Radiation-hardness Studies with Cerium-doped Fused-silica Fibers

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Abstract

We continue our R&D effort in developing scintillating and wavelength shifting fibers by doping fused-silica fibers with cerium. In this report, we summarize fibers' radiation-hardness by providing experimental data and a predictive model based on second-order rate equations. Five different types of cerium-doped and a clear fused-silica fibers were exposed to the gamma radiation (^{60}Co) at different dose rates up to 100 kGy. We evaluated radiation-induced transmission losses as well as photoluminescence efficiency in a wide wavelength range (400-1000 nm). We also present measurements of the effective numerical aperture upon exposure to radiation and offer some thoughts on the use of these fibers in particle physics as well as in other wide-ranging applications.

Description of Fibers and Radiation Measurements

Table 1. All fibers were made with hard-clad fluorinated acrylate cladding and UV-cured acrylate buffer.

Fiber Name	Core OD µm	Glass OD µm	Clad OD µm	Buffer OD µm	Ce ppm
Phase-I	60±7	200±6	230^{+5}_{-10}	350±15	5,780±750
Phase-II	150±20	400±10	430±10	550±30	4,920±890
Phase-III	370±8	-	400±8	550±15	430±100
Phase-IV	200(clear)/15(doped)	600±6	630±10	800±30	2,070±240
Clear fused-silica	600±10	-	630^{+5}_{-10}	800±30	0
T14	150±5	400±5	450±5	500±15	5,230±770

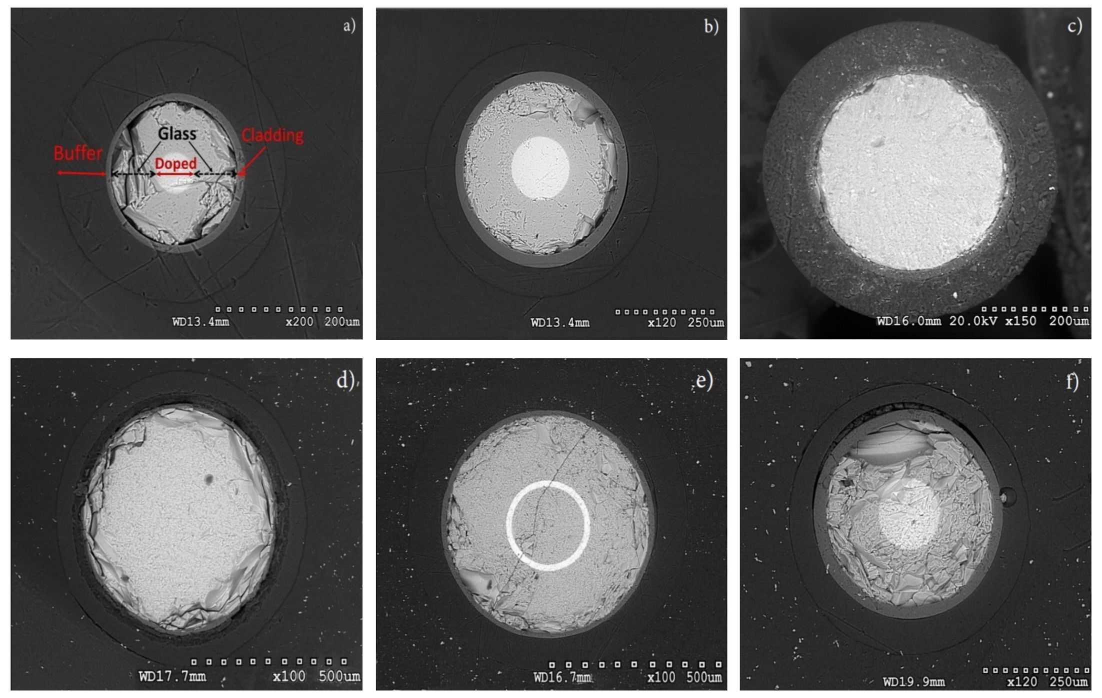

Fig. 1. The cross section of fibers a) Phase-I, b) -II, c) -III, d) clear fused-silica, e) Phase-IV and f) T14. The terminology for different parts of the fiber is indicated on the photographs.

