Optical absorption in commercial single mode optical fibres in a high energy physics radiation field

T. Wijnands, L.K. De Jonge, J. Kuhnhenn, S.K. Hoeffgen, *Member, IEEE,* U. Weinand

***Abstract*—This paper reports on the radiation induced attenuation of light at 1310 nm and 1550 nm in 12 commercially available single mode (SM) optical fibres. The fibres samples are exposed to gamma rays from a ^{60}Co source and to a high energy physics radiation field. The attenuation is studied as a function of total dose, dose rate, light power and temperature. Radiation resistant fibres from one manufacturer show an extraordinary low attenuation for light at 1310 nm that does not exceed 5 dB/km even after a total dose of 1 MGy. Some 3000 km of this type of fibre have been produced by the manufacturer and quality assurance measurements of the production batches are presently ongoing.**

***Index Terms*—Optical Fibres, Radiation Induced Attenuation, gamma rays, high energy radiation field, industrial production, quality assurance.**

I. INTRODUCTION

OPTICAL absorption in silica optical fibres has been studied in great detail over the last few decades and is usually attributed to intrinsic defects from interstitial and structural anomalies and to extrinsic defects from substitution impurities such as hydroxyl and chloride. An important difference between these two types of defects is that extrinsic anomalies can theoretically be entirely suppressed while intrinsic anomalies can only be reduced but never eliminated.

Since the 1970's the fibre manufacturing process has made enormous progress and it is now possible to produce ultrahigh-purity silica (OH and metal ion content below the ppb_w level). In addition, the transmission window has shifted to the long wavelength region (1310-1550 nm) where the loss spectrum of silica glass exhibits its minimum value. This has made it possible to produce high quality step index Single Mode fibres with an optical attenuation lower than 0.15 dB/km at 1550 nm [1] which is close to the theoretical (Rayleigh) limit of transparency. When silica fibres are exposed to radiation, additional defects are generated in the silica through trapping of holes or electrons at intrinsic precursor sites and by atomic displacements from the knock-on process [2] or the radiolysis process [3].

Extensive Electron Spin Resonance (ESR) spectrometry studies have allowed identifying various types of intrinsic paramagnetic defects in silica fibres which are E' centres [4], Non-Bridging-Oxygen-Hole-Centres (NBOHC) [5], the Peroxy Radical [6] and Self Trapped Holes [3]. Furthermore, Photo Luminescence (PL) measurements have demonstrated that some diamagnetic defects such as the Oxygen Deficiency Centre (ODC) may act as defect precursors for paramagnetic defects [7]. These colour defects have been associated with optical absorption bands at short wavelengths below 700 nm [8] and may already be generated during the fibre manufacturing process [9,10].

More recently, the influence of Hydrogen and Fluorine doping on the radiation hardness has been investigated. The Hydrogen should be minimized as it may eventually create an absorption band in the long wavelength region. Under irradiation, hydrogen can react with a NBOHC (denoted as $\equiv$Si-O· where the bar represents a chemical bond and the dot a dangling bond) to form an OH group ($\equiv \text{Si-O}\cdot + H_2 \rightarrow: \equiv \text{Si-OH} + H^o$). When the OH group in the fibre is increased in number, the optical absorption band at 1390 nm will increase [11]. Suitable Fluorine doping of the fibre core and cladding however can result in a higher radiation resistance in the long wavelength range as Fluorine decreases the glassy disorder and strains the Si-O bonds in silica [12].

Despite all the knowledge available in literature, it remains uncertain how a given radiation resistant SM fibre will behave in a radiation field from high energy physics. In order to address this matter, the radiation induced attenuation (RIA) in the long wavelength region of 12 SM fibre samples from various commercial manufacturers was measured with using gamma rays from a ^{60}Co source. A description of the experimental setups is given in section 3.

After the initial screening test described in section 4, the irradiation conditions were varied (wavelength, light power, dose, dose rate, temperature). Samples from the fibres with the lowest attenuation at 1310 and 1550 nm were then exposed to a high energy radiation field with particle energies up to 400 GeV. A qualitative interpretation of the experimental data is given in section 5.

