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Rapid photo-bleaching gamma irradiated Yb-doped optical fibers by high-energy ns pulsed laser

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A B S T R A C T

A rapid and efficient photo-bleaching process was demonstrated with a high-energy nanosecond pulse to recover existing and/or revealed color centers on 10 kGy Gamma-irradiated Yb-doped optical fiber. Multi-mJ pulsed laser based on an optical parametric amplifier system operating at wavelengths of 532 nm, 680 nm and 793 nm was used. The photo-bleaching performance is investigated as a function of the wavelength and energy of the pulsed light source. It was observed that the photo-bleaching level of the Yb-doped optical fiber increased when the exposure time of the pulsed laser light and the photon energy was increased. The maximum PB occurred in the pulsed laser of 532 nm wavelength in the optical fiber. Also, a drastically increase in the PB was observed due to the increasing laser energy at the wavelength of 532 nm and 680 nm pulsed laser. The results show that the recovery levels of color centers in the Yb-doped optical fibers could be reached up to 96 % in a shorter time (h) by using the pulsed laser compared to that of the studies using continuous laser.

1. Introduction

The transmission properties of rare earth doped optical fibers can be disrupted in the Radiation Induced Attenuation (RIA) and the Photo-darkening (PD) processes. These cause a performance loss in the optical fiber. Here, the RIA is an attenuation of the output signals due to radiation-induced defects in optical fibers used in an environment including radiation [1,2]. The PD is a loss mechanism that occurs during high-intensity excitation and laser light generation in high-power Yb-doped fiber lasers and amplifiers. This mechanism directly affects the performance of the optical fiber. The PD limits excitation intensity in fiber lasers and amplifiers and, affects the reliability of the system in the long-term [3–5]. The RIA and the PD are directly related to the formation of color centers in the optical fiber. In the optical fiber structure, the color centers are formed when electrons and holes are produced by an excitation other than radiation are trapped in a defect in the silica matrix. In the transmitted light into the optical fiber, an absorption at certain wavelengths causes a loss in the signal. The occurrence of RIA and PD occurs due to the amount of doped elements (Al, P, etc.) and the amount of Yb^{3+} ions [4], the matrix of elements (Al, P and SiO_2) with Yb^{3+}, the signal wavelength [3] and temperature [6]. Especially, the Yb^{3+} ions and other doped elements may cause an increase in transmission losses. It is a problem that needs to be solved, especially for high power systems with fiber lasers.

Various methods have been proposed in the literature to prevent RIA and PD. One of them is the photo-bleaching (PB) [7] method, which is generally formed by the interaction between an optical fiber and a light with wavelengths of 355 [8], 405 [9], 532 [10], 543 [11], 633 [12] and 793 nm [13]. Other methods are H_2 or O_2 loading method [14], thermal annealing [15], and the adjusting of the ratio of the doped ions such as Al, Ce, P, etc. [16]. The PB is a more useful method than the others because structural change in the optical fiber is not needed. By propagating the light of different wavelengths and different powers into the optical fiber [17], transmission properties of the observed color center absorption bands (at certain wavelengths) are changed and hence the defects are recovered. This recovery mechanism depends on the wavelength and power of the light source, and the type of light source, which consists of photons, excites the oxygen deficiency and/or excess and the bond structures of unpaired electrons and hole defects in the matrix of optical fiber. This means that photons transfer energy to defective areas. Thus, it is achieved by reinstating defective bond structures, or missing ions [18–20].

Preventing or recovering the formation of such defects before and after the production of optical fiber is of great importance in the production of both efficient and long-lasting systems. In order to increase the hardness of the Yb-doped optical fibers, the behavior of the elements, which are in the matrix of the Yb doped fibers, are determined when they expose to gamma radiation or PD. In the literature, few studies are available about Yb doped optical fibers, and it is known that the maturity of the studies fully reveals the problems and specifies

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the solutions. Low-power laser sources that produce continuous laser light at a certain and few wavelengths have been used for PB [21]. In Borman's study, continuous laser light was used on Yb doped optical fiber for 18.3 h; after applying a total dose of 1.45 kGy radiation, the recovery of 34% and 8% were achieved in the transmission of light intensity at 650 nm and 1064 nm, respectively. [21]. In another study, Poulin et al. Yb-doped optical fiber was exposed to total radiation of 1.45 kGy and the recovery of 11% was observed after 118 h using continuous laser [22]. These studies show that the number of photons per unit of time directly affects the duration and level of the recovery process [10,13]. Cao et al. showed the effect of PD in Yb doped optical fibers in their study in 2019 [10]. The loss of the reference signal at 632 nm was analyzed in a Yb doped fiber pumped at 915 nm wavelength. The loss in the reference signal reached 27 dB/m within 400 min during the optical fiber pumping at 915 nm. This reference study is an accepted method for analyzing PD. This photo-darkened fiber was excited at a wavelength of 793 nm from 3 W to 9 W for 400 min, and it was observed that the reference signal at 632 nm wavelength recovered up to 12.5 dB/m depending on the excited power. Thus, it has been concluded that photon enhancement achieves despite the PD in Yb-doped fibers. Similarly, a loss of 35 dB/m in 100 min was observed in the PD event, which is caused by pumping the Yb doped optical fiber at a wavelength of 915 nm. This PD fiber was excited with a light of 532 nm wavelength for 300 min. The PB process was carried out by increasing the power of the light source used in this excitation in the range of 25 mW–5 W. At the end of this process, recovery was observed up to 14 dB/m (25 mW) and 34.5 dB/m (5 W), depending on the increased power [10]. In 2023, the study of Wang et al. showed the influence of pre-radiation and photo-bleaching on the radiation resistance against the gamma-ray of Yb-doped fiber lasers. They used the continues laser for the PB and succeed the 45.2% treatment with 532 nm laser [23]. Consequently, the amount of recovery increases with increasing photon numbers, and photon enhancement is one of the essential methods in the literature [10,13].