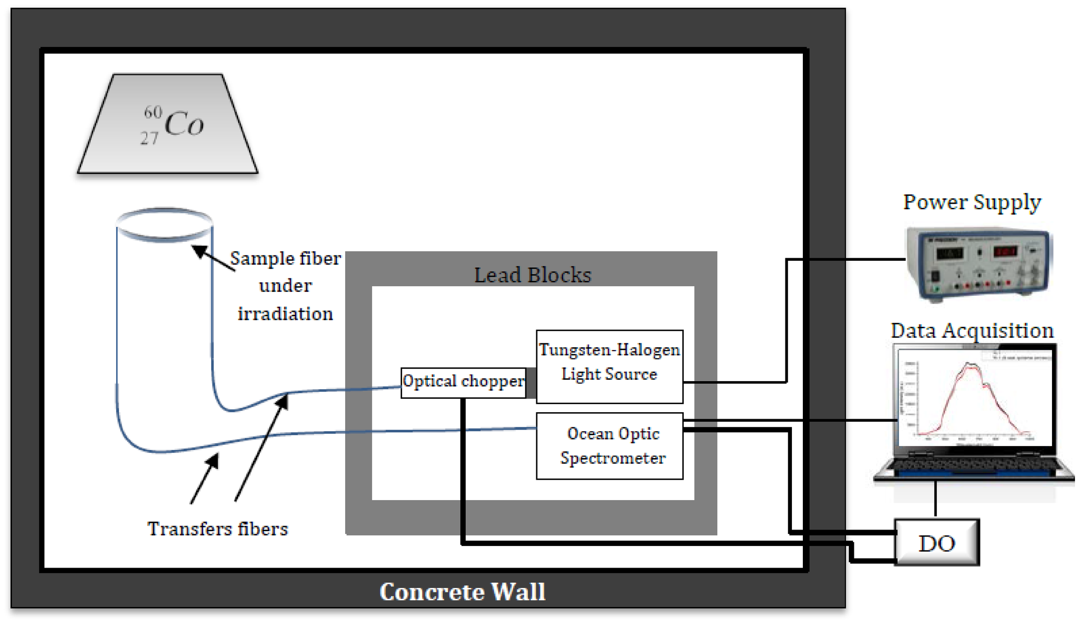

Fig. 2. The schematic of the experimental setup

Table 2. Total dose and dose rates applied to optical fibers

	Total Dose					Dose Rate				
Online	>400				Gy	5	25	106	1,007	Gy/h
Non-online	0.5	5	10	100	kGy	0.05	0.5	1	10	kGy/h

Introduction

The transmission characteristics of the optical fiber have been influenced from the radiation environments due to the generation of radiation-induced defect centers by ionization and atomic displacement within the molecular bonding network of silica glass [1]. The radiation-induced optical attenuation (RIA) varies with internal parameters such as the optical fiber core / cladding composition and refractive indexes, the optical fiber concentration, production conditions and length of the test optical fiber [2]. We briefly describe our R&D effort to develop the scintillating and wavelength shifting fibers by fused-silica doping with cerium and focus on the radiation-hardness study. These type fibers will certainly be deployed in next-generation tracking systems, calorimeters, and beam monitoring systems. They are likely to benefit the health, oil, and nuclear power industries and to find uses in homeland security applications.