II. REQUIREMENTS

For the application at hand, radiation hard SM optical fibres

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are required with a RIA that does not exceed 7 dB/km for light at 1310 nm after exposure to a total ionizing dose of 100 kGy in a radiation field from high energy physics. Although there is no direct interest in the attenuation at other wavelengths than 1310 nm, the RIA at 1550 nm was nevertheless considered because it may be of interest for future applications in which case it should remain of the same order of magnitude as the RIA at 1310 nm after 100 kGy. Only commercial fibre manufacturers with a sufficient production capacity were to be considered but the submission of production prototype samples was allowed. In total 5 of the 12 fibre samples were such development samples and are not considered further on.

The lead time for the entire operation (radiation studies, fibre manufacturing, fibre cable manufacturing, installation and commissioning) was 2 years. It was decided to allocate an entire year for the manufacturing of the fibre and fibre cable and to conduct these manufacturing activities in parallel. A period of approximately one year was available to collect samples from the manufacturers, perform the initial sample screening tests, the tests with parameter variation (wavelength, light power, temperature) and the radiation testing of the randomly chosen samples for the series production.

Final results on the RIA were then confirmed with a radiation test in a field from high energy physics. This test was considered as essential for various reasons. The first reason is that in a complex high energy physics field, radiation damage in silica fibres occurs simultaneously via the knock on process and the radiolysis process. Gamma rays from a ^{60}Co source generate mainly damage via the radiolysis effect but only a very small amount of displacement damage via secondary electrons [13]. Second, it has been reported [14,15,16] that the RIA in optical fibres from gamma rays can differ significantly from that induced by energetic neutrons. At the same total dose, the ratio of the induced loss from gamma rays and neutrons seems to change with the neutron fluence. When the displacement damage caused by neutrons becomes comparable to the initial defect concentration, the generation of new defects becomes the dominant effect and increase of loss with dose will be faster during neutron irradiation. For the (neutron dominated) high energy physics radiation field discussed here, the existence of such a "cross over" threshold fluence needs to be investigated. Finally, the RIA in silica fibres exposed to different types of particles at very high energies may lead to the formation of additional colour defects that have not been observed before and, given the importance of the application at hand, should not be excluded a priori.

III. EXPERIMENTAL

A. *Gamma ray irradiation facility*

All gamma irradiation tests have been carried out with a calibrated ^{60}Co source at Fraunhofer INT Institute (TK1000 Gammamat) in accordance with the IEC 60793-1-54 specifications [17] and at room temperature (24–28°C). The light from the laser diode light source (LD Profile 1310) is divided by a coupler to a reference and measurement channel (figure 1). The reference channel compensates possible drifts of the light source. The fibre samples are wound up on aluminium spools to assure homogenous irradiation by the point source in the centre of the spool. The light transmitted via the fibre samples and via the reference channel is measured with a high precision dual channel optical power meter (HP 8153). Lead tubes avoid the exposure of the fibre cables in the vicinity of the source.

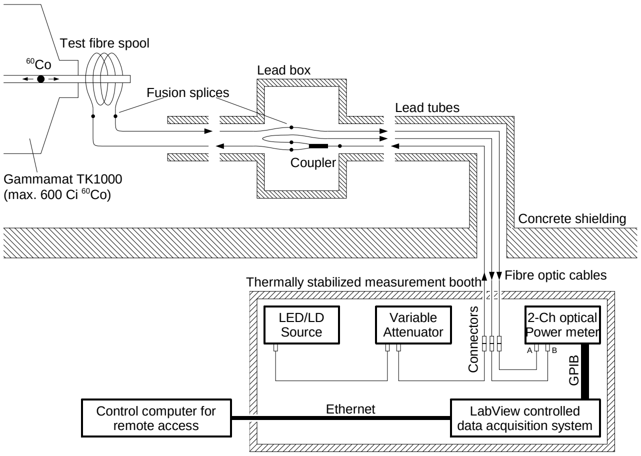

Fig. 1. Experimental setup at the ^{60}Co irradiation facility at Fraunhofer INT to measure RIA in various fibre samples on-line.

Before each irradiation, the system stability in terms of noise and drift is verified. During irradiation, the noise and drift observed via the reference channel was always below 1% of the total induced loss. By varying the length of the samples, the total induced loss after irradiation in each sample was kept between 2 and 5 dB. By limiting the total attenuation in the samples during irradiation, a good compromise is found between the signal to noise ratio in the measurements on the one hand and the light power of the measurement channel on the other to reduce photobleaching effects during the irradiation. It was later confirmed that none of the fibres investigated here showed a high sensitivity to photobleaching, see also section IV.

