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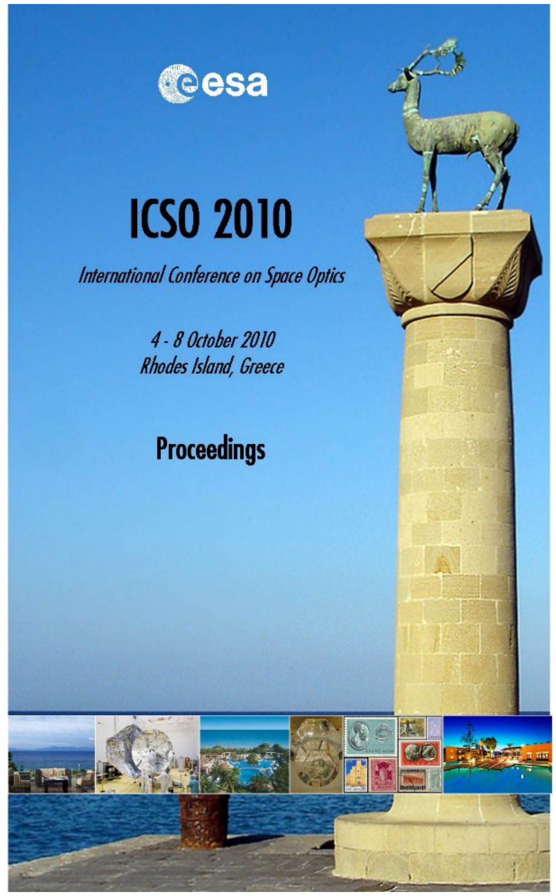

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EXPERIMENTAL DEMONSTRATION OF THE SWITCHING DOSE-RATE METHOD ON DOPED OPTICAL FIBERS

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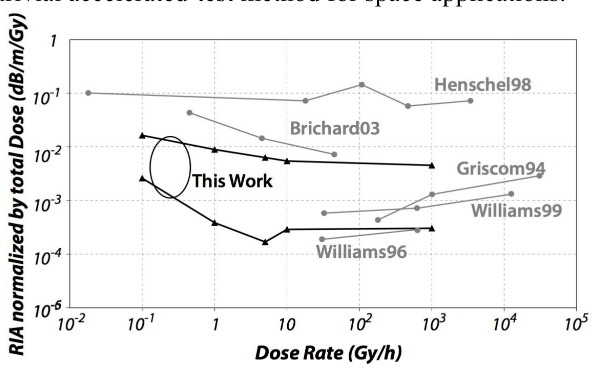
I. INTRODUCTION

Optical technology developed for ground and submarine telecommunications is becoming of strong interest for next generation satellites. In addition to inter-satellite laser communications and LIDAR's, new applications are being considered such as on-board distribution and processing of microwave signals, fiber sensors or gyroscopes as well. Whereas common optical / optoelectronic components are known to be weakly sensitive to radiations, the essential optical amplifiers are strongly degraded in such an environment because of the RIA (Radio-Induced-Absorption) experienced by the Erbium-Doped Fiber (EDF) itself [1-3]. This degradation is mainly caused by the presence of co-doping ions, such as Aluminium or Germanium, inserted in the fibre to assist the inclusion of the Erbium ions in the silica matrix or to provide to the optical fibre its guiding properties.

II. UNDOPED AND DOPED OPTICAL FIBERS DEGRADATION

Previous works [1-3] demonstrate that the doped optical fiber degradation versus the total dose follows a piecewise classical power-law, i.e. the same well-known law already experienced with non-Erbium-doped optical fibers [4,5]. In the above-mentioned works, the degradation always increases as a function of the dose-rate at which the experiments are performed. This behavior is in good agreement with the power-law, and no other kind of tendency can be predicted while using this law. Such a trend is interesting for practical purposes, because, on the one hand, the space environment is a very low dose rate radiation source (~3mGy/h) and, on the other hand, a space mission lasts a long time (>15 years): the degradation resulting from a space-mission total dose (~450Gy) at a high dose rate can thus be considered as a worst-case, and such an observation defines a trivial accelerated-test method for space applications.



- Henschel98[7]: La-doped, λ=1312nm, Dose = 100Gy
- Brichard03[8]: Er-doped, λ=1590nm, Dose = 50Gy
- Griscom94[4]: Ge-doped, λ=1300nm, Dose = 100Gy
- Williams96[5] Er-doped, λ=1550nm, Dose = 1000Gy
- Williams99[6] Er-doped, λ=1350nm$, Dose = 100Gy
- This Work : Er-doped, λ=1550nm, Dose = 300Gy, for the most and the less deteriorated fibers.

