomenon occurs, and it starts to slow down when the pump power reaches 100 mW. Related studies have shown that the photo-bleaching effect can recover part of the amplification performance of optical fibers, and that the higher the radiation dose the lesser the degree of recovery [24], [25]. In our case, the photo-bleaching effect recovers part of the amplification properties of the irradiated EDFs especially for EDFA1 at high doses. A clear comparison of RIGD versus dose in the three EDFAs at a pump power of 100 mW is shown in Fig. 8. Similar to the test results of RIA, EDFA3 expressed better radiation resistance than the other two EDFAs with 0.8 dB RIGD under 1000 Gy. In a low dose condition, the EDFA1 exhibits radiation hardened properties comparable to the EDFA2 and EDFA3 (RIGD<2 dB at 250 Gy). However, as the dose increases, the severe gain degradation arises in EDFA1 (RIGD>10 dB at 1000 Gy). Meanwhile, EDFA2 and EDFA3 showed excellent radiation tolerance at both low and high doses, with gain reduction ratios of 9.3% and 2.3% at 750 Gy and 12.3% and 2.9% at 1000 Gy, respectively. The above experimental results show that the doping strategy of highly doped cerium is an effective solution for improving the radiation resistance of erbium-doped fibers in practical applications such as EDFA. Furthermore, heavy germanium doping on the basis of heavy cerium doping can further improve the irradiation tolerance of the EDF especially in high doses.

The possible mechanism of suppression of RIA and RIGD by co-doping Ge and Ce was also analyzed. Recent studies [21] have shown that the RIA of Al-OHC in the NIR band may be the main reason for the performance degradation of rare-earth-doped fibers under radiation. The tail of the absorption band of Al-OHC causes the attenuation at the pump wavelength (980 nm) of EDFA, and the IR-RIA around 1550 nm while unknown is similar in Al or Al-Er co-doped glasses [26]. The optical absorption peak and FWHM of one type of Al-OHC are 2.3 ev and 0.9 ev, respectively [26]. The generation of this type of Al-OHC could be one of the reasons for the higher RIA of the short wavelength band than the long wavelength band in Fig. 5. The formations of Al-OHC under gamma radiation are as follows:

$$\left[AlO_4^-/H^+\right] \xrightarrow[+h^+]{\gamma} \left[AlO_4\right]^0 + H^+ \quad (1)$$

According to previous studies [27], [28], the [AlO4-/H^+] tetrahedrons consist commonly in the aluminosilicate glasses at low Al content. The proton H^+, as a foreign cation, is called the "compensator" for completing the tetrahedron with four Al-O bonds. When exposed to radiation, the compensator moves away from the group and a hole is trapped in an oxygen atom bonded to the Al atom, forming the $[AlO4]^0$ namely Al-OHC [29] as shown in (1). In our case, the introductions of Ge and Ce are capable of weakening the aforementioned process by snatching the holes under the radiation, as shown in the following equations and Fig. 9:

$$\equiv Ge - Ge \equiv / \equiv Ge\bullet\bullet \xrightarrow[+h^+]{\gamma} \equiv Ge\bullet \quad (2)$$

$$Ce^{3+} \frac{\gamma}{+h^+} \rightarrow Ce^{4+} \quad (3)$$

Where the ≡Ge-Ge≡ and ≡Ge•• are two types of Ge-ODC, and the "≡" and "•"present the bonds with three separate oxygen atoms and an unpaired electron, respectively. The ≡Ge• is GeE', which can be formed through trapping holes by Ge-ODC. Similarly, Ce^{3+} ions can transform into Ce^{4+} by trapping radiation-induced holes [30].

The co-doping effect of Ge and Ce has been investigated in silica-based optical fibers [31], and related results show that cerium doping increases the sensitivity of germanosilicate fibers. This is because γ rays cause the conversion of Ce^{3+} to Ce^{4+} with the release of an electron, these electrons are available for the creation of electron centers such as Ge(1) [32]. The atomic structure of Ge(1) is that of an electron trapped in a tetrahedral coordination of germanium, and the absorption band of Ge(1) is centred at 4.4 ev (280 nm), which is far from the typical pump and signal wavelength of EDFA. In our case, it is currently not possible to determine whether Ge(1) defect has arisen because its absorption band is far from the band in which we tested the RIA. However, according to the literature [34], as the precursor of GeE' [33], Ge-ODCs widely exist in the fibers with a high-concentration of Ge. And by comparing the results of EDF2 and

EDF3 in Fig. 5, high germanium doping on the basis of high Ce doping can further reduce the RIA in the IR band. Based on the above results, we speculate that this may be a combined effect of Ge and Ce, and that the processes shown in (2) and (3) may be predominant in our experiments. The analysis of the above mechanism is consistent with the results of RIA and RIGD as shown in Figs. 5 and 7, increasing the content of germanium or cerium can effectively improve the radiation resistance of EDF. Moreover, the absorption bands of GeE' and Ce^{4+} are both in the UV band, and theoretically, these color centers would not have a negative impact on the amplification performance of EDF. We postulate that the number of color centers (GeE' and Ce^{4+}) in which bands are located in the UV band will increase in Ge-Ce EDFs under the irradiation.

IV. Conclusion

The radiation resistant EDFs based on Ge-Ce co-doping were investigated. Three EDFs with various germanium and cerium concentrations were fabricated by MCVD. The experimental results demonstrate that the RIA of EDF can be significantly reduced by heavily doping with Ge and Ce. In such an EDF, the RIGD of 0.8 dB at 1550 nm was obtained under a 1000 Gy dose and a 0.2 Gy/s dose rate. Furthermore, the irradiation resistance mechanism of Ge-Ce co-doping was also analyzed. We believe that the relevant results are of great significance for the applications of EDF and EDFA in low or high dose environments.

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