The total uncertainty in the optical absorption measurements presented here is estimated to be below 10% (not taking possible temperature effects into account).

B. *High energy physics radiation facility*

Irradiation of fibre samples in a high energy field were carried out in the radiation test facility of the Super Proton Synchrotron (SPS) at CERN, the European Laboratory for Particle Physics. In the SPS, fixed target beams are accelerated from 14 GeV/c to 450 GeV/c in 3 seconds and then dumped on various primary targets during a 5 second long extraction procedure. This process is repeated every 14.4 seconds 24 hours per day and 7 days per week. The high energy protons cause harmonic showers in the targets which create a pulsed radiation field in the test facility situated behind one of the primary targets. During normal operation, the averaged dose rate in the area is 5 Gy/d at the position of the samples up to the total dose of 512 Gy. Later the samples were moved closer to the target and the mean dose rate reached 23 Gy/d[†]. The radiation spectrum [18, 19] in the area is neutron dominated and the maximum neutron energy can reach several GeVs (figure 2). Apart from neutrons, the Electro Magnetic (EM) showers of the incoming high energy protons also lead to the production of lower energy protons, kaons, pions, electrons, muons and gamma rays at various energies.

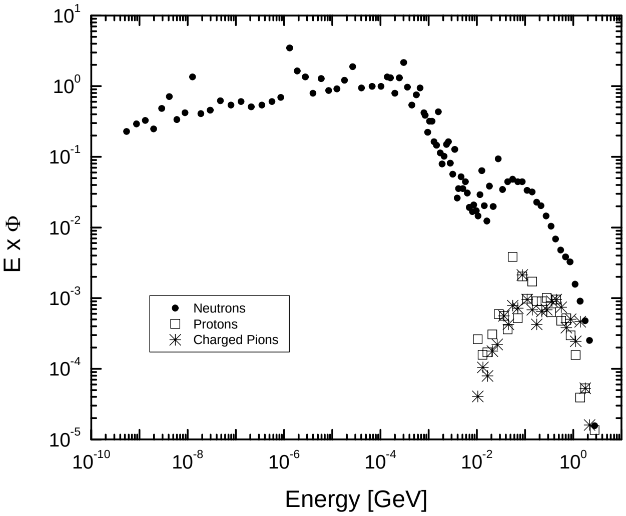

Fig. 2. Lethargy plot of the energy spectrum in the high energy radiation test facility at CERN. Normalization is to 100 keV neutrons.

The dose rate at the fibre samples in this facility is measured on line with various types of ionization chambers [20] and a remote radiation monitoring system using Radiation Sensing Mosfets (RADFETs©) [21].

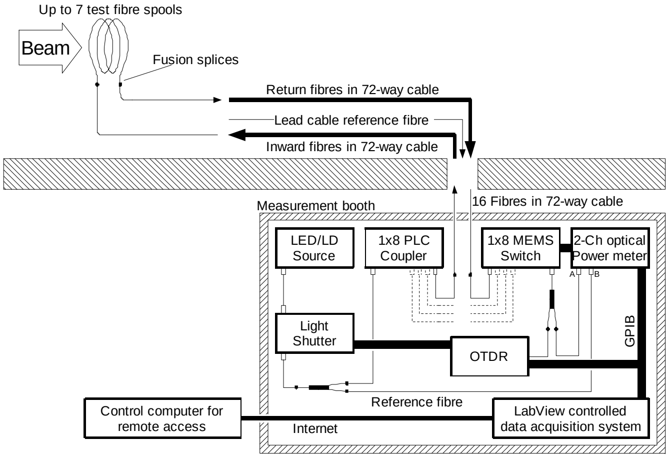

Fig. 3. Experimental setup to measure RIA in various fibre samples on-line. (high energy radiation field of the Super proton Synchrotron at CERN)

Two independent systems were used to measure the RIA in the fibre samples on line during the irradiation test (figure 3). The first system is based on a planar wave guide system to distribute light of a very stable LED light source with cable leads to the fibre samples in the irradiation zone. The light is guided back and multiplexed with a high precision micro-electro-mechanical switch to an optical power meter.

The second system is using a direct measurement with an Optical Time Domain Reflectometer (OTDR) connected to the same micro-electro-mechanical switch. A second independent measurement was needed as a back-up solution to assure a reliable long term loss measurement.

During the test, all components of the test setup are shielded from EM radiation and operated at a constant temperature.

