Combined effect of radiation and temperature: towards optical fibers suited to distributed sensing in extreme radiation environments

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***Abstract*—Combined effect of radiation and temperature on the response of polyimide coated radiation hardened single-mode fibers is investigated in the context of distributed monitoring of large nuclear infrastructures. Radiation induced attenuation (RIA) is evaluated for doses ranging from 1 to 10 MGy(SiO_2) and temperatures up to ~250 °C. Measurements of fiber tensile strength are performed to better estimate conditions of safe operation before and after exposure to the severe environment. Finally, preliminary results obtained for a new optical fiber designed from an alternative preform fabrication process, Surface Plasma Chemical Vapor Deposition are presented. This fiber exhibits 1310 nm RIA below 7 dB/km after a 1 MGy(SiO_2) dose paving the way toward optical fibers suited to extreme radiation environments.**

***Index Terms*—Radiation hardened fiber, polyimide coating, distributed sensing, radiation induced attenuation, mechanical strength, Surface Plasma Chemical Vapor Deposition.**

I. INTRODUCTION

Operation of photonics technologies under various radiation environments is already well spread due to their intrinsic add-values, such as low footprint, low power consumption and extended bandwidth. However, each field of application comprises specificities that need to be addressed in order to ensure long term reliability of the device. In this context, effects of radiations combined with low or high temperatures are encountered in many applications that involve optical fibers. For example, rare earth-doped fiber optical amplifiers and fiber optic gyroscopes are already implemented for space applications [1]. Spun optical fiber based current sensors [2], temperature and/or strain monitoring systems based on fiber Bragg gratings at cryogenic [3] and high temperature [4] or on back-scattered light in optical fibers [3,5] shall be installed inside large nuclear infrastructures. In this context, Raman-distributed temperature sensors (RDTS) in multimode fibers are seen for more than two decades as a good compromise between spatial resolution, precision and operating costs [6]. However, recent studies on single-ended interrogator configurations have shown that Radiation Induced Attenuation (RIA) variations with wavelength generate a temperature measurement error that strongly increases with cumulated dose [7]. Newly developed RDTS systems [8] shall allow distributed temperature measurements up to a few MGy(SiO_2) dose levels using single-mode fibers in a single-ended configuration. Advanced interrogators are also able to discriminate between temperature and strain up to the same level of dose [9]. Specific radiation hardened single-mode fibers have been developed to match the requirements of those applications [10]. Such fibers are investigated in this study both in term of RIA, that impacts the maximum sensing length, and fiber mechanical strength degradation, that impacts the sensing system reliability over the years. Polyimide coated fibers have been irradiated by γ-rays at 1 MGy(SiO_2) up to ~250 °C and up to 10 MGy(SiO_2) at ~100 °C. Finally, a specific preform deposition technique named Surface Plasma Chemical Vapor Deposition (SPCVD) has demonstrated promising features to fabricate a new generation of radiation hardened fibers well suited to extreme radiation environments.

II. RIA AND MECHANICAL STRENGTH EVOLUTION DUE TO COMBINED IRRADIATION AND TEMPERATURE

Investigated single-mode optical fibers belong to iXblue rad-hard portfolio [11]. Those radiation hardened optical fibers comprise a fluorine-doped silica cladding (~2wt% of fluorine) and a pure silica core [10]. Preforms are fabricated by MCVD (Modified Chemical Vapor Deposition) and drawn with polyimide coating in order to operate up to high temperature, 300 °C on long term in radiation-free environments. Table I summarizes the main characteristics of the tested samples.

TABLE I
OPTICAL CHARACTERISTICS OF TESTED OPTICAL FIBERS

parameter	specification
core numerical aperture	0.14 ± 0.01
attenuation@1.55µm	< 0.6 dB/km
cut-off wavelength	< 1450 nm
mode field diameter@1.55µm	9.0 ± 1µm
silica cladding diameter	125 ± 2 µm
coating diameter	155 ± 5 µm

Four samples of 50 m in length have been irradiated by ^{60}Co γ-rays at the IRSN IRMA ^{60}Co facility, Saclay (France). Cumulated dose reaches 1 MGy(SiO_2) for a dose rate of 0.77 Gy/s, at room temperature and up to 240 °C using different thermo-regulated plates. RIA is measured in-line using a specific RDTS interrogator from VIAVI Solutions which operates at two wavelengths (1550 nm and 1625 nm) with an injected power of a few hundred of milliwatts. Its architecture makes the temperature measurement independent