The continues laser are mostly used to PB process in treatment of the optical fibers and the results show that the treatment occurs in the structural of the fiber. The amount of the treatment is about 50% as a maximum value and the treatment time is long due to the power of the source. This amount could be due to the absorbed energy. Because the defects are distributed randomly in the silica matrix and the continues laser provides constant energy. Therefore, when the electron and holes are irradiated with continues laser, the recombination and re-trapped occur at more distant site in the photo-bleaching and the time for the recombination or re-trapped is longer than the expected one. The bleaching effect is associated with transformation of defects from an excited state to some intermediate state [24,25]. For the pulse laser, the duration time is in the nanoseconds and there is a relaxing time between two adjacent pulses. High pulses provide the energy, which absorbs from the electron and holes and therefore, the recombination and re-trapped mechanism occur at close site in relaxation time. This means that the relaxation time is used for the transformation of the defects, resulting recombination or re-trapped mechanism [26]. Additionally, the PB process is examined between visible and infrared (IR) regions because of the pumping region of the Yb doped optical fibers. However, the density of defects in the IR region is lower than that in the visible region [27]. Therefore, the defects in the visible region give an real information about the structural deformations. Because, the Yb doped optical fibers have SiO_2 matrix and such as Al, P elements are added to organize the Yb element in the matrix of optical fiber (also, various reasons such as reduce the PD). The color centers are formed due to these elements after irradiations such as a radiation in the visible region. As a result of these, the color centers are generally observed in the visible region and hence, the recovery is determined due to the PB process. Because the spectrometers operating in the visible region are more easily accessible and portable.

In the present study, a PB study was performed to improve the existing and/or revealed color centers in a Yb doped optical fiber after 10 kGy gamma radiation. To increase the recovery amount of the optical fiber, which is irradiated with the gamma radiation, we used a ns pulsed laser with an optical parametric amplifier (OPA) system. The PB was investigated depending on the wavelength and energy of the light source. The OPA system was used at wavelengths of 532 nm, 680 nm and 793 nm. Additionally, the PB processes were performed as a function of the exposure time of the pulsed laser light. The transmission properties of the optical fibers are almost lost after the irradiation and these are due to the color centers in their structure. After the pulsed laser process, the results show that the recovery levels of color centers in the Yb doped optical fiber have been achieved to 30%–96%. In the optical fiber, the maximum PB was observed as 96% in the pulsed laser with a wavelength of 532 nm. At the same time, the change of PB was presented with increasing applied energy of the 532 nm and 680 nm pulsed laser.

2. Experimental procedure

The PB processes were studied on the well-known commercial Nufern fiber (LMA-YDF-20/400-M). The Nufern fiber has a 20 μm core and 400 μm cladding diameter. The core contains 0.18 mol%, 1.31 mol% and 1.42 mol% of Yb, Al and P elements, respectively. The 2 m optical fiber was used to have a larger surface area to get the effect of the gamma radiation more clearly and to examine the effect of the pulse laser at longer distances.

Two different experimental systems have been set up for PB measurement, and these are shown in Fig. 1. The system in Fig. 1.a was set up to measure the changes in light intensity of optical fibers before irradiation, after irradiation, and after exposure to pulse laser. The optical fibers were irradiated with the gamma rays (Co-60 source) at room temperature. The total dose was 10 kGy and the radiation dose rate was 1.19 kGy/h. The spectra were recorded as a function of the wavelength using the Xe lamp (Newport Oriel LCS-100) light source and a spectrometer (Ocean Optics-Flame-S-XR1) by means of collimating optics. A measurement procedure was determined to obtain the spectra before and after the irradiation. In the procedure, non-irradiated optical fiber (e.g. non-irradiated Fiber 1) was measured, and then the irradiated fiber was performed (e.g. irradiated Fiber 1) to compare in the same condition. For each fiber, the procedure was carried out.

The second system in Fig. 1.b was set up to expose 10 kGy irradiated fibers to the light of different wavelengths and energies with a pulse laser. The pulsed laser works at the wavelength range of 660–2400 nm, and its energy range is 120–10 mJ with a frequency of 10 Hz (pulse duration is 5 ns). There is also a direct output of the pulsed laser with a wavelength of 532 nm (340 mJ). In the measurement system, the laser light was reduced to 3 mJ and 5 mJ levels. Because the optical fiber can only carry these energy levels. The energy value entering the optical fiber was reduced by establishing an optical setup with a semi-permeable mirror and polarized cube. The laser light was collimated with an optical lattice system consisting of lenses. The collimated light was coupled to the inside of the optical fiber. The light intensity was measured from the other end of the optical fiber.