IV. RESULTS

A. Sample screening test (^{60}Co source)

Thirteen commercial companies were contacted and invited to participate in the radiation screening. Each manufacturer was given the specific details of the radiation tests and confirmed that large quantities of fibre could be delivered if required. Eventually 7 fibre samples from 6 different manufacturers were used in the screening test: three Ge-doped silica fibres, two Pure Silica Core (PSC) fibres, one F-doped fibre and one sample for which no information on the composition was given by the manufacturer. These fibres have similar optical attenuation for light at 1310 nm before irradiation. Exemplarily figure 4 shows the intrinsic attenuation of the F-doped fibre.

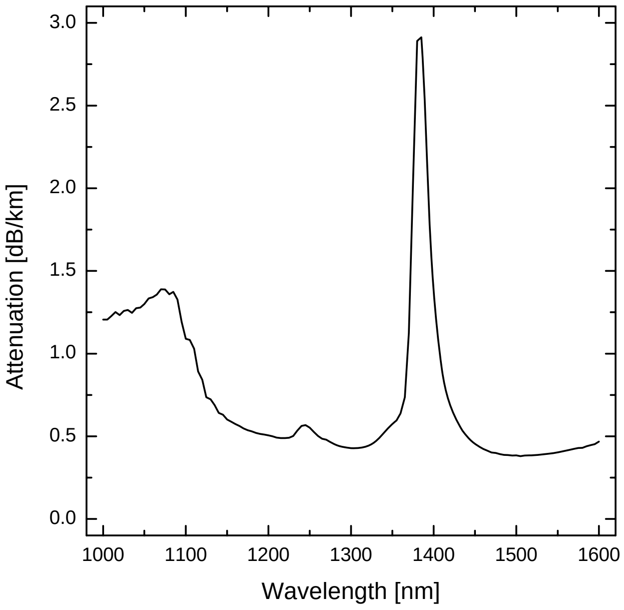

Fig. 4. Attenuation spectrum of the un-irradiated F-doped SM core fibre.

All samples were exposed to γ rays under near identical experimental conditions: wavelength 1310 nm, total dose: 10 kGy, dose rate: 0.2 Gy/s, temperature: 24 to 28°C and light power: 10 µW. Only for one specific sample, the light power was increased from 10 µW to 40 µW to improve the stability of the measurement chain. It was later verified experimentally that photo bleaching effects in this specific fibre sample are negligible and that the variation of light power at 1310 nm had no influence on the measurements. The sample length varied between 50 and 200 m.

[†] Throughout this paper Gy means Gy(SiO_2).

Figure 5 shows the induced loss in dB/km as a function of the total dose for each of the fibre samples. The Ge-doped fibres show the highest induced losses, as expected. There is remarkable difference in performance amongst the Ge-doped fibres from the various manufacturers and the RIA varies by as much as 40% in agreement with similar studies [22].

The PSC fibres show significantly lower losses at the same dose which is also in agreement with previous experimental observations [23]. The performance of the fibre with the unknown composition is considerably better compared to the PSC fibre samples, reaching 10 dB/km after a total dose of 10 kGy. At this stage however, there is no sign of saturation of the RIA.

The F-doped fibre sample has an entirely different behaviour. The loss rapidly saturates in the early stage of irradiation at approximately 2 dB/km which is a remarkably low value in comparison with the other fibre samples.

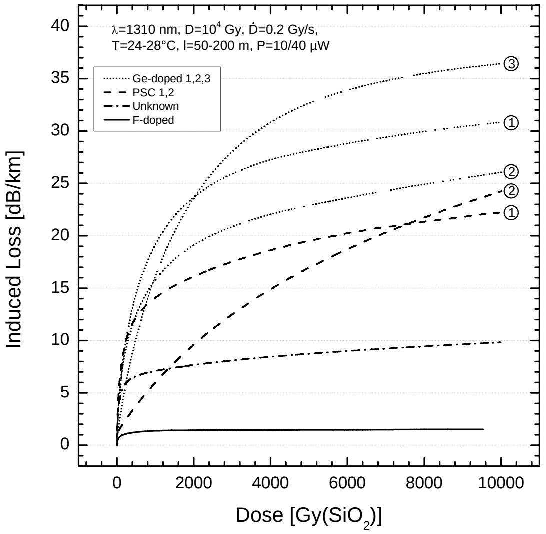

Fig. 5. RIA the initial sample screening test (^{60}Co source).

