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Properties of phosphorus-related defects induced by γ-rays and pulsed X-ray irradiation in germanosilicate optical fibers

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Abstract

Time dependent radiation-induced attenuation changes of germanosilicate (~13 wt%) optical fibers have been measured under steady-state γ-ray and pulsed X-ray irradiations. Particularities of phosphorus (P)-codoped cladding fibers for these environments are presented. For each irradiation type, spectral attenuation measurements show that permanent radiation-induced losses at 1.55 μm are due to the infrared absorption band of P_1 centers. We assume that particular kinetics of recovery and an increase of attenuation measured for P-codoped fibers, after pulsed X-ray irradiation, are induced by a charge retrapping phenomenon from phosphorous oxygen hole (POH) centers to P_1 ones. With this mechanism, we explain the P-codoped fiber characteristics after both types of irradiation. Our study shows that the effect of P-related color centers is increased when the P-codoped cladding (~0.3 wt%) contains also germanium (~0.3 wt%).

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1. Introduction

Optical fibers are of interest for use as sensor devices in different nuclear environments: civil [1], spatial [2] or military [3]. Pure silica and nitrogen-doped core optical fibers are the most radiation-hardened fibers under steady-state environments [4,5]. For pulsed X-ray irradiation, nitrogen-doped fiber has the smallest radiation-induced attenuation for the temporal range 10^{-6} to 10^{+2} s after a pulse [6]. However, for shortest times after pulse (10^{-6}–10^{-3} s), P-codoped germanosilicate optical fibers have differing responses [6]. These fibers have losses less than those of other types of fibers [6]. In the present work we measure the effects of P-codoping of germanosilicate optical fibers on their steady state γ-ray and pulsed X-ray radiation sensitivities. Moreover, based on our experimental results, we are able to propose some complementary explanations for the atypical response of the P-doped optical fibers.

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2. Experimental conditions

2.1. Optical fibers tested

For this study, three single mode germanosilicate optical fibers have been made using the same MCVD process parameters to determine the influence of cladding codopants over germanosilicate fiber response. These special fibers have been designed with the same normalized refractive index profile to obtain the same amount of guided power in the core (~60% at 1.55 μm) and in the cladding (~40% at 1.55 μm). Each fiber compositions has been measured by electron microprobe analysis (EMPA) and are given in Table 1. With these samples, we are able to determine the effects of a cladding codopant (P, Ge) by direct comparison between two of the tested fibers which have exactly the same parameters except for considered dopant.

2.2. Experimental set-up

We characterized the response of each optical fiber under pulsed X-ray and steady-state γ-ray irradiations by measuring the time evolution of the radiation-induced losses at the two Telecom wavelengths: 1.55 and 1.31 μm. The irradiation experiments have been performed at the Centre d'Études de Gramat facilities [7]. For pulsed irradiation, typical deposited dose is less than 1 kGy(SiO_2) and the dose rate is greater than 10^{+6} Gy s^{-1}. For steady-state γ-ray irradiation, the same deposited dose is achieved with a smaller dose rate on the order of 0.1 Gy s^{-1}.

Table 1
Composition of the three tested fibers

Optical fiber	Dopant in core (wt%)	Dopant in cladding (wt%)
Fo1	Ge(~13)	Ge(~0.3), P(~0.3), F(~0.3)
Fo2	Ge(~13)	P(~0.3), F(~0.3)
Fo3	Ge(~13)	F(~0.3)

Given percentage values of germanium in core are concentrations at the maximum of this element in each fiber. Those of cladding codopants are average values of element concentrations.

Two test benches were developed to measure the time evolution of radiation-induced losses under pulsed X-ray and γ-ray irradiations [6]. With these test benches, we are able to measure simultaneously induced attenuation in two fiber coils, at two different dose levels. Tested fiber samples were 60 m in length and were wounded on 6 cm diameter coils. The two optical sources used have a power level on the order of 100 μW. Each fiber coil under test was spliced with a standard fiber in order to get the signal from the irradiation zone to the instrumentation one. The induced loss time changes were recorded from 10^{-6} to 10^{+2} s after pulse and during and after γ-ray irradiation. The test bench is fully controlled by a personal computer. This system can achieve a dynamic between 0.5 and 300 dB km^{-1} with a resolution of 0.3 dB km^{-1}. The experimental uncertainties were mainly attributed to the dosimetry measurements: ~15%. Experiments have been made to verify that no photobleaching effect appears at this power level for the two tested wavelengths.