Fig. 1. *RIA normalized by the total dose versus the dose rate for many results reported by both the literature and this work. For this work, we only display the results obtained with the most and the less degraded fibres.*

In contrast to these results, this work, as well as previous works[8,9] exhibit an enhanced low-dose-rate sensitivity (called "ELDRS") to radiations. However such a response to the dose-rate has never been explained in doped and undoped optical fibers. In this paper, 5 Erbium Doped Fibers were tested, each fiber being different in terms of Erbium concentrations and co-doping atom concentrations (0<Al<6%(wt), 0.5<Ge<25%(wt), 0<P<0.5%(wt)) ; all the fibers under test exhibit increasing Radio-Induced Absorption (RIA) with decreasing dose rates, in a range from 10^{-1}Gy/h to 10^{-3}Gy/h, at the two main interesting wavelengths (980nm and 1550nm). The results for both the most and the less sensitive fibers are given in fig. 1. The ELDRS does not suggest any intuitive quick test method for doped optical fiber, and a priori supposes a real-time (15 years) test for doped fiber assessment for a real space mission. This problem is however well-known in bipolar transistors for which the increasing degradation at low-dose rate is mainly due to passivation oxides[10]. For these devices, a short-time test method - the Switching Dose Rate Method - has been developed. In this paper, experiments are performed to check the validity of this method once it is applied to optical fibers.

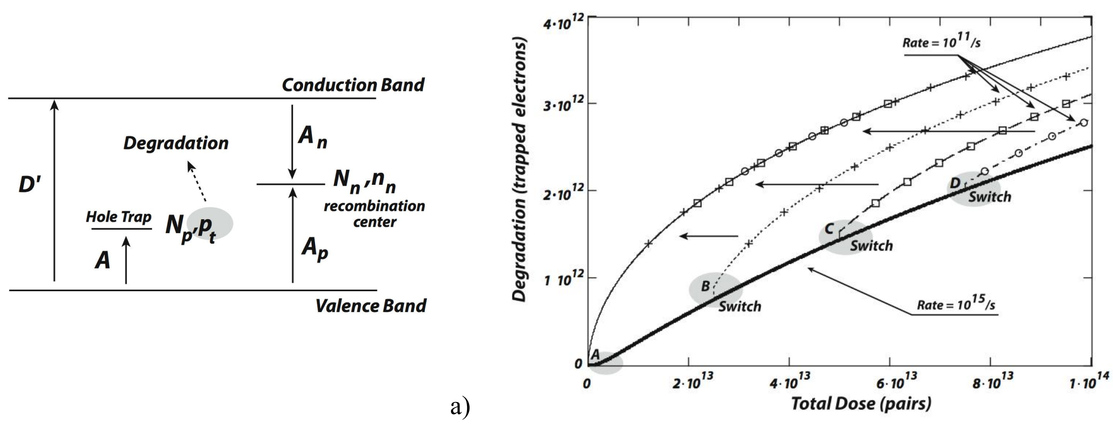
III. ENHANCED LOW-DOSE-RATE SENSITIVITY THEORY

Many models, based on quite different physical bases, can predict ELDRS and lead to similar degradation tendencies versus the dose rate[10,11,12]. Therefore, we use in this paper the historical R. Chen's model[10] as a simple theoretical base. This model consists in a 4 energy-level system (fig. 2.a), taking into account valence and conduction bands, an electron-trap population at a given energy level, and a recombination-center population inside the material's gap. Because of the involved transition probabilities, the trap and the recombination center populations are coupled by way of the conduction band[10]. This coupling is the point that makes this model different to the classical power-law models, that consider only independent traps. Numerical experiments using Chen's equations can exhibit a degradation increase while the dose rate decreases[10], depending on the *chosen* transition rates and trap populations. Usually, the values injected into the model do not require to make physical sense and are chosen to demonstrate the possibility to reach increasing or decreasing degradations as a function of the dose rate. ELDRS can thus find an interpretation in the coupling between traps inside the gap. Following this approach, it is however very difficult to obtain quantitative simulation values that could be compared with experimental results on the optical *fiber*, because an optical-fiber degradation is physically due to many traps [13] which associated time-constants must be obtained separately. In spite of that, this simple model is still adequate to justify the switching-dose rate method, as well as other models do[10,12].