The annealing relative to the final induced loss of the fibre samples at room temperature is shown in figure 6 for a period up to 100 000 seconds after the end of the ^{60}Co irradiation. In the Ge-doped and the PSC fibres, a large fraction of the radiation induced losses anneal out. This provides no substantial gain however, because the attenuation rapidly attains the value before annealing once irradiation is restarted (memory effect). This has also been experimentally confirmed.

The annealing behaviour in the F-doped fibre is very different from that observed in the other fibre samples. Immediately after the irradiation is stopped, the F-doped fibre exhibits the fastest annealing rate, annealing nearly 20% of the total loss in only a few seconds. The annealing is so fast that only 2 data points could be recorded which explains the discontinuity in the annealing curve in figure 6. After 100 seconds, the RIA does not reduce any further. Eventually, only 25% of the loss in the F-doped anneals out at room temperature. In the other fibre samples, at least 35% of the RIA anneals out after 100 000 seconds.

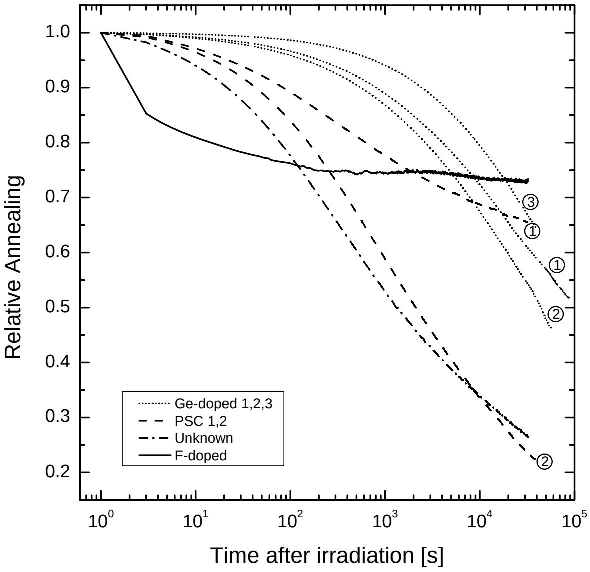

Fig. 6. Annealing (normalized) of the RIA after gamma ray irradiation

B. *Variation of irradiation conditions (^{60}Co source)*

The impact of a variation of the wavelength, light power, temperature and dose rate on the RIA was investigated for the best performing Ge-doped fibre (figure 7) and for the F-doped fibre (figure 8). The F-doped fibre was selected because it exhibited the best performance in the initial screening test. The reason for equally investigating the Ge-doped SM fibre is that this fibre is extensively used for other applications [24]. This fibre is a standard SM communication fibre produced by Draka Comteq Optical Fibre BV in the Netherlands.

The dependence of the loss on wavelength, temperature and light power was investigated because it is of interest for future applications that may use the same fibre infrastructure. For the application at hand here, however, all these parameters are fixed and not subject to any change.

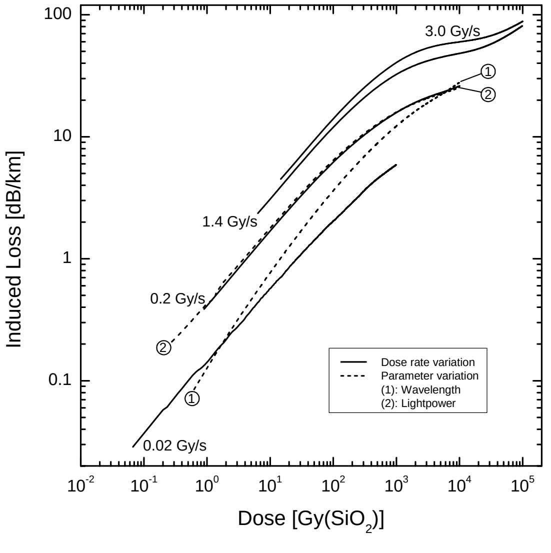

Fig. 7. Dependence of the RIA on irradiation conditions (Ge-doped fibre)

The dose rate dependence of the loss at 1310 nm is of particular importance as it allows scaling the experimental results from the test facilities to the final application.

For both the Ge-doped and the F-doped fibre sample, the dose rate has a large impact on the total RIA for a given dose while the influence of temperature, wavelength and light power is at most a few percent.

