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# On-site Regeneration Technique for Hole-Assisted Optical Fibers Used In Nuclear Facilities

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***Abstract*—In this paper, we demonstrate and highlight a proof of concept for the feasibility of an innovative technique to regenerate on-site irradiated optical fiber links in nuclear facilities. Using Hole-Assisted optical fibers (HAOF), a longitudinal gas-loading is easy to perform thanks to the fibers' dedicated holes located in the outer part of the cladding. All along the fiber length, gas ($H_2$ or $D_2$) diffuses from the holes into the silica matrix, interacts with radiation induced point defects and passivates them, reducing the Radiation Induced Attenuation (RIA) levels. The validity of our approach is demonstrated considering the changes occurring at infrared wavelengths during the $H_2$ treatment of a MGy irradiated single mode Ge-doped HAOF. Within just a few hours, a reduction of about 50% is observed for the RIA at 1550 nm of the 10 MGy irradiated HAOF, acting only from one of its two ends. An additional study is done on a set of fibers with various core dopants (F, Ge, P) and without holes to give an overview of the pertinence of developing HAOF fibers with these dopants for various applications. Using HAOF and this recovery technique appears very promising for samples based on pure-silica, Ge or F-doped cores and operating in the ultraviolet-visible spectral domains such as plasma diagnostics. This approach exhibits another interesting feature which may be extension to higher dose ranges and lifetime of P-doped distributed dosimeters used in high energy physics facilities or nuclear power plants.**

***Index Terms*—Hole-assisted optical fibers, hydrogen, MGy irradiation, optical fibers, radiation-induced attenuation.**

## I. INTRODUCTION

OPTICAL fibers and optical fiber sensors are considered for implementation in various nuclear fields, from space applications to the monitoring of next generation nuclear power plants. Previous studies reveal that these technologies present a much higher radiation tolerance level than those of most micro- or opto-electronic technologies. Today, optical fibers for applications above the MGy dose levels are commercially-available and prototype specialty optical fibers allow to design radiation-hardened fibers and sensors to even higher doses [1]. At the component or system levels, radiation induces three main macroscopic changes. The first and main limiting one is the Radiation Induced Attenuation (RIA) that degrades the fiber signal transmission capacity and the sensing range of distributed sensors [1]. RIA is caused by the generation of optically active point defects in the silica-based glass layers of the fiber core and cladding. The second phenomenon is Radiation Induced Emission (RIE), a parasitic signal that superimposes to the transmitted data and decreases the signal to noise ratio. This signal can also be due to point defects and to Cerenkov emissions [1]. Fewer applications are affected by the RIE than by the RIA and RIE is today more exploited as an innovative way to monitor the radiation flux than considered as a limiting problem [2], [3]. The last mechanism is the Radiation Induced Compaction (RIC) that is mainly observed under exposure to high neutrons fluences. This leads to changes of the refractive-index, impacting the fiber guiding properties. RIC is also potentially detrimental for all fiber-sensors based on the evolution of silica structural properties (*such as Brillouin, Rayleigh, Raman scattering phenomena*) when the measurands change. This effect becomes of primary importance when optical fibers that are robust to RIA are used [4]–[6].

An important point concerning the vulnerability study of a fiber-based system is that no simulation tool exists today allowing to predict the degradation of a given optical fiber for a specific profile of use in a given radiation environment, even if codes now exist to solve parts of the problem [7]–[9]. This is a serious limitation for all applications and/or environments implying test procedures not compatible with existing facilities or projects schedule, eg. for space missions durations of which are incompatible with existing radiation tests. This implies to investigate the fiber radiation response at a higher dose rate than in real space missions, thus altering in a complex way the competition between point defect generation and recovery mechanisms [10]. This issue is also encountered when the radiation environment of interest cannot be reproduced using ground testing facilities: a good example being the laser-driven ignition facilities like Laser Mégajoule (LMJ) in France or National Ignition Facility (NIF) in the USA [11]. All these limitations to the current fiber and fiber sensor vulnerability studies imply that for most future facilities (*another example is nuclear waste repository or nuclear power plants*), maintenance schedules or large operation margins are mandatory and have to be scheduled years in advance. For Earth-based facilities, backup plans are neces-