IV. THE SWITCHING DOSE-RATE METHOD

A. Elementary Principles

The switching dose-rate method can be well illustrated thanks to R. Chen's model. In this model, the degradation is exclusively given by the amount of trapped carriers. Thus, regarding the trap-level, there is no kind of "memory effect" that indicates the path that was followed to reach a given degradation state. Thereby, starting a new experiment at another dose-rate from a specific degradation state will not have any impact on the degradation dynamics. In other words, any degradation state can be quickly reached at high dose rate, then switching to the targeted low-dose-rate allows the study of the degradation kinetics at high degradation level: that's the main principle of the switching-dose-rate method. We performed a numerical experiment based on R. Chen's model to predict such a behavior (fig. 2.b) with arbitrary parameters. We apply two dose-rates: one high, 10^{15}/s and one low 10^{11}/s. We switch from the highest rate to the lowest one at the points B, C and D and observe the resulting degradation dynamics at low dose-rate. As expected, we notice that the low-dose rate dynamics is maintained after switching. Thus, performing simple horizontal translations of the low-dose rate curves issued from points B, C and D allows us to describe the overall low-dose rate curve starting at point A. That's the confirmation that the degradation dynamics at a fixed dose-rate stays unchanged whatever the path that allowed to reach a given degradation state. That last point permits to define the switching-dose-rate method as an accelerated test method.



a) b)

Fig. 2. *a) Chen's Model b) Numerical Switching Dose-Rate Experiment built thanks to Chen's Model*

B. General Protocol and Experiments

We established that once a switch is performed, we can study the degradation dynamics at low-dose-rate. However, we don't know the total dose necessary to reach this degradation state at the low-dose-rate, because this degradation was obtained at high-dose-rate. That's why we have to perform many experiments at low-dose rate - thus many switching operations - to rebuild the whole degradation curve. Although, if we use some optical fiber samples instead of a single one, all the low-dose-rate steps can be performed with a strong temporal overlap: that's why the switching-dose-rate method saves a lot of time. This principle is illustrated in fig. 3, considering a simple linear RIA evolution versus the total dose whatever the dose-rate, and 4 pieces from the same optical fiber. This figure demonstrates that the total-time necessary to rebuild the low-dose-rate degradation is simply given by time elapsed during the high-dose-rate experiment, augmented by the time consumed in a single low-dose-rate step. Thus, using a lot of samples allows decreasing the total irradiation time by strong factors.

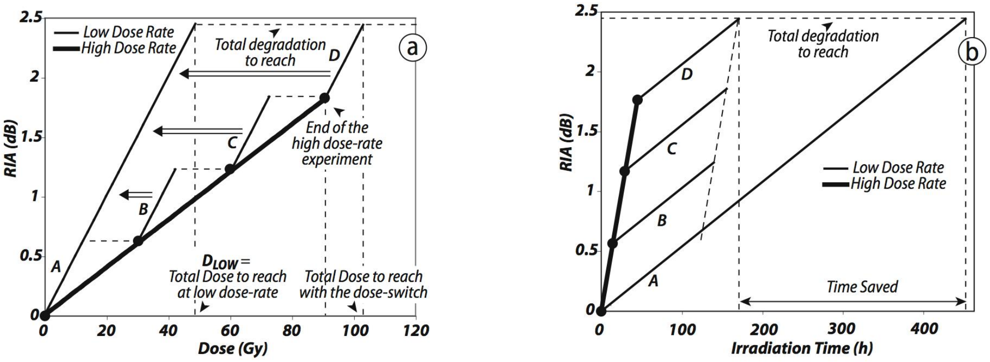
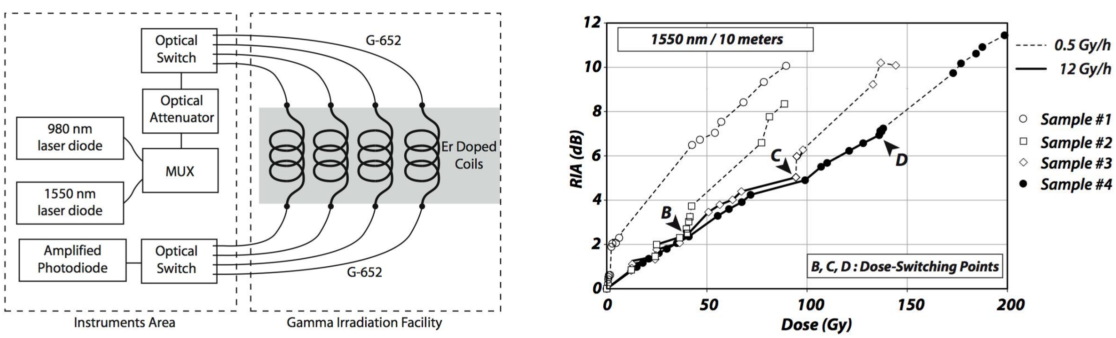


Fig. 3. Building the low-dose-rate degradation from switching-dose-rate experiments. a) switching dose-rate experiment vs the total dose. b) switching-dose-rate experiment vs the irradiation time.