The impact of the dose rate on the RIA at a given dose has been investigated in detail in [25] for the Ge-doped fibres. The relaxation of the Ge-doped fibre presented here indeed follows the same 'universal' power law for diffusion controlled reactions from random distributions in the transport parameters that govern transport in disordered solids such as silica.

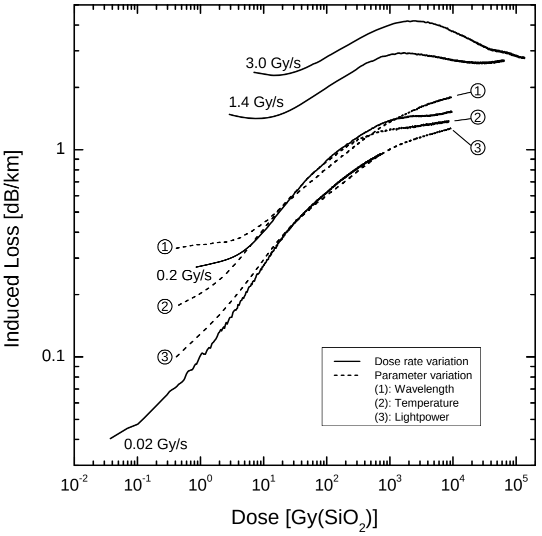

Fig. 8. Dependence of the RIA on irradiation conditions (F-doped fibre)

The behaviour of the F-doped fibre under varying irradiation conditions is again very different compared to the Ge-doped fibre. The loss seems to converge to the same value of approximately 2 dB/km independent of the irradiation condition. This indicates that the radiation effects in the F-doped fibre are belonging to another class in which hierarchically limited dynamics lead to correlated relaxation processes that consist of several steps [25]. The observed overall behaviour is the ensemble of several relaxation processes, each with their proper relaxation constants.

C. *Exposure to a high energy radiation field*

Figure 9 shows the induced losses in the Ge-doped fibre, the fibre with an unknown core composition and in the F-doped fibre as a function of the total dose in the high energy physics radiation field (see section III). The data was accumulated in a total time span of 1.5 years. The occasional annealing in the loss curves is due to stops of the accelerator for maintenance or repairs. After a total dose of approximately 500 Gy, the accelerator was shut down for a period of 6 months and the samples were moved closer to the target.

The induced losses in the high energy physics radiation field show a similar evolution as function of the total dose as observed during the ^{60}Co irradiation. This is in contrast to the observations in [16] where the permanent loss from neutron irradiation in SM F-doped fibres was found to be larger compared to gamma ray irradiation. The losses in the F-doped fibre are very little influenced by annealing. The F-doped fibre shows the same saturating behaviour as observed during ^{60}Co irradiation tests in which a saturated value of approximately 1 dB/km was reached.

The period of annealing around 500 Gy is clearly visible for the fibre with the unknown core composition and that with a Ge-doped core, whereas the F-doped fibre does not show any annealing in this scale. For all samples the attenuation quickly reaches again the previous levels.

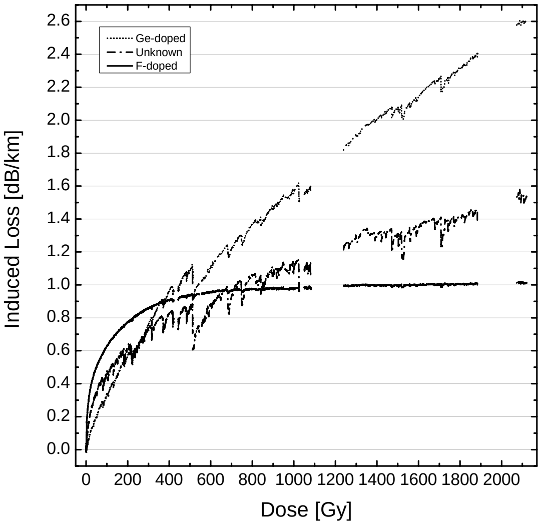

Fig. 9. RIA of the fibre samples in a high energy physics radiation field.

In figure 10, the RIA attenuation in the Ge-doped fibre and the F-doped fibre in a high energy physics radiation field (dose rate 5 Gy/d up to 512 Gy, thereafter 23 Gy/d) is compared to that observed during ^{60}Co irradiation (dose 1.8 kGy/d).