Results

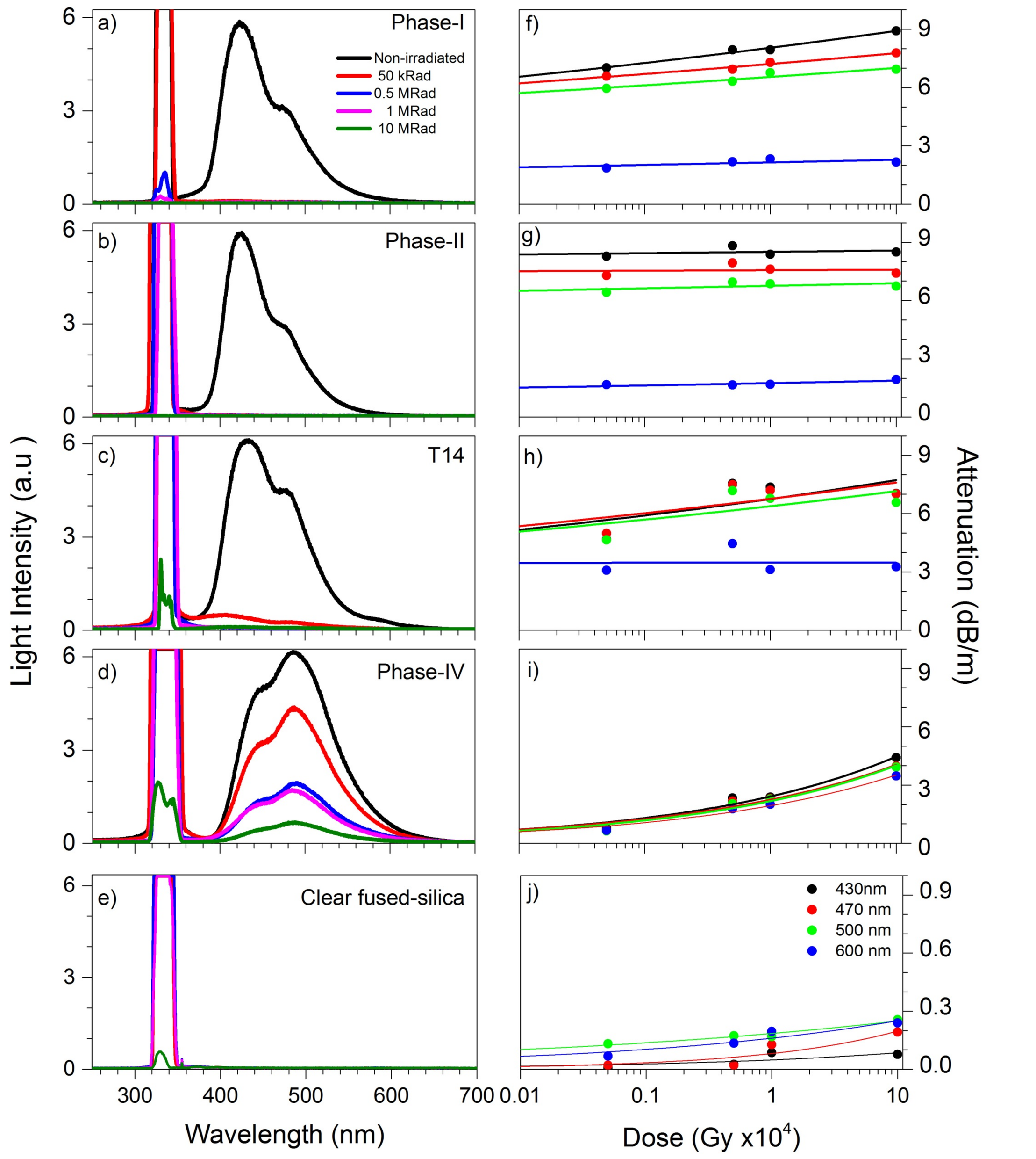

Fig. 3. Gamma-irradiated Phase-I, -II,T14, Phase-IV, and clear fused-silica fibers show varied levels of loss of transmission and photoluminescence when the fibers are excited at 337 nm (N2 laser light axially injected into the fibers).