3. Experimental results

3.1. Pulsed X-ray irradiation

Fig. 1 shows the radiation-induced attenuation time evolution at 1.55 and 1.31 μm for the three tested fibers. The radiation-induced attenuations have been normalized by the deposited dose to correct results from the small fluctuations of the irradiation source. Measurements at three dose levels have been made to confirm the linear dose dependence of the radiation-induced losses for the three germanosilicate fibers at 1.55 and 1.31 μm. These results, confirmed by the study of other germanosilicate fibers [8], allow us to characterize the effect of P-codoping on the germanosilicate fiber sensitivity. Firstly, for times smaller than 10^{-3} s and for the two tested wavelengths, phosphorus suppreses the transient radiation-induced attenuation associated to germanium color centers, [9]. The responses of Fo1 and Fo2 fibers seem to be independent of a Ge-codoping in the cladding. P-codoped fibers show different kinetics of recovery, especially at 1.55 μm, with an important decrease

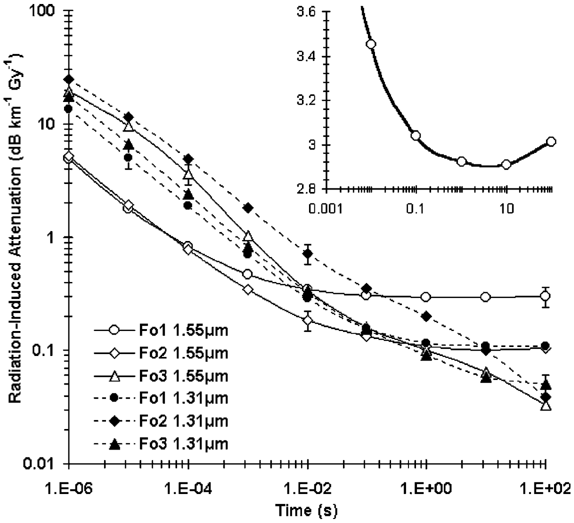

Fig. 1. Time evolution of radiation-induced attenuation at 1.55 and 1.31 μm after pulsed X-ray radiation. For Fo1 fiber, an increase of optical losses is illustrated in inset. The error bars were estimated within 15%.

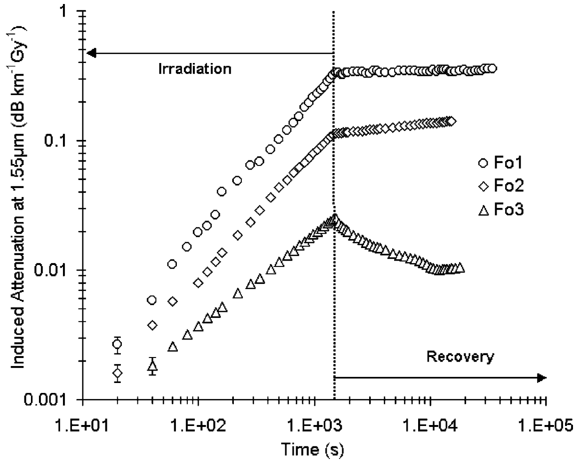

Fig. 2. Time evolution of radiation-induced attenuation at 1.55 μm during and after steady-state γ-ray irradiation. The error bars were estimated within 15%.

of the recovery compared to P-free Fo3 fiber for times greater than 0.1 s. This implies that P-co-doped fibers have greater level of permanent radiation-induced attenuation than P-free fibers. It is interesting to notice that Fo1 and Fo2 fibers have quite different responses. Fo1 fiber with a smaller germanium-codoping in the cladding has larger permanent induced loss. Moreover, we noted for several P-codoped fibers [8] an increase of radiation-induced attenuation at 1.55 μm for longer times after pulse. This is illustrated for Fo1 fiber on the inset of Fig. 1. The difference between the P-codoped fiber kinetics of recovery at the two wavelengths could have at least two explanations. First, at 1.31 μm, the fundamental mode is more confined into the core than at 1.55 μm. This implies that the transmitted power attenuation is less sensitive to the cladding composition. Secondly, the spectral dependence of color centers absorption bands may affect the fiber response. Germanium-related color centers, with their absorption bands in the ultraviolet have more impact at 1.31 μm than at 1.55 μm. At 1.31 μm, the three tested germanosilicate fibers have power law dependence, as predicted by West [10].