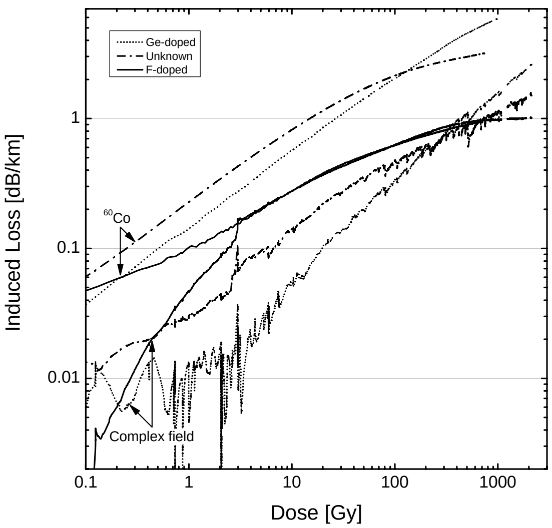

Fig. 10. Comparison of the RIA from gamma rays (1.8 kGy/d) and from a high energy physics radiation field (5 Gy/d)

For the Ge-doped fibre, the difference in absolute attenuation can be explained by the difference in dose rate between the two experimental environments. After the initial onset of the loss, the attenuation in the F-doped fibre is again converging to the same saturated value of approximately 1 dB/km, independent of the dose rate and the total dose.

The remarkable fluctuations around 3 Gy are due to a period of very high dose rate that led to the rapid increase of the induced loss for the F-doped fibre as already observed in the ^{60}Co irradiations.

V. DISCUSSION

The F-doped SM optical fibre from Fujikura Ltd Japan presented here exhibits a very unusual behaviour under irradiation as compared to the standard Ge-doped communication fibres and the PSC fibre samples. The RIA in this fibre for light at 1310 nm saturates after a total dose of approximately 1 kGy and does not exceed 5 dB/km for light at 1310 nm.

Both the loss and the annealing data are suggesting that hierarchically ordered transport processes dominate in the early stages of irradiation and annealing. Although details of the manufacturing process have to remain confidential, it is evident that the manufacturing process for the F-doped fibre has been optimized to reduce the presence of drawing induced defects in the first place. The rapid increase of the attenuation that is observed at low total doses may therefore correspond to the population of initial defects generated by the manufacturing process. In this case, the unusual annealing behaviour would be explained by a rapid depopulation of the defects in the first few seconds after the irradiation.

At higher doses, no additional absorption bands in the long wavelength region have been observed in the F-doped fibre. It was experimentally observed that the saturated loss in the F-doped fibre is strongly influenced by the OH content of the pristine fibre. The lower the OH content, the lower the value of the saturated loss. Furthermore, the doping concentration of the core and cladding plays an important role, perhaps by inhibiting the growth of the overtone and combination bands from the residual OH that is dominant at longer wavelengths. A microprobe analysis of the fibre indeed revealed a low concentration of F in the fibre core and very high concentration of F in the fibre cladding. A complete spectral attenuation study could make this issue more precise.

No significant differences between the RIA from gamma rays or from a high energy physics radiation field have been observed. In particular, the existence of a fluence threshold, after which neutron irradiation will cause a higher loss as compared to gamma rays, was not observed. We also conclude that the dominant radiation effect for optical loss in a high energy physics radiation field is the radiolysis effect and that displacement damage effects play a minor role. Finally, the various high energy physics particles at very high energies (GeV range) do not create new defects that cause absorption bands in the long wavelength region between 1300 and 1550 nm.

However, it should be noted that these results are currently only based on the data obtained up to a dose of 2000 Gy.

VI. CONCLUSION

A comprehensive survey of the radiation tolerance of present day commercially available SM optical fibres has been conducted. The F-doped radiation resistant SM fibre from Fujikura Ltd. shows exceptionally good radiation tolerance under gamma radiation and in a high energy physics radiation field. This fibre fully meets the specifications outlined in section 2 and recently, the production of 2500 fibre kilometres has been completed.

The behaviour of the fibre under irradiation was studied under various irradiation conditions using measurements of the attenuation of light. In all cases, a saturating loss curve was observed with a final value less then 5 dB/km in line with the specifications. The measurements presented here do not allow a complete understanding of the underlying mechanisms but it was experimentally observed that the manufacturing conditions, the doping concentrations and the OH content are amongst key factors. A complete spectrum analysis combined with a Photoluminescence and ESR measurements could perhaps make the understanding of the underlying radiation effects more complete.

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Sumitomo.

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