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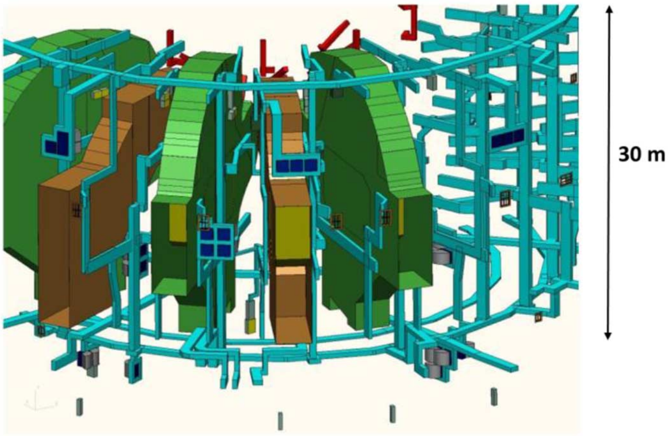


Fig. 1. Illustration of the complex pathways in nuclear facilities with the example of the LMJ. In cyan is illustrated only a part of the fiber pathways within its experimental hall (30 m length for both diameter and height). All fibers located in this hall will be exposed to the harsh radiation constraints associated with ignition shots [14].

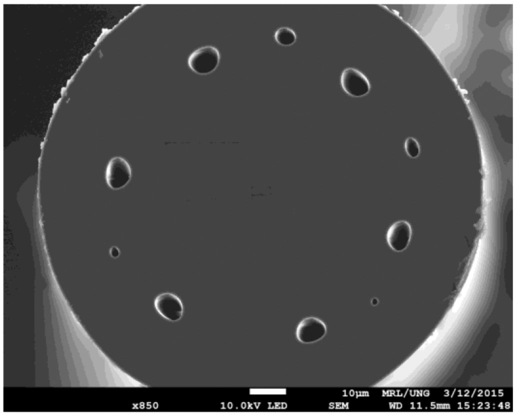


Fig. 2. Scanning Electron Microscope picture of the HACC-Ge fiber. The whole fiber diameter is 125 $\mu$m, the core diameter is about 10 $\mu$m and six holes of large size and 4 smaller holes are present in the outer part of the fiber cladding where no light propagates.

sary to overcome unexpected degradation of the optical links. A possible action lies in the removing of the irradiated fibers and installation of new ones. For some applications, this task can be associated with huge constraints and costs considering the complexity of the fiber pathway and their extremely difficult accesses, especially if human presence is needed in high radiation level zones. Fig. 1 illustrates some of the fiber pathways for the fiber-links of data communication links, plasma and laser diagnostics of LMJ, highlighting this issue in such kind of huge facility. Among the other existing mitigation approaches, an innovative technique was also suggested for fiber-based dosimeters (*phosphorus-doped fibers*): heating them at temperatures higher than 300°C all along the link to bleach the RIA caused by unstable optically-active defects [12]. This method has a high potential of efficiency but is also very difficult to implement in most radiation facilities. The photo-bleaching effect has also been considered and investigated, however available results report limited efficiency [13].

The purpose of this work is to investigate a new fiber treatment procedure allowing to 1) reduce the needs for hardening studies of fiber links (*dedicated fiber composition*), 2) authorize to regenerate an irradiated fiber link without removing and replacing the fiber, having access to only one of its two output ends. As a demonstration of the potential of this technique, we apply this procedure in-lab to a germanium-doped single-mode optical fiber (10 m length), similar to the Telecom-grade SMF28 optical fiber. It is important to notice that this technique can also be extended to 1) multimode fibers, 2) fibers doped with other chemical elements as far as the gas used ($H_2$ or $D_2$) is efficient enough to passivate the radiation induced point defects related to these various dopants, 3) fiber links varying in length from a few meters to several km and with operating wavelengths from UV to visible. The potential of this technique is more deeply discussed in this paper thanks to a study of $H_2$-effect on the RIA observed in F-doped, Ge-doped, and P-codoped optical fibers without this HA structure in the [$0.3\ \mu$m $- 2\ \mu$m] wavelength range. From this work and preliminary results, a good evaluation and promising potential of this technique is achieved.

## II. TESTED OPTICAL FIBERS & IRRADIATION CONDITIONS

### A. *Tested Optical Fibers*

Two single-mode optical fibers with a Ge-doped core (6 wt.%; 10 $\mu$m diameter) and a pure-silica cladding are used as devices under test to evaluate this regeneration method. These fibers have been drawn from the same preform, fabricated by iXBlue Photonics Division with the Modified Chemical Vapor Deposition (MCVD) technique [15], one with a classical acrylate coating and without holes while the second presents HACC structure (*carbon coating and holes).* It should be noticed that for this work, the presence of the external carbon layer is not mandatory for the regeneration technique. The first fiber is called IXSM-Ge while the second one HACC-Ge. The HACC-Ge fiber structure is illustrated in Fig. 2. The fiber has six large holes and four small ones. The holes (location and form) should not have any effect on fiber optical properties, their geometry is then of minor influence on the regeneration procedure. Their main goal is just to allow the longitudinal gas diffusion from one fiber end along the whole fiber link and then into the fiber core and cladding.