3.2. Steady-state γ-ray irradiation

Fig. 2 shows the radiation-induced attenuation changes with time during and after steady-state irradiation. Radiation-induced losses at 1.55 μm are normalized to the deposited dose. P-codoped Fo1 and Fo2 fibers have radiation-induced attenuation levels one order of magnitude greater than P-free Fo3 fiber. A number of former studies have shown that a P-codoping increases the radiation-induced losses in the infrared region [1,8,9]. Furthermore, the two P-codoped fibers exhibit no form of recovery after the end of the irradiation. In fact, their losses at 1.55 μm still increase after irradiation. The comparison between the two Fo1 and Fo2 fibers shows that the Ge-P codoping in cladding induces greater losses than P-codoping.

4. Discussion

4.1. Nature of permanent radiation-induced losses

P-codoped germanosilicate optical fiber responses at 1.55 or 1.31 μm to pulsed X-ray or steady-state γ-ray irradiation, could be explained by the dynamics of the same color centers. This assumption is reinforced by the comparison of the

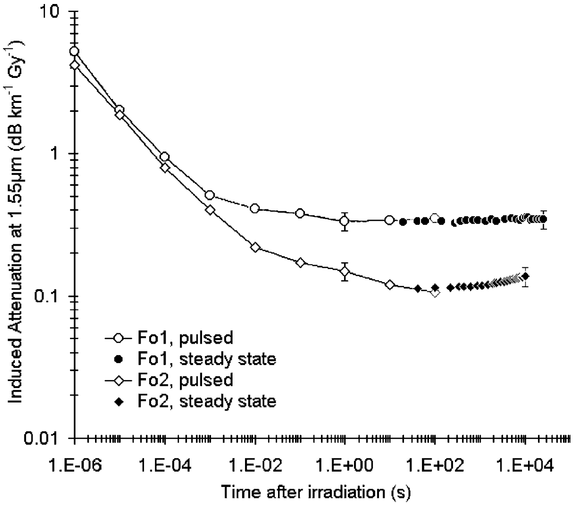

Fig. 3. Comparison of the time evolution of radiation-induced losses at 1.55 μm after pulsed X-ray irradiation and steady-state γ-ray irradiation for P-codoped Fo1 and Fo2 fibers. The error bars were estimated within 15%.

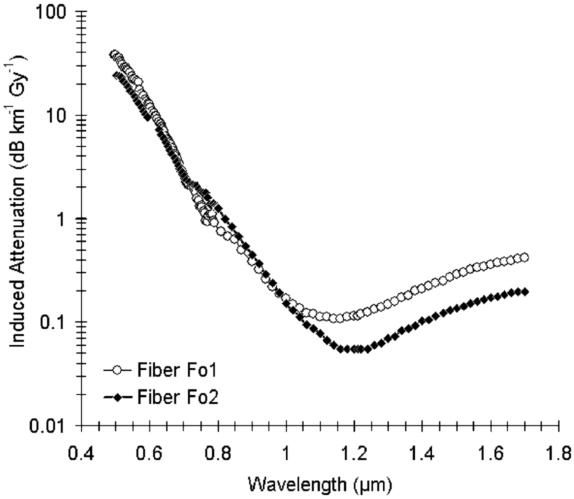

Fig. 4. Radiation-induced attenuation of P-codoped Fo1 and Fo2 fibers six months after steady-state radiation.

time dependent changes of radiation-induced losses after the two types of irradiation. This comparison is illustrated on Fig. 3 and shows that radiation-induced losses, for the total deposited dose considered in our experiments, are independent of the dose rate and the energy of irradiation for the two P-codoped optical fibers. This implies that the same stable color centers are created for a similar dose by pulsed X-ray irradiation or steady-state γ-ray irradiation.

4.2. Origin of radiation-induced losses at 1.55 μm

We performed spectroscopic measurements in the spectral range 400–1700 nm in pulsed X-ray and steady-state γ-ray irradiated samples to determine the origin of the induced attenuation at 1.55 and 1.31 μm. At this time, only the larger permanent loss level in P-doped Fo1 and Fo2 fibers was studied with our apparatus. Results obtained six months after irradiation for the two steady-state γ-ray irradiated P-codoped fibers are shown in Fig. 4.

Radiation-induced attenuation spectra measured for pulsed X-ray irradiated samples (not shown here) are comparable. For both types of irradiation, an absorption band centered around 1.7 μm is correlated with the permanent radiation-induced loss in P-codoped fibers. This band is only present in P-codoped fibers (as evidenced by spectral attenuation measurements on other P-free germanosilicate fibers, not shown here) and explains the permanent loss level difference between P-free and P-codoped fibers. The particularities of P-related color centers in glasses and optical waveguides, induced by steady-state irradiation have been described by former studies [1,11]. In particular, D.L Griscom [11] described the different P-related color centers detected by electron spin resonance (ESR) and absorption measurements. From his works, it appears that the absorption band around 1.7 μm could be assigned to P_1 color centers. This defect is a stable and efficient hole trap, corresponding to a phosphorus atom surrounded by three oxygen atoms, analogous to the SiE' center [11]. This color center is responsible for the permanent radiation-induced attenuation after both types of irradiation.