Manuscript received April 13TH, 2019.
This work has been made in the framework of the Joint Research Laboratory "LabH6" between iXblue and Laboratoire Hubert Curien

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from differential attenuation between the Stokes and Anti-Stokes signals [8]. Figure 1 presents temperatures measured by PT-100 probes (Platinum resistance Thermometers) placed close to the four irradiated fiber coils. Averaging those data leads to mean temperatures respectively of 32 °C, 59 °C, 92 °C and 240 °C, with variations of ± 2 °C. In the three following figures, bold and dashed vertical lines represent shutdowns of irradiation and heating plates.

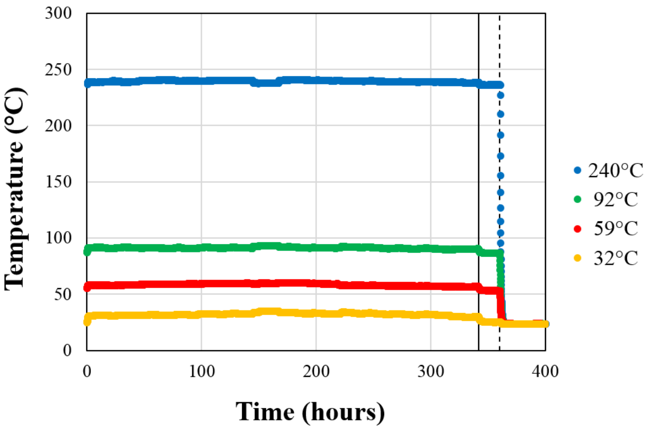

Fig. 1. Temperature monitoring during irradiation and after shutdown for the four samples

The RIA growth kinetics measured in-line at 1550 nm and 1625 nm during irradiation up to 1 MGy(SiO_2) as well as the RIA evolution post-irradiation are presented in figures 2 and 3 at the different temperatures of irradiation. Fiber strength is measured before/after irradiation according to IEC 60793-1-31 norm using an uniaxial table top tensile tester from FIBER SIGMA for a set of 15 fiber samples of 0.5 m. Figure 4 provides obtained results for a strain rate of 30 mm/min which corresponds to an elongation rate of 6 %/min. Failure probability of sample (i) is calculated by (i – 0.5) / 15. Red lines represent minimal strength requirements as stated in IEC 60793-2-50 norm for generic optical fibers.

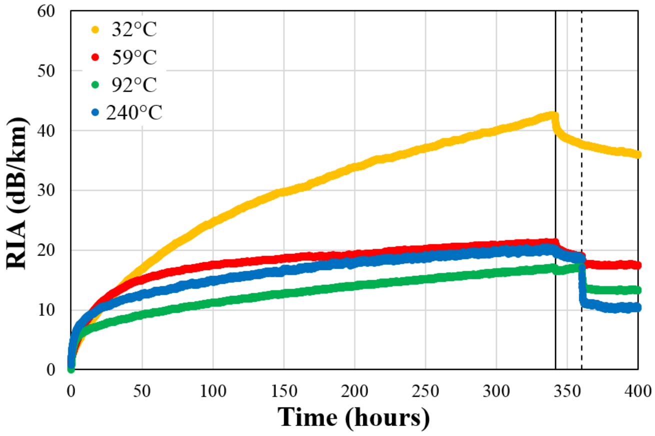

Fig. 2. RIA versus time at 1550 nm at different temperatures up to 1 MGy(SiO_2)

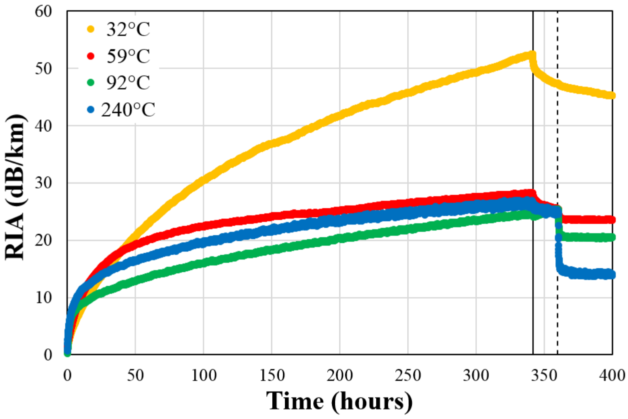

Fig. 3. RIA versus time at 1625 nm at different temperatures up to 1 MGy(SiO_2)