The PB measurements were performed using a ns pulsed laser system and a Xenon light source in the irradiated optical fibers. The irradiated optical fibers were exposed to 10 kGy gamma radiation. Firstly, the spectra of non-irradiated and irradiated optical fiber were taken in the 400–1000 nm range using the Xenon lamp light. Then, the irradiated optical fibers were exposed to a pulsed laser for 1 h and their spectra were also taken. Recovery spectra were obtained in optical fibers. These measurements were repeated 3 times. Before each recovery process, the spectrum of the optical fiber was checked in the non-irradiated fiber. The PB measurements in optical fibers were taken

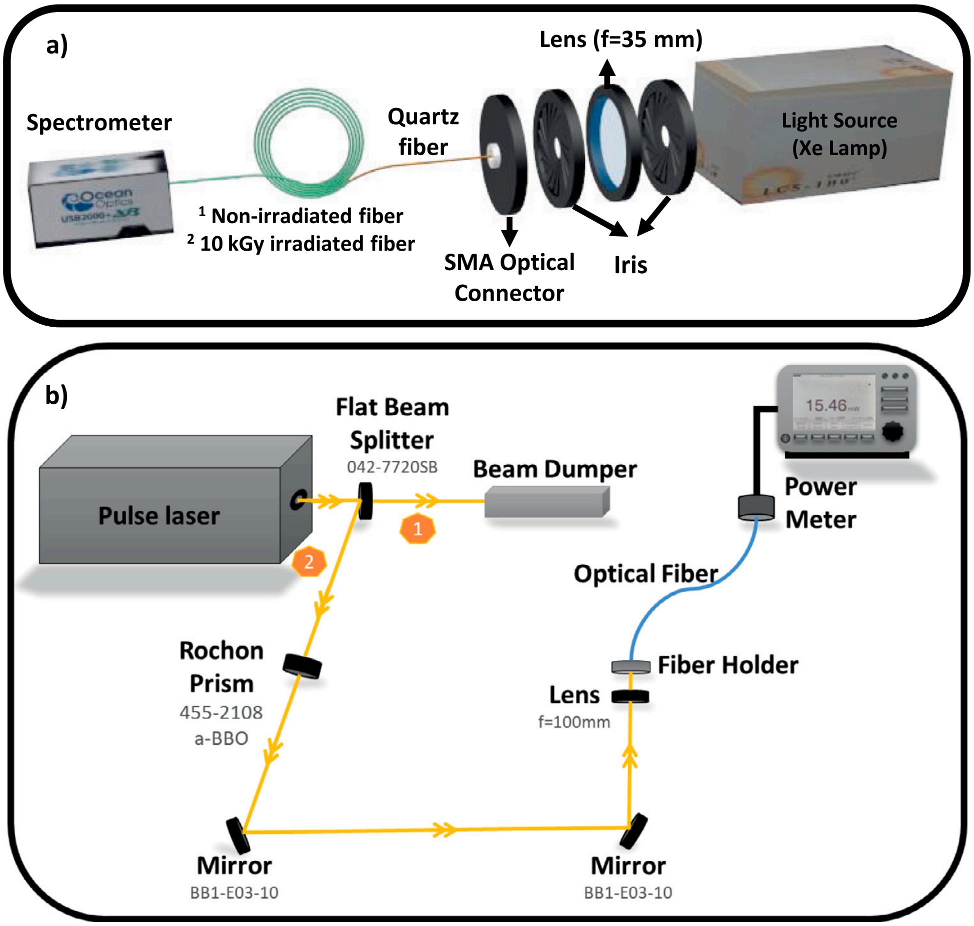

Fig. 1. Experimental setup (a) the system for measurement of the spectra for non-irradiated, 10 kGy irradiated, and PB optical fibers (b) the system in which a pulsed laser to Yb-doped optical fibers at wavelengths of 532 nm, 680 nm, and 793 nm.

at three different wavelengths of 532 nm, 680 nm, and 793 nm and at 3 mJ and 5 mJ energy values.

The optical fibers were exposed separately at each wavelength with the pulsed laser for a total of 3 h. For each wavelength, the light intensity versus wavelength spectrum was recorded. To analyze, four different wavelengths (420 nm, 490 nm, 575 nm, and 650 nm) were selected from the obtained spectra. The RIA values were calculated using Eq. (1) for these wavelengths.

$$RIA = -\frac{10}{L} log\left[\frac{T(\lambda)}{T_0(\lambda)}\right] \quad (1)$$

where $T_0(\lambda)$ and $T(\lambda)$ are the transmission of the sample before and after irradiation, respectively, and L is the length of the optical fiber [28].