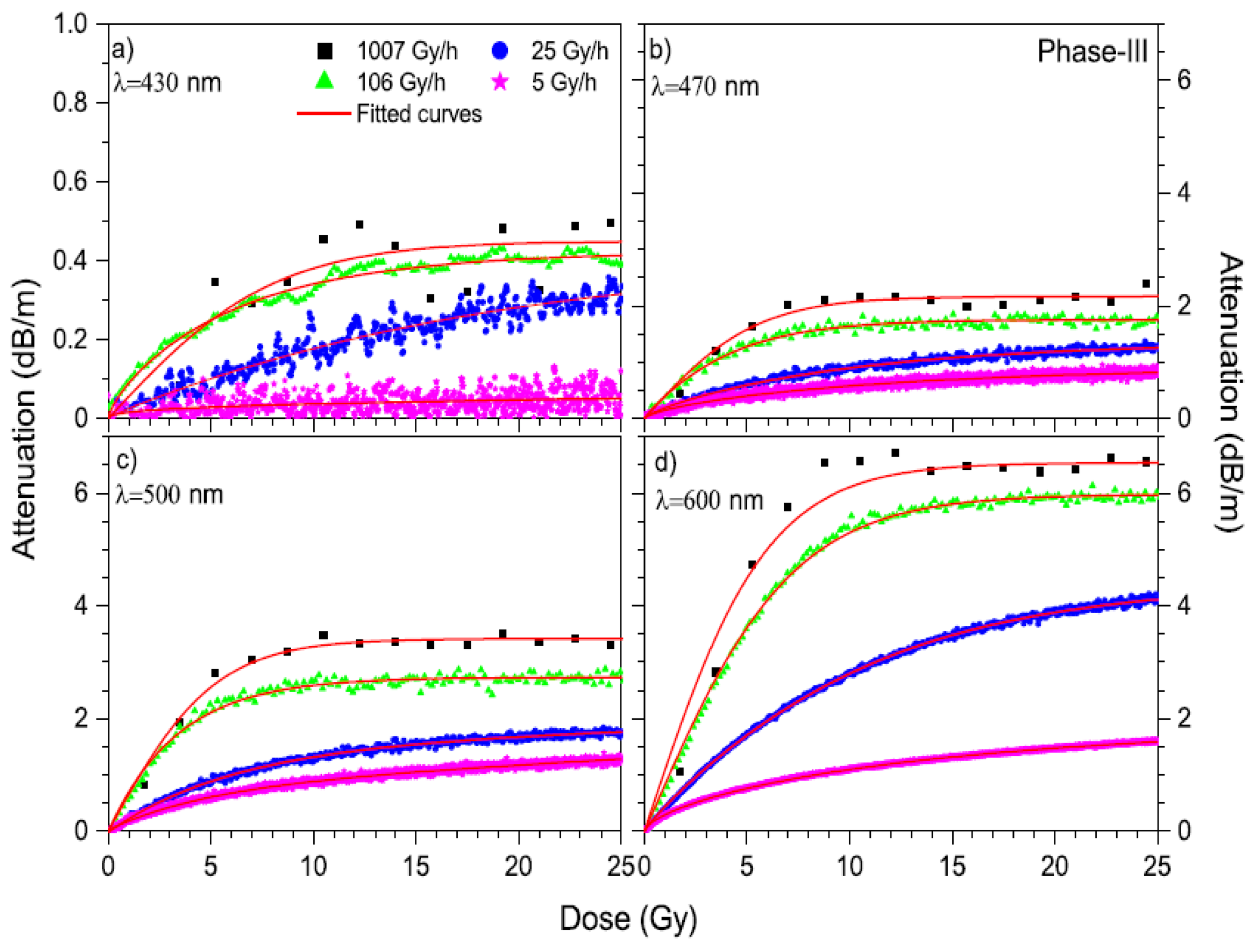

Fig. 5. The attenuation at four different wavelengths under gamma ray irradiation at four different dose rates are shown: a) 430 nm, b) 470 nm, c) 500 nm, and d) 600 nm. The black, green, red, and blue symbols indicate dose rates of 1,007, 106, 25, and 5 Gy/h, respectively.