In addition to these two Ge-doped single mode fibers (SMFs), we also performed a study of $H_2$ influence on the permanent RIA in several commercial fibers with diversely doped cores. One of these three fibers can be considered as radiation hardened at MGy dose levels thanks to a core and cladding doped only with Fluorine (max of about 5 wt.%). The second one is only Ge-doped core whereas the third one contains both Ge and P ($\sim$ 1 wt%) in its core. This set of fibers permits us to investigate the potential of the gas (here, $H_2$) loading to passivate the various Si, Ge or P-related defects absorbing in the ultraviolet and in the near-infrared (2 $\mu$m) spectral ranges. Indeed, it is known that in Ge and P containing fibers, Ge and P-related defects are mainly responsible for the visible-IR RIA respectively. These additional tests and fibers allow us to define the application area of our HACC regeneration technique without developing systematically HAOFs for this preliminary study. For this, we compare the RIA between those $\gamma$-ray irradiated fibers and the same samples after a posttreatment with $H_2$. As these fibers present no hermetic outer carbon structure, only a classical transversal $H_2$ loading is performed, under conditions comparable to the ones used to increase the photosensitivity of germanosilicate fibers before Fiber Bragg Gratings (FBG) inscription [16]. It should be noted that the procedure has been investigated using $H_2$ gas, but $D_2$ treatment is also possible with the used setup and expected differences are discussed in the last part of this paper.

## III. IRRADIATION CONDITIONS

All fiber samples have been $\gamma$-ray irradiated at different doses from 1 to 10 MGy at the Brigitte facility of SCK-CEN in Belgium (*dose rates from 1 to 20 kGy/h and irradiation temperature below* $50^\circ$C) except one P-codoped one that was irradiated at the RITA facility also at SCK-CEN up to 1.2 kGy. All the experiments presented in this work were done *post mortem* around three months after the end of the irradiation. Only the permanent damages caused by radiations are investigated.

## IV. REGENERATION PROCEDURE

### A. HAOF Structure Advantage

In [17], [18], we presented the progress offered by the HA carbon coated (HACC) structure to enhance the radiation hardness of Erbium-doped optical fibers and fiber amplifiers. In that case as for HAOF, the aim of the hole structure is not to participate to the fiber guiding properties such as in microstructured or hollow-core optical fibers [19]. For the Er-doped case, the HA structure objective was to provide a way to inject gases through the holes from one fiber end after the fiber was coated with an impermeable to hydrogen carbon layer at nominal conditions of temperature and pressure. The carbon layer ensures that the gas is kept into the fiber for a long period and especially during the whole duration of a space mission.

### B. Regeneration Procedure

In this article, we show how this Hole-Assisted structure (*with or without the carbon layer*) also represents a breakthrough for increasing the lifetime of optical fibers in radiation environments. The approach for the fiber regeneration is schematically illustrated in Fig. 3.

When an optical fiber link is highly affected by the RIA phenomenon, the treatment can be applied even if operators have access to only one of the fiber ends.

This accessible output end is put within a gas tank containing a small volume of gas ($H_2$, or $D_2$) under pressure (typically $> 100$ bars). This tank could be as the one illustrated in Fig. 3, a commercial system designed to transversally $H_2$ ($D_2$) loading, putting the whole fiber length within the tank. However, an adaptation was necessary for our purpose. Indeed, we have to connect the end (few cm) of the HAOF fiber to this under-pressure system with an appropriate adapter whereas the whole fiber link remains outside the tank. As soon as the fiber end is in contact with the $H_2$-rich atmosphere (*158 bars, room temperature in our HAOF experiments*), gas starts to diffuse longitudinally along the whole fiber length through its holes, the efficiency of this kinetic being almost independent of the considered HAOF length. Then the gas starts to diffuse from the air holes into the silica glass matrix, with well-established kinetics that depends mainly on the gas pressure and temperature of operation [20]. After a certain time that depends on the hole location, size, fiber size properties, the gas diffuses up to the fiber core and inner cladding regions where the light signal is guided. For sure, this loading technique is far less efficient than the one used for increasing the photosensitivity of fibers as the whole fiber is under pressure and routinely *at an increased temperature* to accelerate the diffusion rate. For the Ge-doped, P-doped or F-doped multimode fibers (MMFs) discussed in this paper, we used this classical loading conditions (the whole fiber is put inside the gas tank) occurring along the whole fiber through its outer envelope and coating. However, to decrease RIA in HAOF, the objective is not to saturate the fiber with $H_2$ or $D_2$, but only to passivate a limited number of defects, on the order of $10^{18}$ cm$^{-3}$, even at high doses [21]. For such a challenge, the needed concentration of $H_2$ or $D_2$ remains low ($< 1\%$ of the saturation value) even if it is very difficult to estimate precisely the threshold from previous studies reported in the literature.