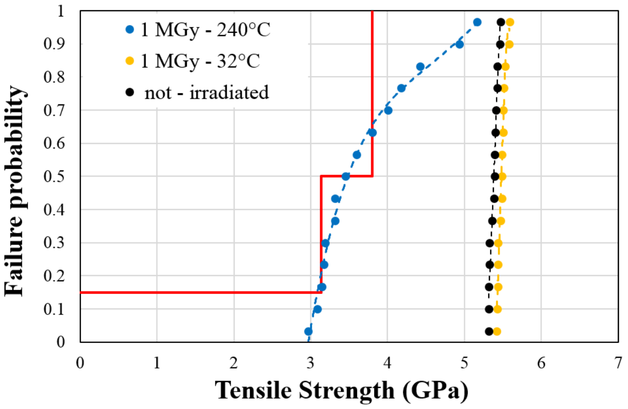

Fig. 4. Tensile strength versus failure probability before/after irradiation at 1 MGy(SiO_2)

A second set of fibers has been irradiated at 90 ± 10 °C up to 10 MGy(SiO_2) at ~21 Gy/s of ^{60}Co γ-rays, corresponding to a total dose delivered in ~132 hours. Irradiation was performed in an industrial facility, at Beta-Gamma-Service, Wiehl (Germany), where RIA was not monitored in-line. Extrapolation of experienced RIA up to 10 MGy(SiO_2) from previous experiment data is provided in figure 5 for the worst-case condition (1625 nm and 32 °C) and a dose rate of 0.77 Gy/s. Fiber strength evolution before/after irradiation is presented on figure 6.

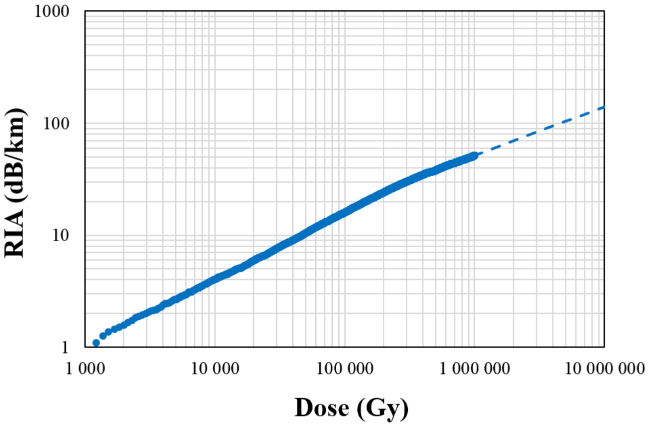

Fig. 5. Measured RIA at 1625 nm at 32 °C up to 1 MGy(SiO_2) and extrapolation up to 10 MGy(SiO_2) in dashed line

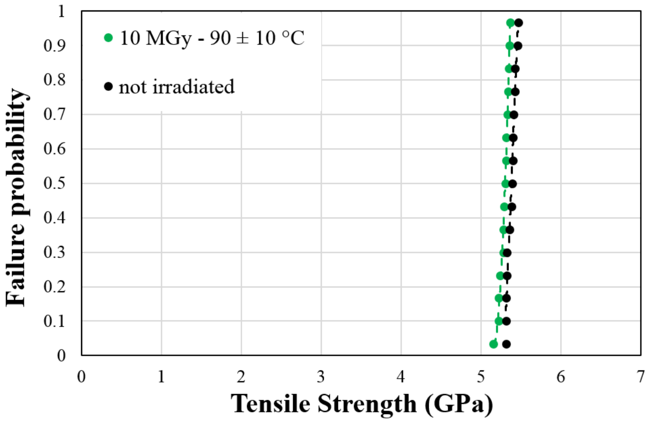

Fig. 6. Tensile strength versus failure probability before/after irradiation at 10 MGy(SiO_2) and 90 ± 10 °C