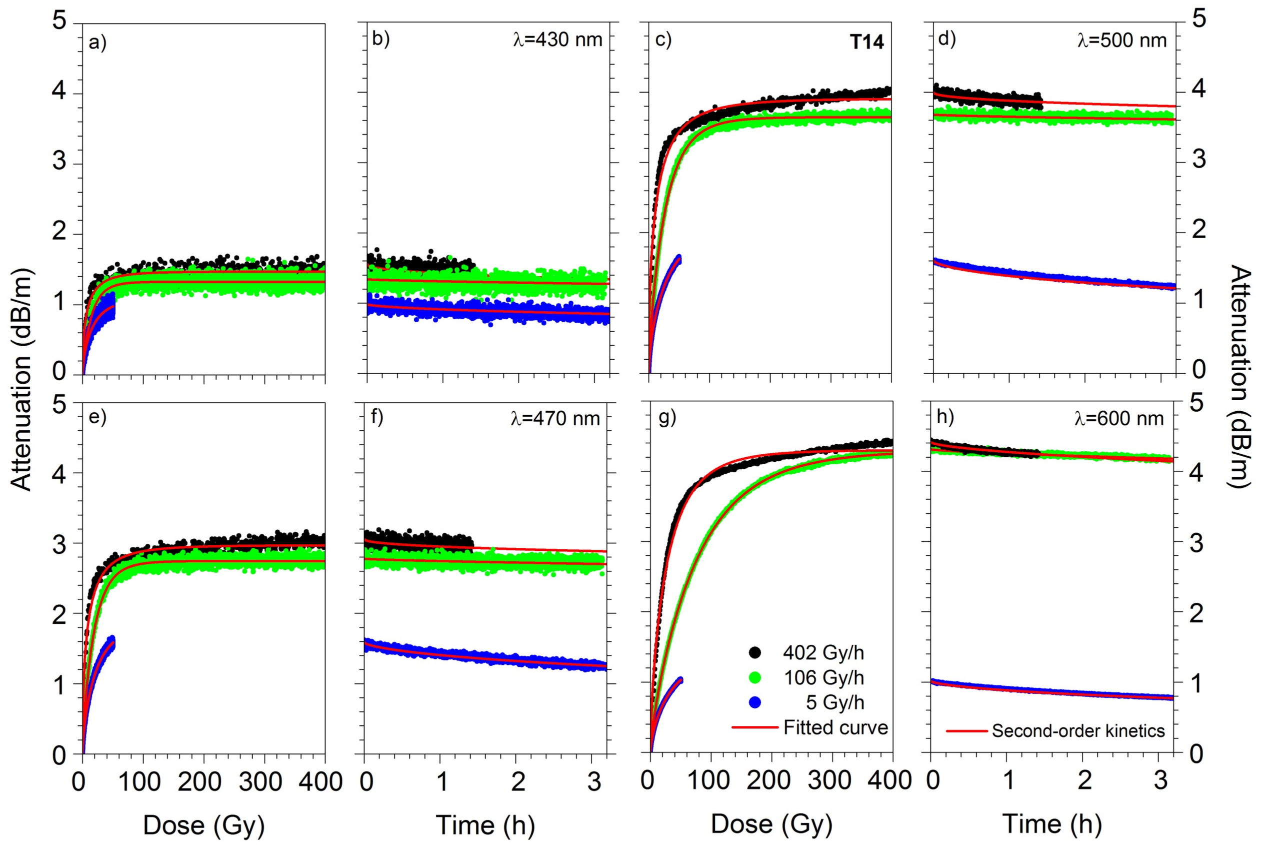

Fig. 4. The attenuation of 430, 470, 500 and 600 nm wavelength are shown under gamma ray irradiation. a; c; e and g) The attenuation at 400 Gy total dose and b; d; f and h) The 3 hours and 80 min recovery periods of T14 after irradiation. The black, green and blue dots indicate dose rate of 402, 106 and 5 Gy/h, respectively.