3. Result and discussion

The obtained results indicate that the optical fibers lost 94% of their transmission properties when exposed to radiation at a total dose of 10 kGy. The transmission properties of the fibers show that the defect centers occur in the optical fiber and these defects are specific color centers. These absorb the light, which passes through the fiber, and hence, the light intensity losses a large part of it. Fig. 2 presents the RIA spectra for 10 kGy total doses. The color centers have been investigated in the literature, and, their wavelengths and full-width-half-maximum (FWHM) values have been indicated in most of the studies [27,29]. Therefore, the expected and known color centers were fitted to the black data, and the sum of these fitted curves equals the cumulative fit peak (orange line) in the figure. Consequently, the color centers were found at the same optical absorption (OA) band wavelengths and the same FWHM values. Fiber's RIA spectra consist of intrinsic color center NBOHC, and extrinsic color centers AlOHC and POHC. The OA bands of the POHC, AlOHC and NBOHC color centers in the optical fiber were found at wavelengths of 400 nm, 466 nm, 536 nm and 664 nm, respectively [30].

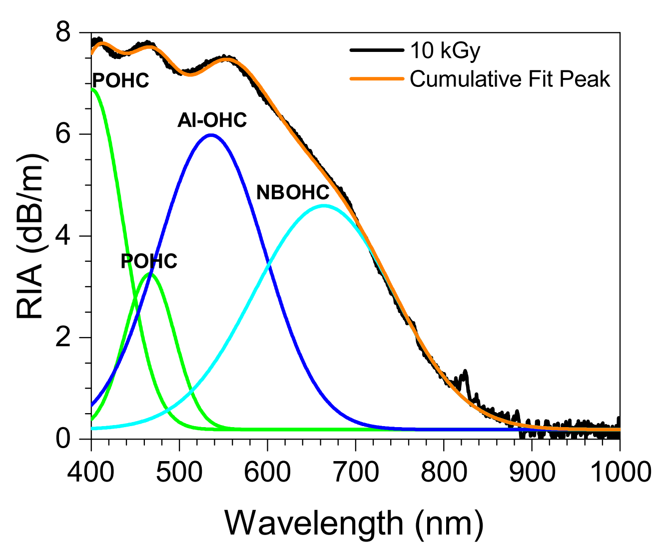

Fig. 2. The obtained color centers of Fiber at 10 kGy [30].

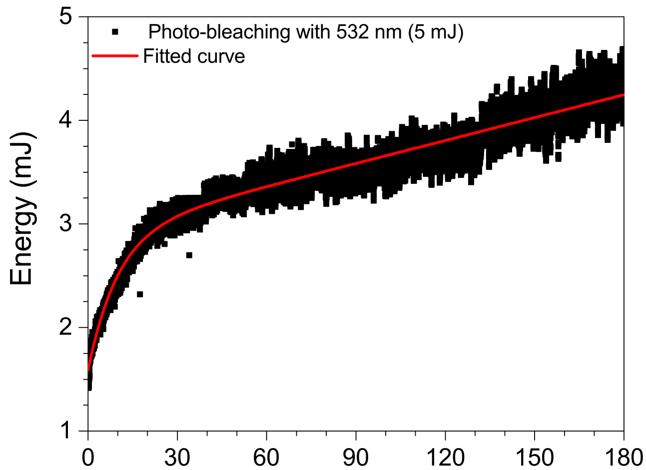

Fig. 3. The output energy variation of the optical fiber due to the time. The optical fiber, which was irradiated to 10 kGy total doses, was exposed to a 532 nm pulsed laser (5 mJ input energy) for PB process.

Fig. 3 shows the output energy variation from the optical fiber depending on the irradiation time with the pulsed laser. The obtained data are fitted with the binary fit equation and shown with the red straight line. The Yb doped optical fiber, which was irradiated to 10 kGy total doses, was exposed to a 532 nm pulsed laser for the PB process. The energy of the pulsed laser was 5 mJ. The output energy begins to increase to 3 mJ value, rapidly, and then the increase slowly continues through 5 mJ value. The variation in the energy indicates that the Yb doped optical fiber was recovered depending on time.

Fig. 4.a–c shows the spectra obtained from non-irradiated (black line) and irradiated with 10 kGy (red line) of optical fibers for PB with various wavelengths. A pulsed laser at wavelengths of 532 nm, 680 nm, and 793 nm was coupled to inside the optical fiber irradiated with the radiation. The energy of the pulsed laser was 3 mJ. For each wavelength, different samples were used for the PB process. The RIA values were calculated from the obtained spectra for the chosen wavelengths as seen in Fig. 4.d–f depending on the irradiation time.

Fig. 4.a shows the change in normalized light intensity versus wavelength during the PB with 532 nm. Here the optical fiber irradiated with 10 kGy was exposed to pulsed laser light with a wavelength of 532 nm. Changes in the output light intensity of the optical fiber were recorded after each hour of exposure and are shown in the graph with solid lines colored green (1 h total irradiation later), blue (2 h later), and pink (3 h later). The normalized light intensity of the optical fiber begins to increase after the 1 h PB process (from the red line to the green line). After 3 h, the optical fiber gains the light intensity property by the pulsed laser with 532 nm. After exposing the optical fiber to the pulsed laser, the RIA changes at 420 nm, 490 nm, 575 nm and 650 nm wavelengths were calculated in Fig. 4.d. The RIA values decrease with increasing exposure time at all wavelengths. This means that the PB increases as the wavelength increases. For example, when the optical fiber is exposed to 10 kGy radiation, the RIA is 7.20 dB/m at 575 nm. After being exposed to the pulsed laser for 3 h, the RIA value of the fiber decreased from 7.20 dB/m to 1.10 dB/m.