III. DISCUSSION ON MCVD FIBER PERFORMANCES

Rising the temperature during irradiation can have a positive, a negative or no impact on RIA according to the fiber composition, the irradiation conditions and the signal wavelength [12]. In the case of polyimide coated pure silica core multimode fibers, a strong RIA reduction is observed at 854 nm (factor ~18) and 1047 nm (factor ~4.6), when temperature increases from to 20 °C to 300 °C for a ^{60}Co γ-rays cumulated dose of 26 kGy [6]. Figure 7 presents RIA at 1.55 µm extracted from data of figure 2 at different doses for the tested pure silica core single-mode fiber. Temperature impact is dose dependent, but most likely time dependent, considering the kinetic of defects annealing by temperature. Below ~30 kGy, RIA is weakly affected, but above this value and up to ~60 °C, it increases strongly with the level of dose whereas above 92 °C, there is only a minor impact of temperature on RIA. A detailed study of defects creation and annealing in this particular type of fiber remains necessary as the current state-of-the-art about the Si-related point defects [13] does not yet allow a clear understanding of the complex interactions between temperature, wavelength and irradiation parameters.

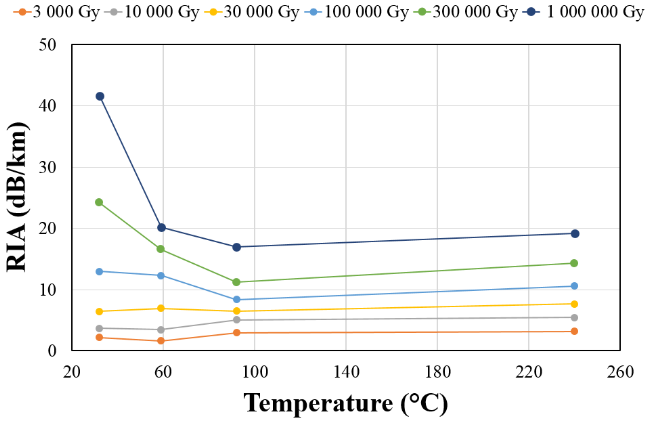

Fig. 7. RIA at 1550 nm at 32 °C, 59 °C, 92 °C and 240 °C for different cumulated doses

For a total dose of 1 MGy(SiO_2), RIA is maximal, ~50dB/km at room temperature and 1625 nm. This value is a good basis for an optical budget calculation, as a worst-case condition, even though the system can operate at higher temperature. For a total dose of 10 MGy(SiO_2), maximal RIA reaches at least 150 dB/km at 1625 nm, from the estimation presented on figure 5. Considering an optical budget of ~10 dB, which is typical of the used interrogator, estimated sensing length drops from ~200 m down to below 70 m for both cumulated dose levels. Therefore, RIA experienced by the tested fibers directly limits the sensing length in extreme radiative environments. Another important issue is fiber mechanical reliability. Polyimide coating weakening after irradiation at the MGy dose level has been demonstrated by thermal gravimetric analysis and safe operating temperature is expected to drop of ~50 °C [10]. Results presented on figure 4 indicate that combined effect of temperature and radiation leads to reduce median value and increase dispersion of the tensile strength measured at room temperature. It is worth noticing that minimal strength requirements of generic optical fibers (red lines in figure 4) are reached for a temperature of 240 °C, whereas long-term operating temperature for non-irradiated polyimide coated fibers is of ~300 °C. So, both approaches lead to the conclusion that operating temperature of polyimide is limited to ~250 °C in the case of combined irradiation at the MGy dose level. As indicated in figure 6, for a 10 times higher dose delivered at ~100 °C, no strength degradation is experienced, with most likely a further margin on temperature before reaching minimal strength requirements of generic optical fibers.