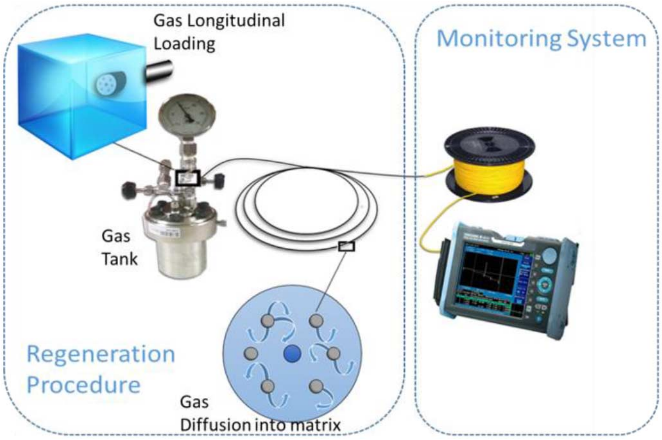
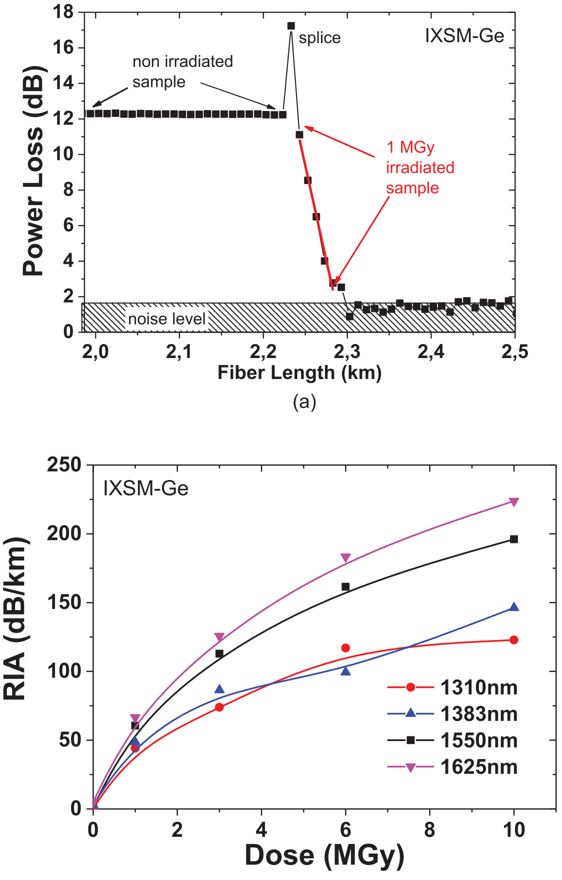


Fig. 3. Schematic illustration of the approach used for the fiber link regeneration and the monitoring of the efficiency of this technique.

## V. IRRADIATION RESULTS & REGENERATION OF GE-DOPED SMFS

### A. Permanent RIA Levels

After irradiation, both Ge-doped SM fibers present similar RIA levels, in agreement with those reported for other commercial Ge-doped fibers in literature and from the fact that they were produced from the same preform [22]. Here, the RIA is preliminarily evaluated through Optical Time Domain Reflectometry (OTDR) measurements at 4 wavelengths: 1310 and 1550 nm (which correspond to the second and third Telecom windows), 1383 nm for the OH overtone (hydroxyl groups) that limits the signal division multiplexing and 1625 nm the higher wavelength considered for telecom applications. Fig. 4(a) presents a typical OTDR trace at 1550 nm, highlighting the degradation of the transmission along the 30 m long irradiated fiber compared to a pristine one spliced to it. From the slope of the trace, one can extract the RIA value at the probe laser wavelength. As the



(a)

(b)

Fig. 4. (a) Example of OTDR trace in evolution in IXSM-Ge fiber. (b) Growth kinetics of permanent RIA with dose in IXSM-Ge fiber at 1310, 1383, 1550, and 1625 nm.