Similarly, it was observed that the light intensity value increased rapidly as the exposure time increased by the 680 nm pulsed laser in the PB process of the optical fiber (Fig. 4.b). At the 575 nm of wavelength for the PB, the RIA value is 7.20 dB/m after the 10 kGy irradiation. The RIA value decreased to 1.17 dB/m when the optical fiber was exposed to 680 nm pulsed laser for 3 h. In Fig. 4.c, the recovery percentage of the irradiated optical fiber is lower than that of Fig. 4.a and b. The results indicate that the pulsed laser with low wavelength carries high energy, and therefore, the defects, which are created by the radiation, can be easily recovered at a certain value by the PB process. As a result of the irradiation of the optical fiber with 10 kGy gamma radiation, it was observed that the light intensity losses in the 400–700 nm range of the spectra. These are related to the color centers, which are due to the structure of the optical fiber. The optical fiber is doped with Al, P, and Yb, and also, it consists of the SiO_2. Therefore, the color centers could be related to the POHC, AlOHC, and NBOHC [30]. In the PB process, especially with 532 nm and 680 nm pulsed laser, the color centers were recovered very well. The energy of the pulse laser light rearranges the bonds between the Yb ions and their neighboring ligands during the healing process of the optical fiber. The decrease in the RIA values of the optical fiber may be related to the rearrangement of the local charge defined as $Yb^{2+} \rightarrow Yb^{3+}$ [12].

For long wavelengths, the processes were performed with a 793 nm pulsed laser. After the optical fiber was exposed to pulse laser light for 3 h, it was observed that the light transmission of the optical fiber was recovered as to be 6.7%–51.0%. The percentage of PB was less at 793 nm compared to the PB at 532 nm and 680 nm wavelengths of optical fiber. The reasons for less PB are; (a) Certain color center defects could not be bleached with an IR photon exposure (793 nm) due to different mechanisms of color center creation, which provided different qualities and color center energy levels (b) The photon energy of the applied wavelength of 793 nm may be low [12]. After the optical fiber has been exposed to three different pulse laser wavelengths, the percent recovery values calculated at three different PB wavelengths are listed in Table 1.

Fig. 4.g–i shows the variation of the RIA depending on the wavelength after the PB process when the optical fibers are exposed to three different wavelengths (532, 680, and 793 nm). In the figures, the black line indicates the RIA change of the irradiated optical fibers. The red, green, and blue lines are the measurement after the PB process. As seen in the figure, the RIA change of the optical fiber decreased for all wavelengths with the exposure time of the pulsed laser light. For the 532 nm of wavelength, the PB process works better than other wavelengths. For example, the RIA is about 1 dB/m in the range of 800–900 nm when the 10 kGy radiation is irradiated in Fig. 4.g, and it is nearly zero after the pulse laser is applied for 3 h. The results show that the pulsed laser with 532 nm transports high energy as compared to that with 793 nm. This energy level provides to increase the recovery rate of the irradiated optical fiber.

As the application time of the pulse laser is increased, the PB increased, and hence the intensity of the color centers decreased in the optical fiber. Similar PB behaviors were observed as a result of excitation with a pulsed laser at wavelengths of 532 nm and 680 nm. The maximum PB was observed after excitation with 532 nm. When we examine the spectrum of the optical fiber, the most PB occurred in the NBOHC color center observed at a wavelength of 650 nm. The color center in this OA band was recovered after 3 h of pulse laser exposure and returned to its former transmission value.

In the literature, the short wavelengths are more aggressive to the color centers, and the PB process in the short wavelengths is better than in the long wavelengths [18,31–33]. As seen in our results, the 532 nm pulsed laser provides better results because it transfers high energy compared to other wavelengths. The NBOHC and a part of AlOHC can be bleached very well with both 532 and 680 nm pulsed laser, but the RIA values below 650 nm, where there are the POHC and a part of AlOHC, are higher than that above 650 nm, and they need more energy to bleach. Therefore, the short-wavelength pulsed laser below 532 could be better for the PB process.

The PB process in optical fiber was investigated to analyze the energy value of the wavelength by increasing the energy of the pulsed laser. These measurements were performed for pulsed laser wavelengths of 532 nm and 680 nm. The results show that the 532 nm pulsed laser was better than 680 nm. The applied energy of 532 nm and 680 nm pulsed laser lights was increased from 3 mJ to 5 mJ and similar measurements were repeated for 1, 2 and 3 h. Fig. 5 shows the