IV. SURFACE PLASMA CHEMICAL VAPOR DEPOSITION FIBER

Initially designed to produce conventional germanium-doped single-mode fibers, the SPCVD process has been first described in 1986 [14]. It is based on a low-pressure (~1 mbar) microwave (2.45 GHz) plasma created within a silica substrate tube, itself placed into a tubular furnace at temperatures over 1000 °C, which enables the dissociation of gaseous precursors. The dissociation of a mixture of $SiCl_4$ and O_2 in the plasma column is followed by a recombination of Si and O atoms in the volume of the column. Then, the SiO molecules diffuse to the inner surface of the substrate where they are adsorbed, and the oxidation into glassy silica is obtained using the excess oxygen available in the column. Due to an energetically-favorable recombination of Si and O, the $SiCl_4$ precursor is quickly consumed and the deposition of silica occurs only on the first centimeters of the column. By modulating the microwave power to apply a variation of the column length, one can shift forward and backward the deposition area of silica to get a long deposit, made of thousands of nanoscale layers. The preforms are obtained by collapsing the SPCVD-made deposits using a glass lathe under an oxidant atmosphere. This process is suited to fabricate both passive and active fibers [15,16]. We describe in this section results obtained from a preliminary fluorine-doped single-mode fiber made from a SPCVD preform and drawn with a standard dual acrylate coating. Obtained optical properties are indicated in table II. This fiber contains respectively ~0.6wt% and ~2.2wt% of fluorine in the core and in the cladding.

TABLE II
OPTICAL CHARACTERISTICS OF TESTED SPCVD FIBER

parameter	measured value
core numerical aperture	0.12
attenuation@1.55µm	0.8 dB/km
cut-off wavelength	1280 nm
mode field diameter@1.55µm	8.0 µm

A sample of 70 m in length has been irradiated by ^{60}Co γ-rays at the IRSN IRMA facility, Saclay (France). Cumulated dose reaches 1 MGy(SiO_2) for a dose rate of 0.77 Gy/s, at room temperature. RIA at 1310nm, 1550 nm and 1625 nm are measured in-line using an OTDR (Optical Time Domain Reflectometer) from VIAVI Solutions for an injected power in the range of a few milliwatts. Figure 8 presents the obtained RIA dose dependences at the selected wavelengths.

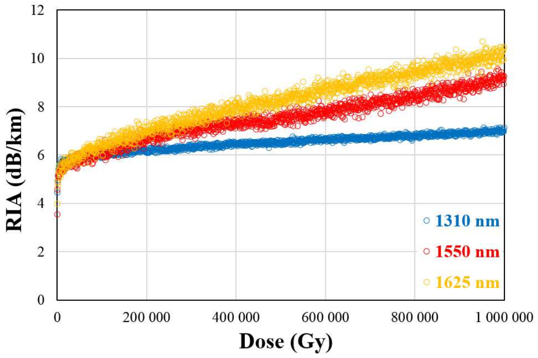

Fig. 8. RIA of SPCVD fiber sample at 1310 nm, 1550 nm and 1625 nm up to 1 MGy(SiO_2) at room temperature

Those results demonstrate a five-fold RIA reduction at 1 MGy(SiO_2) and room temperature for this fiber made by SPCVD process, as compared to the MCVD ones. This fiber exhibits performances comparable to state-of-the-art radiation tolerant single-mode fibers installed at CERN for data transmission applications [17].

V. CONCLUSION

Specific single-mode radiation hardened fibers have been investigated in the context of distributed sensing in large nuclear infrastructures. Radiation Induced Attenuation and fiber tensile strength have been evaluated after combined effect of radiation and temperature. Polyimide which presents the highest operating temperature among available polymer fiber coatings remains functional even after 1 MGy(SiO_2) at ~250 °C and 10 MGy(SiO_2) at ~100 °C. Only metal-coated fibers resist to higher temperature, but their sensitivity to micro-bending limit their use to short lengths. RIA measured for MCVD based fibers exhibits a rather low sensitivity to temperature at telecom wavelengths (~2 fold reduction between room temperature and ~250 °C) for a cumulated dose of 1 MGy(SiO_2). An alternative preform fabrication process, SPCVD, has demonstrated a promising potential, when combined with polyimide coating, to withstand radiation environments among the most severe encountered outside nuclear reactors. Photobleaching effect will be investigated to better estimate maximal sensing length in the case of specific interrogators that deliver a high optical power.

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VII. ACKNOWLEDGEMENT

The authors acknowledge Mrs Hortense Desjonqueres, Céline Monsanglant-Louvet and Carina Balland from IRSN (France) for their help in doing the combined temperature/radiation tests at IRMA facility as well as André Champavère and Alexandre Cebollada from VIAVI Solutions (France) for fruitful discussions on the RDTS instrumentation.