RIA exceeds largely the value of optical losses in the pristine fiber, the calculated value corresponds to RIA.

Fig. 4(b) summarizes the results for IXSM-Ge fiber; similar results have been obtained for HACC fiber. As expected from previous studies, RIA is higher at larger wavelengths (1550, 1625 nm) for such high irradiation doses [22]. This is assumed to be due to some defects absorbing in the IR rather than from the tail of UV and visible absorption bands. By analogy with results obtained in pure-silica core fibers, it was suggested that Ge-STHs may absorb in this part of the spectrum [23]. For such a single mode fiber, the spectral RIA dependence is also affected by the evolution of the radial distribution of light power with the wavelength, indeed at 1.55 $\mu$m, about 25% of the light is propagating in the cladding of pure-silica.

### B. *On-Site Treatment of the HACC Optical Fiber*

To investigate the kinetics of regeneration, we used the test bench illustrated in Fig. 3. At the second output end of the HACC-Ge fiber, we connect an OTDR to probe online the effect of gas loading through the fiber holes on the RIA. By this technique we point out that the OTDR trace at a given wavelength evolves with the treatment duration and a clear reduction of the RIA is observed over the whole fiber length within a few hours. In Fig. 5 we plotted the evolution of the RIA at 1550 nm versus the time of treatment, and in about 12 hours, the RIA is reduced by more than a factor of 2 in dB. After a period of RIA decrease, the attenuation increases again. It is related to the formation of Si or Ge-OH groups, absorbing around 1380-1410 nm as the result of the interaction between $H_2$ and the radiation-induced point defects (particularly the Non-Bridging Oxygen Hole Centers, NBOHCs). A possible scheme is the following (considering only the Si-defects, similar mechanisms for Ge-defects)

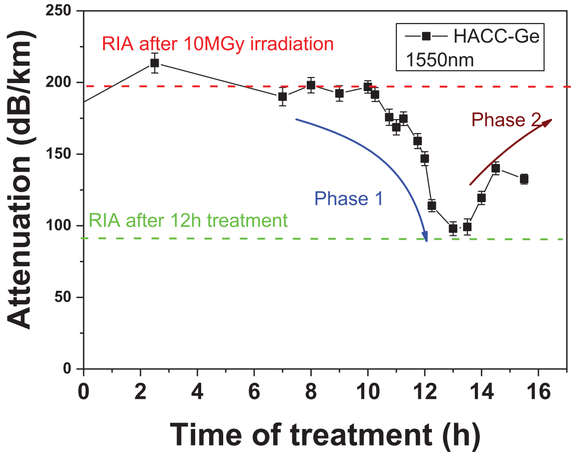


Fig. 5. Effect of the regeneration procedure on the 1550 nm RIA of a HACC-Ge fiber irradiated at 10 MGy dose.

$$\begin{array}{c}(Si-O-Si)_{strained}\xrightarrow{\gamma}SiE'+NBOHC\\ SiE'+NBOHC\xrightarrow{H_2}SiH+SiOH\end{array}.$$

From these preliminary results, one could expect tha:t 1) the $D_2$ treatment of the fiber should lead to a better RIA recovery percentage than the $H_2$ one as it will limit the growth of the RIA related to the loading at wavelengths below 1550 nm; and 2) that the regeneration procedure will be even more efficient in the visible part of the spectrum as NBOHC centers are mostly responsible for the RIA.

## VI. Potential of the $H_2$ Loading by HAOF Regeneration Technique: Area of Applications

To verify these assumptions and to better provide evidence of the HAOF regeneration technique for a large panel of applications, we investigated the set of 3 MM fibers that will authorize to discuss the $H_2$ influence on the Ge-, P- and Si-related defects. Indeed, it should be noted that even if for these commercial fibers, we did not use the HAOF structure, we expect to obtain the same optical and radiation results in the future by developing HAOF with similar core and cladding compositions.