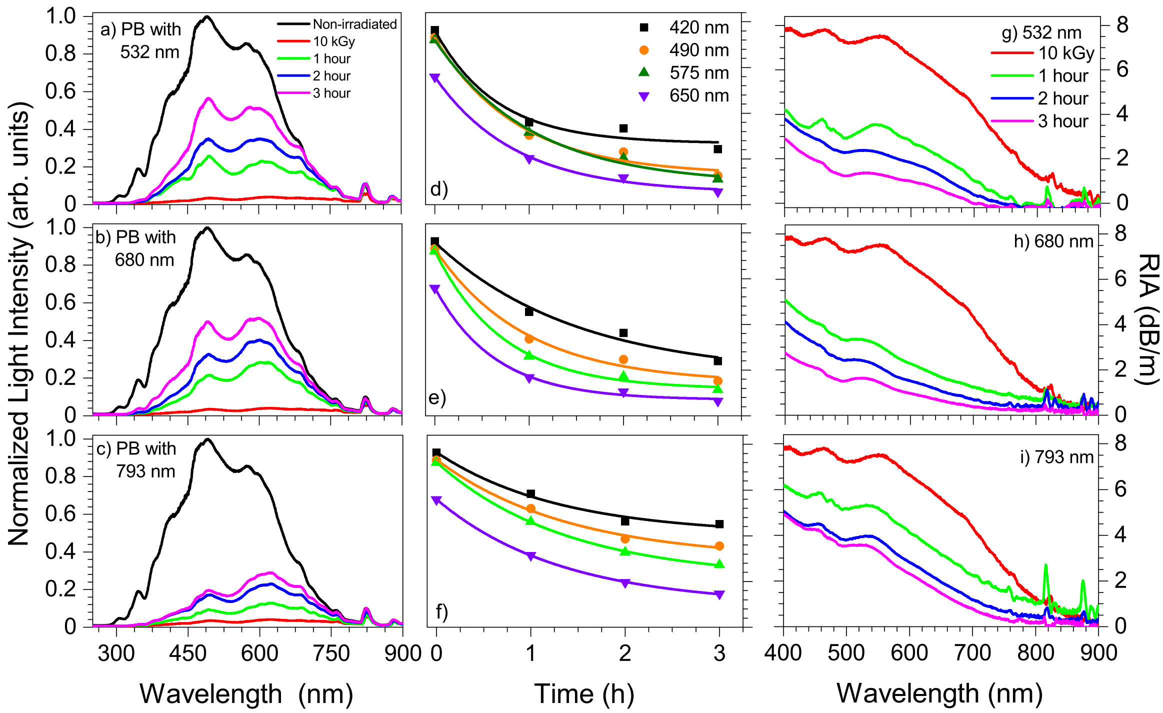

Fig. 4. Normalized light intensity change of non-irradiated and 10 kGy irradiated Yb-doped optical fiber after exposure to pulsed laser at 532 nm (a), 680 nm (b), and 793 nm (c) for 1 h, 2 h, and 3 h. Time-dependent RIA changes at PB wavelengths selected (420 nm, 490 nm, 575 nm ve 650 nm) from the spectra after healing with a pulsed laser of 532 nm (d), 680 nm(e), and 793 nm (f). (g), (h) and (i) The RIA changes of optical fiber depending on the wavelength after PB process at three different wavelengths.

Table 1
Percent recovery values of 10 kGy irradiated Yb-doped optical fiber after exposure to pulsed laser at 532 nm (a), 680 nm (b), and 793 nm (c) for 1 h, 2 h, and 3 h. (Variation of recovery values are percentage).

Wavelengths selected from the	420 nm			490 nm			575 nm			650 nm		
spectrum Irradiation wavelength	1 hour	2 hour	3 hour	1 hour	2 hour	3 hour	1 hour	2 hour	3 hour	1 hour	2 hour	3 h
532 nm	19.6	22.1	33.6	25.4	35.6	57.8	24.2	40.6	62.2	42.7	62.7	77.0
680 nm	12.3	18.8	33.2	21.3	32.1	49.7	30.0	45.2	59.1	46.2	61.5	74.4
793 nm	6.7	11.8	12.4	9.1	16.8	19.4	11.9	22.0	28.4	23.4	40.5	51.0

comparison of spectra obtained at one hour intervals for 3 h at 3 mJ and 5 mJ energy values. The black and red lines are non-irradiated and irradiated with 10 kGy, respectively. In the graph, the measurements taken during the recovery process in the optical fiber are shown in solid (1 h), dotted (2 h), and dot-line (3 h) green color for 3 mJ energy value, and blue color for 5 mJ. Fig. 5 shows the comparison of spectra obtained at one-hour intervals for 3 h at 3 mJ and 5 mJ energy values. When the non-irradiated optical fiber was exposed to gamma radiation, the light intensity, which is the passing through into the fiber, decreases to nearly zero value (red line). As seen in the figure, a high energy value causes an increase in the PB process. For example, the largest PB in the spectrum of the optical fiber was observed at 650 nm. The PB is 77.0% (532 nm) and 74.4% (680 nm) when exposed to 3 mJ pulsed laser energy, while the recovery of 5 mJ pulsed laser energy after 3 h and 96.9% (532 nm) and 81.5% (680 nm) (Table 2). Also, the PB was observed due to the increased energy at both wavelengths of the pulsed laser light to which the Yb-doped optical fiber was exposed.

