Temperature Influence on the Radiation Responses of Erbium-Doped Fiber Amplifiers

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The gain degradations of an Er-doped fiber amplifier (EDFA) during the exposure of its active Er-doped fiber to 40 keV X-rays ($\approx 2.7 \text{ mrad(SiO}_2\text{)} \text{s}^{-1}$ up to 300 krad) at three different temperatures: $-40$, $25$, and $120 \degree C$, are characterized. The spectral dependence of the fiber radiation-induced attenuation (RIA) is monitored in situ in the 900–1600 nm spectral range, highlighting a combined temperature and radiation effect on the near-infrared RIA levels and kinetics. At the system level, the kinetics of EDFA gain degradation are only slightly affected by varying the irradiation temperature for the tested backward pumping EDFA configuration. On the theoretical side, a homemade computer code based on the particle swarm optimization and the rate equations to model the radiation behavior of EDFA is used, considering only the RIA impact on its gain. Despite a good agreement between experimental and simulation results below the dose of 70 krad corresponding to current space missions, the comparison between the modeled and measured gain degradation kinetics at higher doses shows that a more precise modeling of the temperature impact on the absorption properties of the erbium ions is necessary to better reproduce the EDFA radiation behavior for future space missions.

1. Introduction

After having revolutionized the telecommunications, optical amplifiers and lasers exploiting the unique properties of rare-earth-doped fibers (REDFs) are today deeply evaluated for space applications. Indeed, these fibers are key elements of amplifiers or laser sources to be implemented in light detection and ranging (LIDAR) systems, inertial navigation systems, or to enhance the intersatellite and satellite–Earth optical communication links. Space environment is associated to both radiations and temperature constraints to which spacecrafts have to survive. Usually, the considered temperature of those devices ranges from $-40$ to $80 \degree C$ but for some of the targeted future space missions, variations from $-200$ to $300 \degree C$ are expected at the satellite level and may lead to more severe constraints. Telecom-grade erbium-doped fiber amplifiers (EDFAs) are very radiation sensitive and they exhibit gain degradation increasing quickly with the deposited dose. This high vulnerability is mainly explained by the radiation response of the active REDF. Its radiation sensitivity is rather explained by the degradation of their host-glass silica matrix than by the rare-earth ions themselves. For example, the core silica of erbium-doped fibers (EDFs) is generally codoped with aluminum to avoid the rare-earth ions quenching phenomena. It is today well established that radiation-induced attenuation (RIA) associated to Al-related defects is very high in the spectral domains of interest for the pump and signal transmissions. It has been proved that the RIA at the pump and signal wavelengths mainly explains the gain degradation of the REDF amplifiers at low doses ($<100 \text{ krad}$). Several techniques have then been applied to enhance the fiber radiation resistance such as codoping the fiber core with cerium or loading the fiber with H$_2$ or D$_2$ gas. These hardening techniques at the material levels are based on the passivation of the Al-related defects by the H$_2$ or D$_2$ gas or on favoring the competition between radiation-induced defects to lower the RIA at the operating wavelengths. It is also possible to improve the radiation tolerance acting at the component level with appropriate fiber designs. Both radiations and temperature are known to impact the rare earth doped fiber amplifier (REDFA) properties and then it is very important to investigate how these two parameters will act when both...
constraints are simultaneously applied. Some studies on passive (without rare-earth doping) fibers show that the irradiation temperature strongly influences the RIA kinetics and levels.\cite{11,12,13} Regarding active fibers, we previously observed that combined temperature and radiation does not strongly influence the gain radiation responses of EDFAs in the temperature range between \(-40 \, ^\circ\text{C}\) and \(120 \, ^\circ\text{C}\) and in the dose range up to 300 krad(SiO\(_2\)).\cite{14}

Taking into consideration the RIA impact on the amplifier gain efficiency, a preliminary estimation of the performance degradation of such devices and the consideration of mitigation techniques are mandatory to be able to design an optimized instrument for the space mission whether in terms of its holding power or its longevity. A modeling code has then been developed\cite{15,16,17,18,19} basing on the particle swarm optimization (PSO) algorithm to predict the amplifier performance as well as to help in the design of dedicated radiation-hardened REDFA architectures for future space missions. This simulation tool requires knowledge about the spectroscopic properties of the EDF (erbium concentration, refractive index profile, fiber geometry, etc.) as well as the amplifier parameters (pump and signal powers, length, pumping scheme, etc.). The numerical code implements the most relevant active phenomena in rare-earth-doped systems and provides the gain of the selected amplifier architecture. Moreover, it enables the recovering of most relevant spectroscopic parameters. In the current version of the code, the radiation effects are included by considering the RIA values at the pump and signal wavelengths, measured during dedicated experimental tests. We showed that this approach was sufficient to correctly reproduce the gain degradation kinetics at room temperature, e.g., for erbium–ytterbium codoped fiber amplifiers.\cite{3} In the case of E DFA, the problem is more complex as the RIA level is more affected by the photobleaching phenomenon,\cite{18,19} making more difficult a correct evaluation of the RIA at the pump and signal wavelengths. On the basis of this knowledge and with the aim to extend the code capabilities, in this article, we compare the simulated and measured gain degradations of an E DFA as a function of the deposited dose, up to 300 krad, and at different irradiation temperatures.