### A. *Germanosilicate and F-doped Optical Fibers*

Fig. 6 represents the spectral dependence of the optical absorption (OA) for the two Ge and F-doped fibers over a large spectral range extending from 300 nm to 2 $\mu$m. These OA measurements could be considered as RIA measurements due to the high RIA levels. These results were obtained several months after a 10 MGy irradiation dose using the cut-back technique applied to different lengths of fibers adapting this length to the RIA levels and to the dynamics of our detectors (*HR4000 and NIRQuest spectrometers from Ocean Optics for UV-visible and*

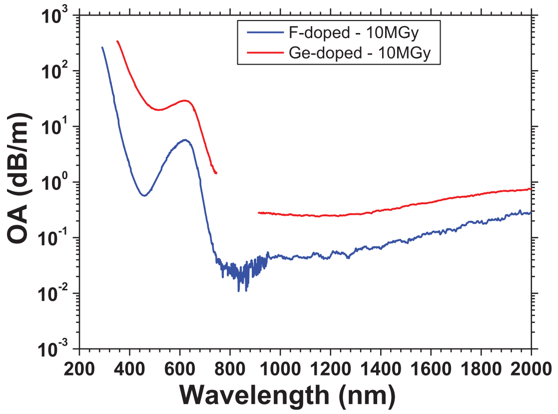


Fig. 6. Permanent RIA Spectral dependencies measured after 10 MGy irradiation dose in the F-doped and Ge-doped multimode optical fibers.

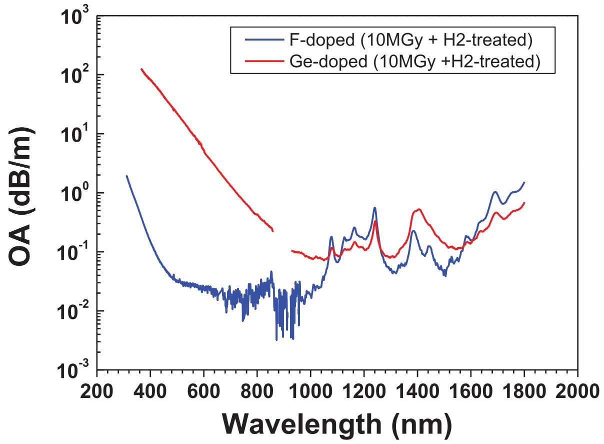


Fig. 7. Spectral dependences of the RIA measured after 10 MGy irradiation in the F-doped and Ge-doped multimode optical fibers after exposure of the samples to $H_2$ loading (150 bars, 50 h, RT).

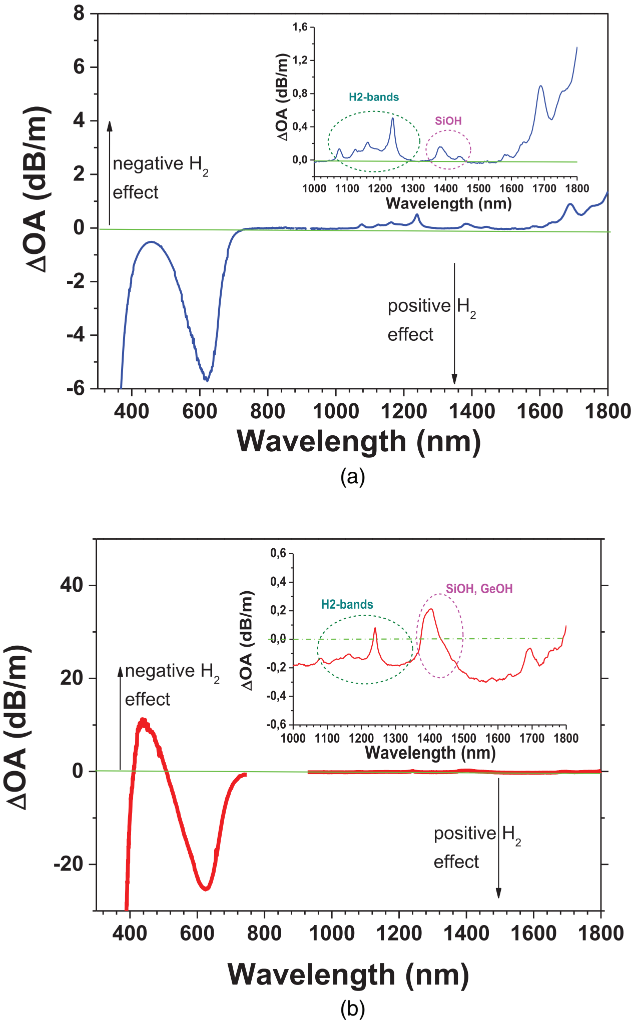


Fig. 8. Impact of the $H_2$ loading (150 bars, 50 h, RT) on the RIA measured in the (a) F-doped and (b) Ge-doped multimode optical fibers previously irradiated to 10 MGy. This impact is evaluated by calculating the difference of absorption ΔOA after and before the gas loading. Insets are magnification of the obtained results in the IR parts of the spectrum.