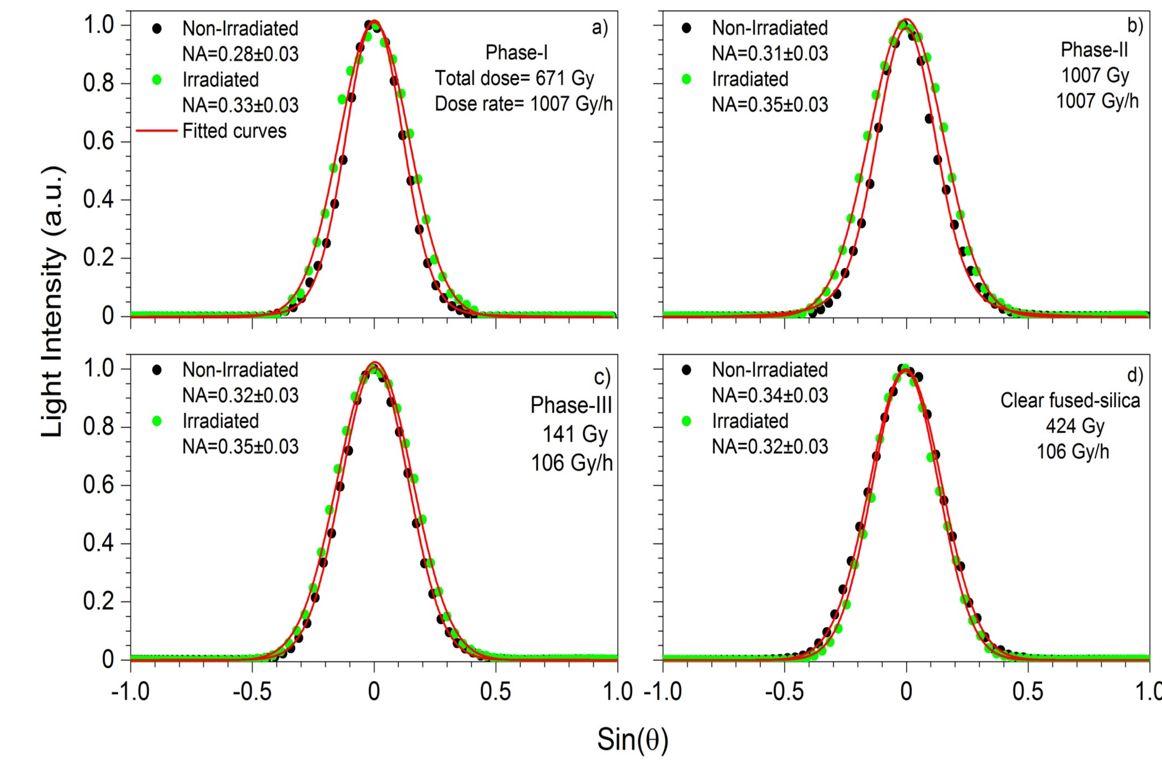

Fig. 6. The radiation-induced changes in NA for four fibers (Phase-I, Phase-II, Phase-III, and clear fused-silica) are displayed before (solid back circles) and after (solid green circles) irradiation. The solid red lines are fits to the data points.

Data Analyses

The radiation-induced attenuation at a given wavelength λ and accumulated dose D is calculated;

$$A(\lambda, D) = -\frac{10}{L}\log\left(\frac{I(\lambda, D)}{I_0(\lambda)}\right)$$

where A is attenuation in units of dB/m, L is the exposed fiber length, I is the transmitted light intensity at D, and I_o is the transmitted light intensity for an un-irradiated fiber.

We used the second order kinetic approach in modeling the radiation-induced optical attenuation and recovery processes of Ce doped and clear fused-silica optical fibers [3]. The classical rate equation for second-order growth with thermally activated decay, can be written as

$$N\left[(\mathrm{kt})^{\beta}\right] = N_{sat}\tanh\left[(\mathrm{kt})^{\beta}\right]$$

where $Nsat = \left(K\dot{D}/R\right)^{1/2} N^*$ and $k = \left(K\dot{D}R\right)^{1/2}$, N stands for the number of density of color centers and K governs the creation of new color centers. The classical time-independent decay rate constant R, and β are determined by fitting the experimental data. The recovery in this system of equations is

$$N\left[(\mathrm{Rt})^{\beta}\right] = N(0)\left\{1 + \left[N(0)/N^*\right](\mathrm{Rt})^{\beta}\right\}^{-1}.$$

Where N^* replaces N_o and is defined to have unit magnitude but with the dimensionality of the color center number density.

Conclusion

•The attenuation of the Ce-doped optical fibers was found between 2 dB/m and 6 dB/m values at different dose rates (0.05 - 10 kGy/h) and different total doses (0.025 - 100 kGy).

•In photoluminescence measurements, there is no transmission in Phase-I and -II fibers after 0.5 kG. however, the T14 fiber is not completely damaged and there is a low transmission. Phase-IV fiber shows better results. There is a gradual loss of performance with increasing dose, however, after 100 kGy, the transmission of UV light, and emission (and transmission) of the wavelength-shifted light was clearly visible.

•Phase-III has particularly "radiation-sensitive" at different dose rates since there is no clear glass component, thereby, the considerable absorption takes place in the doped-core.

•The recovery is quite slow at Phase-I, -II and T14 fibers. The presence of phosphorus both the core and the glass layers prevents the recovery process. The formation of color centers P1 (oxygen vacancy centers) and POHC (phosphorus-oxygen hole centers) are responsible in this process.

•The recovery process for these fibers has been studied both experimentally and theoretically. The model for the damage and recovery processes describes the experimental data well. The agreement between the data and formulation is "good", capturing all salient features of both damage and recovery.

•The numerical aperture with irradiation for Phase-I, -II and III fibers increase a 10 to 20%. The numerical aperture of the clear fused-silica fiber within the precision of the measurement do not observe a change.

References:

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