2. Theoretical Model of Simulation

2.1. The Model Equations

A detailed description of the EDFA model used in this work can be found\cite{15,16,20,21,22,23}\(^\dagger\) its validity was assessed by benchmarking theoretical and experimental results. The model is based on rate equations, and the schematic energy levels diagram used in our calculation is shown in Figure 1.

This model includes the effects of 975 nm pump signal, stimulated emission and absorption of the input signals, amplified spontaneous emission (ASE) noise, uniform cooperative up-conversion, and cross-relaxation processes between a pair of neighboring Er\(^{3+}\) ions. In particular, the population-rate equations and conservation laws can be written as

\[
\frac{dN_i}{dt} = W_{121}N_1 - W_{212}N_2 + W_{131}N_1 + W_{312}N_3 + \frac{N_j}{\tau_{21}}
\]

\[
+ C_{up}N_2^2 + C_4N_4^2 - C_{14}N_1N_4
\]  

\[
(1)
\]

\[
\frac{dN_2}{dt} = W_{122}N_1 - W_{212}N_2 + A_{123}N_3 - \frac{N_2}{\tau_{21}} - 2C_{up}N_2^2 + 2C_{14}N_1N_4
\]  

\[
(2)
\]

\[
\frac{dN_3}{dt} = W_{133}N_1 - W_{313}N_3 + A_{134}N_4 - 2C_3N_3^2
\]  

\[
(3)
\]

\[
\frac{dN_4}{dt} = -A_{345}N_4 + C_{up}N_2^2 + C_4N_4^2 - C_{14}N_1N_4
\]  

\[
(4)
\]

\[\sum_{i=1}^{4} N_i = N_{Er}\]  

\[
(5)
\]

In these equations, \(N_i\) is the population density of Er\(^{3+}\) ions at the \(i\)-th energy level, \(\tau_{21}\) is the spontaneous emission lifetime for \(^4I_{13/2}\) manifold, \(N_{Er}\) is the total concentration of Er\(^{3+}\) ions, \(A_{ij}\) and \(A_{ij}\) are the nonradiative transition rates, \(W_{ij}\) terms represent the stimulated transition rates between the \(i\) and \(j\) levels, \(C_{up}\), \(C_3\), and \(C_{14}\) are the homogeneous up conversion and cross-relaxation coefficients, respectively. We assume here that the total distribution of Er\(^{3+}\) ions is homogeneous within the whole fiber core cross section and along the fiber length as well as it satisfies the conservation Equation (5). The forward (+) or backward (−) propagation of the pump power along the fiber can be calculated by solving the following differential equation\cite{22,23}

\[
\frac{dP_p(z)}{dz} = \pm\Gamma(\nu_p)[N_3\sigma_p(\nu_p) - N_1\sigma_a(\nu_p) -\alpha(\nu_p)]P_p^0(z)
\]  

\[
(6)
\]

The input signal and ASE powers, in the erbium emission wavelength range and in both directions, are amplified according to the equations

\[
\frac{dP_s^\pm(z)}{dz} = \pm\Gamma(\nu_s)[N_2\sigma_s(\nu_s) - N_1\sigma_a(\nu_s) -\alpha(\nu_s)]P_s^0(z)
\]  

\[
(7)
\]

\[
\frac{dP_{ASE}(z,\nu_k)}{dz} = \pm\Gamma(\nu_k)[N_2\sigma_s(\nu_k) - N_1\sigma_a(\nu_k) -\alpha(\nu_k)]P_{ASE}^0(z,\nu_k)
\]

\[
\pm 2N_2\Gamma(\nu_k)h\nu_k\Delta\nu_k\sigma_a(\nu_k)
\]  

\[
(8)
\]

In the Equation (6)–(8), \(\nu_p\) and \(\nu_s\) are the pump and input signal frequencies, respectively, \(\sigma_p\) and \(\sigma_a\) are the emission and absorption cross sections, respectively, \(\alpha\) is the frequency-
dependent background attenuation of the active fiber. Moreover, because the forward and backward ASE noise spreads in a continuum wavelength range, the whole Er\(^{3+}\) spectrum has been divided in \(K\) slots having \(\Delta \nu_k\), \(k = 1, 2, \ldots, K\), bandwidth and centered around \(\nu_k\). The wavelength-dependent overlap factors \(\Gamma\) between the rare-earth ions and the pump, signal, and ASE field intensities were calculated using the following equation

\[
\Gamma(\lambda_k) = \int_0^R \int_0 \left| E(r, \phi, \lambda_k) \right|^2 \, r \, dr \, d\phi
\]  

(9)

where \(R\) is the radius of the doped core and \(E(r, \phi)\) is the transverse electric field envelope normalized so that the surface integral of \(|E(r, \phi)|^2\) is equal to one. Furthermore, the transverse field distribution was obtained by solving the Helmholtz eigenvalue equation for the fundamental core mode.