The switching-dose rate method was performed on the most radiation-sensitive Erbium-Doped fiber from the 5 optical fibers that we tested, in order to reach the best measurement dynamics and low measurements error. We decided to use 4 ten-meters-long samples from this Er-doped fiber. As displayed in fig. 4.a, the experimental set-up is made of two distinct parts. The first part is the gamma irradiation facility: The dose-rate experiments were performed at the SCK-CEN (Belgium) with the RITA equipment, which provides gamma radiations. The chosen dose-rates have been calibrated with a dosimeter to be12Gy/h for the highest one and 0.5Gy/h for the lowest one. The second part is the instruments area: This area is made of 2 laser sources, one at the signal wavelength (1550nm) and the other one at the pump wavelength (980nm). After the MUX, each laser light passes through an optical attenuator in order to ensure that the measurements are always performed under the saturation power (a few µW) for each wavelength[14]. Because we work under the saturation power, and because of the effect of the RIA, an amplified ultra-low dark-current photodetector system (at pW level) is necessary. A set of optical switches allows obtaining automatic and accurate measurements.



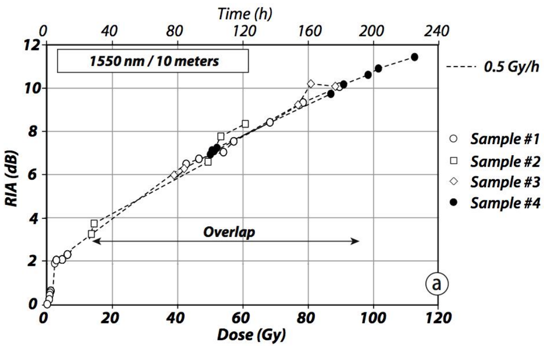
a) b)

Fig. 4. a) Experimental "in-line" set-up. b) RIA versus the dose deposit for each of the 4 samples at 1550nm. Sample #1 was irradiated at low-dose-rate during the whole experiment. Samples #2, #3 and #4 were respectively switched from high-dose-rate to low-dose-rate at respectively points B, C and D.

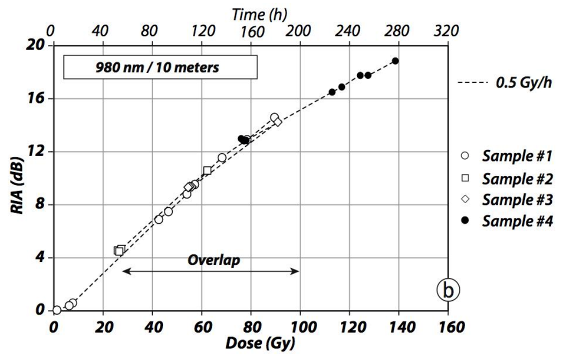
All the measurements were made "in-line", i.e. the RIA were measured during the irradiations. The coils of Er-doped fibers are linked with the instruments thanks to a set of 30m-long G-652 optical fibers, which RIA - that never exceeds some tens of dB/km[13] - can be neglected regarding degradation level of Er-doped fibers, which values are estimated in dB/m. The lasers are only biased during the measurements themselves and not throughout the whole irradiation, and thus no photobleaching effect has to be considered with our measurements.

C. Results

The results obtained thanks to this set-up are presented in fig. 4.b at 1550nm. Similar results were obtained at 980nm but are not displayed in this short paper. The dose-rate-switches performed at points B, C and D exhibit, as expected by R. Chen's model, a change in the degradation dynamics after a transient regime, with a stronger degradation slope at low-dose-rate than at high-dose-rate. Moreover, we can mention that the RIA at pump wavelength is much higher than at the signal wavelength. Such a consideration is well-known in literature, and is due to the fact that the energy of the traps responsible for the RIA in optical fibers are generally located at energies stronger than 2eV, leading to wide absorption bands centered at short wavelengths (UV and visible)[13,15]. We rearranged these results to build the whole low-dose-rate curve, by performing horizontal translations and matching the degradation values in the regions that exhibit a degradation overlap. The result of this process is given in fig. 5. The fact that the different low-dose-rate curves are superimposed over a wide range is the experimental proof that the switching dose-rate can be applied as an accelerated-test method for the assessment of optical fibers that present an ELDRS.



a)



b)

Fig. 5. *Degradation kintetics at low-dose-rate, obtained from the switching dose rate experiments at 1550nm (a) and 980nm (b)*

V. CONCLUSION

Our experimental results confirm the ELDRS that was already observed in [8] on Erbium-Doped optical fibers. Such a behavior is critical for potential space applications that rely on optical amplification, and must be accurately studied before embedding such optical fibers in spacecraft systems. Inspired by previous works performed on bipolar transistors and owing to the results obtained thanks to R. Chen's model, we developed an accelerated test method dedicated to optical fibers. This new method validity was confirmed thanks to experimental results.

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