Fig. 6 shows the comparison of the RIA changes of selected PB wavelengths against the time at 3 mJ and 5 mJ energies at 532 nm and 680 nm pulsed laser. It was observed that the RIA values decreased, and the recovery was greater depending on the increasing energy value in all selected PB wavelengths. When we compare this value, which we found at 5 mJ, with the 532 nm pulsed laser value of 3 mJ, it is seen that when the energy value of the 680 nm pulsed laser increases, there is a better recovery according to the value obtained with the 532 nm pulsed laser. In the optical fiber, after 3 h of exposure to 532 nm pulse laser, the percentages of recovery at 3 mJ and 5 mJ for 650 nm are 77.0% and 96.9%, respectively. When the 680 nm pulse laser was used for exposure, the recoveries are 74.4% and 81.5% for the same energy values. It is seen that when the energy value of the 532 nm pulse laser increases, there is a better recovery than the value obtained with the 680 nm pulsed laser. These results indicate that short wavelength lasers and high energy pulses are more suitable for PB.

3.1. Comparison of the literature and PB Mechanism

The Yb doped optical fibers have been used in high power laser applications, and their performance depends on environmental effects such as radiation, and high power. They are used for many hours in the applications. Therefore, the efficiency of the fiber decreases with time. We know that the cost of these systems is high, and they must be periodically changed due to the environmental effects. In the literature, some techniques have been investigated for recovery of damaged optical fibers, such as irradiation using the continuous laser [18,21,22,34]. In the study on PB of Yb doped optical fibers, a recovery of 8% was achieved in the transmission of light intensity after a total dose of 1.45 kGy radiation was applied by using continuous laser light for 1.5 h [21]. In another study, Yb doped optical Fiber was exposed to a total radiation of 1.45 kGy, and recovery of 11% was observed 118 h after radiation [22]. Although the continuous laser is an effective process, the recovery can take a long time, and when the radiation dose increases, the time is so longer than expected. In the present study, it has been observed that the laser system, which has a wide wave spectrum powered by the optical parametric amplifier

Table 2
The percent recovery values of Fiber-4 were calculated after the PB process (after 1 h, 2 h, and 3 h) with 680 nm pulsed laser (energy values of 3 mJ and 5 mJ). These percentage values were for selected PB wavelengths of 420 nm, 490 nm, 575 nm, and 650 nm.(Variation of recovery values are percentage).

Wavelengths selected from the	420 nm			490 nm			575 nm			650 nm		
spectrum Irradiation wavelength	1 h	2 h	3 h	1 h	2 h	3 h	1 h	2 h	3 h	1 h	2 h	3 h
532 nm (3 mJ)	19.6	22.1	33.6	25.4	35.6	57.8	24.2	40.6	62.2	42.7	62.7	77.0
532 nm (5 mJ)	53.5	71.0	84.4	72.9	87.6	95.5	69.5	85.0	95.5	75.7	90.2	96.9
680 nm (3 mJ)	12.3	18.8	33.2	21.3	32.1	49.7	30.0	45.2	59.1	46.2	61.5	74.4
680 nm (5 mJ)	13.2	24.5	48.9	25.2	43.4	72.1	34.8	52.8	76.0	49.1	65.0	81.5

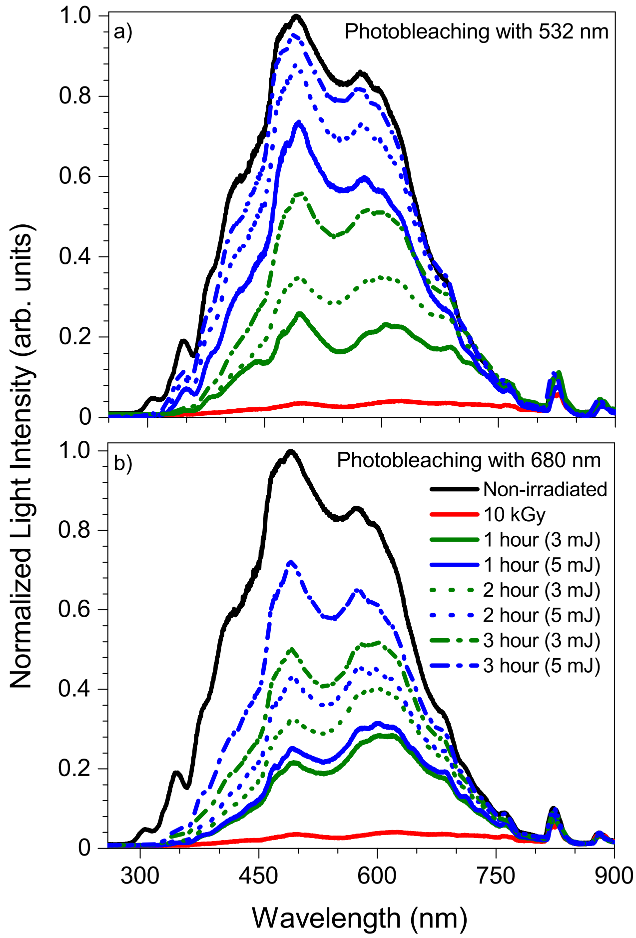

Fig. 5. Comparison of the PB spectra of Yb doped optical fiber non-irradiated, irradiated (10 kGy) and exposed to 680 nm pulsed laser (two different energies at 3 mJ and 5 mJ) for 1, 2, and 3 h.