*IR, respectively*). These measurements provide evidence for several interesting features concerning RIA. First, these results clearly show that the RIA in the IR cannot be explained (as often done) by the sole contribution of the defects absorbing in the UV and visible regions. It seems that specific defects or mechanisms lead to the degradation of the IR transmission. The exact nature of these defects is still debated and remains outside the scope of the present paper but explains the difficulty for most of the IR applications to predict the degradation of a given fiber for a given application from accelerated radiation tests.

This lack of knowledge supports the needs for an alternative method such as the presented regeneration technique to compensate for extrapolation errors, reduce margins and if necessary act on the fiber link and regenerate it. Transmission in the visible domain is strongly affected by absorption bands located around 600 nm that are attributed to Si or Ge-NBOHCs. As expected UV part of the spectrum is highly affected by radiations caused by the tails of absorption bands centered below 400 nm. From a pragmatic point of view, even if these defects are mostly unknown, it is interesting to see if they can be passivated by $H_2$ (or $D_2$) loading.

For this investigation, we put samples of these 10 MGy irradiated fibers within the $H_2$ tank at a pressure of 150 bars during 50 hours at room temperature. For sure, this treatment will not saturate the fiber with the gas but should be sufficient enough to have a clear view of the $H_2$ positive or negative impact on the RIA and this for the whole spectral range from UV to visible. Fig. 7 reports the obtained spectral OA results for the two fibers. Fig. 8 more clearly illustrates the $H_2$ loading impact through the difference ΔOA between the OA spectra of the 10 MGy fibers measured before (Fig. 6) and after gas loading (Fig. 7).

These measurements provide evidence for the efficiency of $H_2$ species to interact with the glass matrix and radiation-induced point defects. OA spectra are clearly changed by the presence of $H_2$ species with a decrease of the visible OA bands in both fibers and the appearance of several OA peaks in the IR. To understand the nature of the observed changes one should consider different origins for these various absorption bands. They are discussed in details in [20]for both $H_2$ and $D_2$ loading and are briefly summarized hereafter. During the measurements, the fiber still contains a large amount of molecular $H_2$ as the delay between the gas loading and the cut-back measurements takes only of few hours. The presence of $H_2$ molecules give rise to several absorption bands in the IR, the main one being centered around 1.24 $\mu$m with other signatures of minor amplitudes at smaller wavelengths. This contribution to the optical losses of the fiber is directly related to the presence of $H_2$. In the case of a HAOF structure without carbon layer, this contribution will decrease with time and disappears when the $H_2$ will have fully out-diffused from the entire fiber core and cladding. Part of the incorporated $H_2$ interacts with the radiation-induced point defects (*or precursor sites of lower concentration*) such as Non-Bridging Oxygen Hole Centers (NBOHC) or peroxy centers (POR) to create various forms of hydroxyl groups: Si-OH, Ge-OH, Si-O-OH with OA bands absorbing at specific and well-known IR wavelengths.

In silica, the first overtone of Si-OH is located at around 1390 nm [20], the 1.41 $\mu$m band is attributed to Ge-OH [20] whereas the SiO-OH is associated to a signature around 1.52 $\mu$m, [24]. At room temperature, these bands can be considered as stable, and related optical losses as permanent. This is clearly a limiting factor for our HAOF approach applied to optical links operating as it means that the hydrogen loading should be carefully monitored and controlled to stop it before the positive effect (*bleaching of radiation-induced point defects*) is overcomed by the negative effect (OH species grow). This is exactly what occurs during the on-site HAOF regeneration of the SMF-Ge (Fig. 5) during the first part of the treatment, the $\Delta$OA is negative (*positive impact*) but at a certain time, the increase of the OA related to the growth of the OH formation exceeds the decrease of radiation-induced point defects and $\Delta$OA becomes positive (*meaning negative impact of* $H_2$). It should be noted that for this test, we use a HACC structure and that this is a worst case as the $H_2$-related bands will be stable in time as $H_2$ species cannot out-diffuse such a fiber structure. Furthermore, at Telecom wavelengths, it can be assumed from [20], that the positive impact will be enhanced by the use of D2 instead of $H_2$ as the $D_2$ or Si-OD related OA bands will be less impacting at Telecom wavelengths such as 1310 nm.

Results are simpler in the visible part of the spectrum with a clear decrease of the NBOHC (Si or Ge) absorption bands around 650 nm for both fibers. This positive impact of $H_2$ on NBOHCs is well known [25] but our results demonstrate that the lifetime of pure-silica-core or fluorine doped fibers used for ITER diagnostics could benefit from the HAOF technique if the suggested patented procedure [1], [25], [26] is applied.