4.3. Creation of P-related color centers

P-related color centers are mostly created during the X-ray irradiation pulse. In particular, POHC (phosphorus oxygen hole centers) and P_1

centers are created from different precursor sites [11]. However, we measured an increase of radiation-induced attenuation after pulsed radiation and a slight increase of induced losses after steady-state irradiation which could only be explained by a post-irradiation color center generation. Furthermore, this new color center must have an absorption band in the IR, as involved by the loss ratio (1.31/1.55 μm) inversion, illustrated in Fig. 5.

For all the P-codoped fibers, the loss ratio time dependence is similar. The ratio decreases from near 3–4 for shortest times after irradiation to less than one for longer times. For times greater than 0.1 s, the ratio became smaller than one so the optical losses at 1.55 and 1.31 μm are predominantly due to the P_1 centers. An explanation of P_1 centers creation after the end of the ionization is that these centers could be generated by the retrapping of thermally detrapped charges from POH centers. A similar mechanism has been proposed by Griscom et al. [11] to explain the temperature dependence of P-related color center concentrations in P-doped glasses. They evidenced by ESR measurements that the bleaching of a POH center implies a P_1 center generation. For longest times after pulse, the comparison between

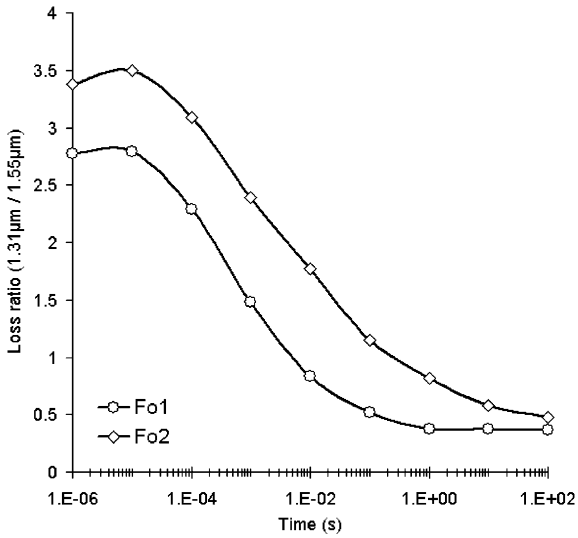

Fig. 5. Time evolution of the radiation-induced attenuation loss ratio (1.31/1.55 μm) after pulsed X-ray irradiation for the P-codoped Fo1 and Fo2 fibers.

P-free and P-codoped fibers shows that permanent radiation-induced losses at 1.55 μm are predominantly due to P-related color centers. At these long times, the bleaching of POH centers induced a diminution of their UV and visible absorption bands and a smaller diminution of the global radiation-induced losses in the infrared. However, their charges, retrapped by P_1 centers, implied simultaneously the growth of the absorption band centered around 1.7 μm. Finally, at 1.55 μm, this mechanism will result in a possible increase of infrared-radiation-induced losses after pulsed irradiation. Moreover, it explains the increase of induced losses after the end of steady-state γ-ray irradiation.

4.4. Interactions between codopants

Spectral attenuation measurements have shown that the P_1 absorption band is more important in Fo1 fiber with Ge–P–F cladding codoping than in Fo2 fiber with P–F ones after both pulsed and steady-state irradiation. However, these two fibers have similar induced loss spectra at wavelength <0.8 μm, where losses are mainly induced by the POH centers and by permanent radiation-induced color centers, absorbing in the ultraviolet and visible regions. It seems that a Ge–P cladding codoping increases radiation-induced attenuation related to P_1 centers. This attenuation has an impact for long time after pulsed and steady-state irradiation ends.

5. Conclusion

We characterized the radiation sensitivities of three germanosilicate optical fibers for pulsed X-ray and γ-ray irradiations. P-doped fiber responses are influenced by the POHC and P_1 color center properties. For this type of fibers, the kinetics of loss recovery after pulse can be induced by a conversion mechanism between the POHC and P_1 centers. Permanent losses at 1.55 μm after both types of irradiation are due to the P_1 absorption band, which seems to be more important in a germanium–phosphorus-codoped cladding.

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