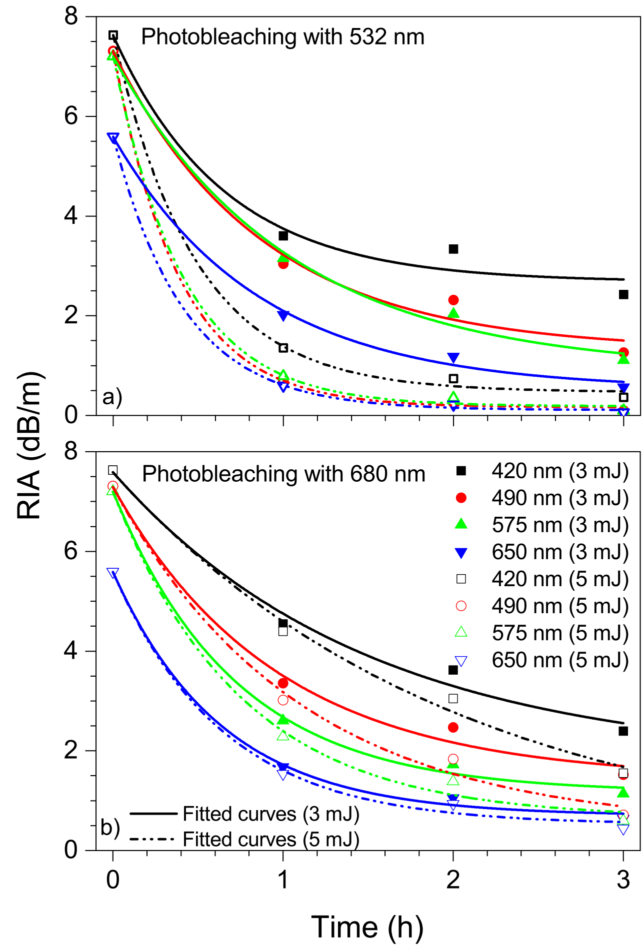

Fig. 6. Comparison of RIA changes of selected PB wavelengths (420 nm, 490 nm, 575 nm ve 650 nm) overtime at 3 mJ and 5 mJ energy values. The applied pulse laser wavelength was 680 nm.

(OPA) system, which is a new laser technique and can produce photons at a very high level in unit time compared to continuous laser light, shortens the recovery time and increases the recovery level at the same time. In the literature, the recovery of around 10% in 1.5 h and the time is more than 118 h observed in studies performed with continuous laser. We took place in shorter times as a process, and recovery levels of 33%–88% were achieved. At the same time, it has been seen that the number of photons per unit of time directly affects the duration and level of recovery [10,13]. In our study, we observed that the optical fibers, which were exposed to the 10 kGy radiation, can be well recovered within hours as to be high amount recovery levels with the pulse laser.

The mechanism of photo-bleaching plays an important role in the dopant and adjustment elements in the structure of the optical fiber. Therefore, the color centers related Yb dopant, Al, P, and SiO_2 show different behavior due to electron and hole deficiency in the PB process. In the processes such as the radiation-induced, the PD, charge transfer occurs, where belonging to the surrounding ligands are transferred to the Yb^{3+} ion and enable the transformation of Yb^{3+} ion into Yb^{2+} ion, leaving a hole around the ligands [35]. An electron-related color center is created in Yb^{2+}, as well as a hole related color center such as AlOHC, and NBOHC at the same time. The PB is the reverse action of these processes and could eliminate color centers. Hence, Yb^{2+} ion recombines with the released hole of surrounded ligands with the PB (converting Yb^{2+} ion into Yb^{3+} ion) and simultaneously eliminating the hole-related color centers such as AlOHC, and NBOHC [10,11].

4. Conclusion

Yb-doped optical fibers are widely used in many applications like high-power fiber laser systems and harsh radiation environments. It is crucial to improve the existing color centers resulting from using Yb doped optical fibers in these applications and exposure to high radiation doses. We used the commercial Nufern optical fiber to analyze the radiation effect (10 kGy) and PB processes. The optical fibers were exposed 10 kGy radiation and then recovered with the ns pulsed laser system, which has a wide wave spectrum powered by the optical parametric amplifier (OPA) system. The OPA system is a new laser technique and can produce photons at a very high level in unit time compared to continuous laser light. Therefore the pulse laser shortens the recovery time and increases the recovery level at the same time, and was used to recover the color centers. Measurements were taken with a pulsed laser at 532 nm, 680 nm, and 793 nm, depending on the wavelength and exposure time. It was observed that the improvement increased as the exposure time of the Yb doped optical fibers to the pulsed laser light increased. The recovery levels of color centers in the Yb doped optical fiber have been achieved to 30%–96%. In the optical fiber, the most PB was observed in the pulsed laser with a wavelength of 532 nm. In addition, it was observed that the PB in the optical fiber increased when the applied energy of the wavelength of the pulsed laser was increased.

CRediT authorship contribution statement

Esra Kendir Tekgül: Data curation, Writing – original draft, Conceptualization, Visualization, Methodology, Investigation. **Bülend Ortaç:** Conceptualization, Supervision, Writing – reviewing & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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