The case of P-doped or codoped optical fibers is different It is well known that these fibers should be avoided in radiation environments, when RIA has to remain limited to ensure the system functionality. However, such fibers can be useful as part of dosimetry systems. Combining reflectometry technique (such as OTDR [27] or Optical Frequency Domain Reflectometry [6], [28]) and the high RIA, it becomes possible to make distributed dose measurements along a single fiber with a spatial resolution better than 1 m. A recent study [29] dealing with this subject, and limiting factors for such systems are first, the saturation of the RIA at IR wavelengths when doses exceed kGy levels and the today difficulty to reset the dosimeter if no a distributed heating of the line above 300°C is possible. For such applications, HAOF-P-doped fibers may present interesting features as shown by the results illustrated in Fig. 9.

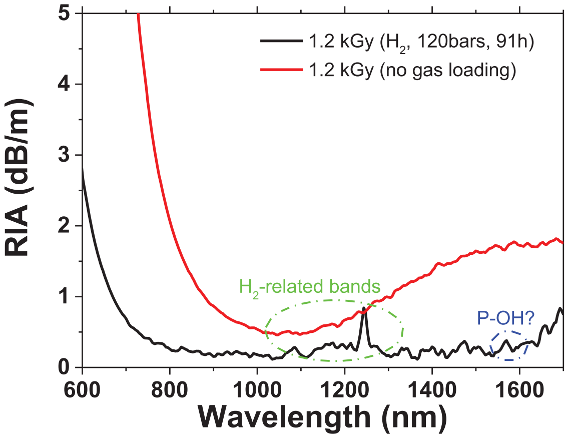


Fig. 9. Spectral dependences of the RIA measured after 1.2kGy $\gamma$-ray irradiation in the P-codoped multimode optical fiber and after exposure to $H_2$ loading (120 bars, 91 h, RT).

These results provide evidence for a clear effect of the $H_2$ loading that is able to eliminate both the RIA related to P1 centers and their absorption band around 1600 nm and the long tail of the RIA induced below 600 nm by Phosphorus Oxygen Hole Centers (POHC). The remaining 1240 nm absorption peak related to $H_2$ molecules highlighted in the Fig. 9 should disappears after few days via out-diffusion processes. In [20], P-OH band is centered at $\sim$ 1.6 $\mu$m, results of Fig. 9 show that the amplitude of this signal remains low within our measurement uncertainties. Compared to what is observed in the MGy Ge and F-samples, the limited amplitude of this band is also explained by the smaller number of P generated defects at 1.2 kGy. Then, HAOF-P-doped dosimeters could be reinitiated by this technique. Further studies are in progress to determine if the radiation response of the fiber is affected by this $H_2$ treatment in case of a second irradiation. If not, very versatile dosimeters will be accessible using the Hole Assisted Optical Fibers in the near future.

## VII. CONCLUSION

We present and validate a very innovative technique opening the way to the on-site regeneration of irradiated optical fibers in today's and future nuclear facilities. Hydrogen and Deuterium are known to passivate most defects both in pure silica glass and in glass doped with F, Ge, P. The main advantage of our patented technique is that km-long optical fiber can be regenerated having only access to one of its ends and in a few hours, independently of the complexity of the link pathway and of its length as the $H_2$ propagates quickly along fiber's holes. The use of Hole-Assisted optical fibers will permit to reduce both the margins and the maintenance operation in future complex facilities such as high energy physics facilities, fusion-devoted installations, nuclear waste repositories and future nuclear power plants.

The efficiency of this procedure will be dependent on the nature of the point defects at the origin of the RIA at the operating wavelength of the fiber-based systems. It is really efficient in the visible parts of the spectrum where highly challenging and systems of difficult access operate like the diagnostics of ITER, LMJ or NIF facilities. However, for some applications, mainly operating in the IR, the technique presents some limitations. Indeed, the passivation of radiation-induced defects is shown to be accompanied by the increase of the hydroxyl group concentrations the main one of SiOH being at 1.38 $\mu$m. For such applications, one could take advantage of the different bands associated to $H_2$ or $D_2$ overtones to reduce this limitation: as an example, it will be better for a system operating at 1310 nm as the Large Hadron Collider optical network does [30] to consider $D_2$ loading that allows to shift the main absorption band to the IR. As a perspective, an on-site test will be performed to demonstrate the easy use of this technique in "industrial" environment.

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