Equation (6)–(8) form a two-boundary values problem which is solved using an iterative forward and backward integration technique suitably developed. Moreover, along with the rate equations, they form a system of coupled differential equations since the pump transition rates satisfy

\[
W_{13}(z, \nu_p) = \frac{\Gamma(\nu_p) \sigma_s(\nu_p) [P_p^+(z) + P_p^-(z)]}{\hbar \nu_p A_{\text{core}}}
\]  

(10)

\[
W_{31}(z, \nu_p) = \frac{\Gamma(\nu_p) \sigma_s(\nu_p) [P_p^+(z) + P_p^-(z)]}{\hbar \nu_p A_{\text{core}}}
\]  

(11)

and the transition rates caused by the signal and ASE noise are given by

\[
W_{12}(z, \nu_s) = \frac{\Gamma(\nu_s) \sigma_s(\nu_s) [P_s^+(z) + P_s^-(z)]}{\hbar \nu_s A_{\text{core}}}
\]  

(12)

\[
W_{21}(z, \nu_s) = \frac{\Gamma(\nu_s) \sigma_s(\nu_s) [P_s^+(z) + P_s^-(z)]}{\hbar \nu_s A_{\text{core}}}
\]  

(13)

Equation (10)–(13) consider \(A_{\text{core}}\) as the doped core area.

### 2.2. PSO Principle

To carry out an accurate design and analysis of the EDFA, it is essential to know several spectroscopic and fiber parameters that are used as input parameters for the modeling. However, the measurements of some of these parameters are very difficult, sometimes needing very specific instrumentation. Therefore, to overcome these drawbacks a combined experimental and simulation approach was developed with the aim to refine and recover these EDFA parameters. We then selected the PSO algorithm as an automated optimization procedure to identify the best solution to match our experimental data. The PSO, inspired to the movement and intelligence of bird flocking, is an evolutionary algorithm introduced.\(^{[24,25]}\) It implements a method which performs a global search of parameters over a specified problem space by means of a population of individuals, called swarm. This population, initialized with a group of random particles, is updated by applying a proper velocity operator which is computed according to the information of a fitness function.\(^{[26]}\) Each particle adjusts its trajectory in the solution space by considering 1) its location having the best fitness value and 2) the location with the best fitness function found by the remaining agents. In this way, the entire swarm moves toward positions characterized by minimum/maximum values of the fitness function. The \(i\)-th particle updates its velocity and position according to the following two equations

\[
x_i(t + 1) = x_i(t) + v_i(t + 1)
\]

(14)

\[
v_i(t + 1) = \chi (v_i(t) + \phi_1 r_1 [s_i(t) - x_i(t)]) + \phi_2 r_2 [s_i(t) - x_i(t)]
\]

(15)

where \(x_i\) and \(v_i\) are two \(D\)-dimensional vectors representing the positions and velocities of the \(i\)-th particle, respectively, into a \(D\)-dimensional search space, \(r_1\) and \(r_2\) are two random numbers uniformly distributed in the range \([0,1]\), \(s_i(t)\) is the best previous position of the \(i\)-th particle according to the best fitness value, whereas \(x_i(t)\) is the best position among all the particles in the population. Moreover, \(\phi_1\) and \(\phi_2\) are two real constants constrained by the condition \(\phi = \phi_1 + \phi_2 > 4\) and the constriction factor \(\chi\) is given by

\[
\chi = \frac{2}{2 - \phi - \sqrt{\phi^2 - 4\phi}}
\]

(16)

### 3. Experimental Section

To evaluate the radiation impact on the EDFA gain, we irradiated an EDF manufactured by iXblue photonics\(^{[27]}\) under X-rays using the MOPERIX machine of the Laboratoire Hubert Curien (Saint Etienne, France). The fiber, whose characteristics are given in Table 1, has been exposed at a dose rate of \(\approx 27\) mrad(SiO\(_2\)) s\(^{-1}\) during 3 h reaching a dose of 300 krad. The sample had been placed on a thermal plate instrumented with thermocouples to check the stability of the temperature during the whole run. We investigated three irradiation temperatures: \(-40\) °C, room temperature (RT) = 25 and 120 °C. A probe signal at 1550 nm had been injected in the fiber with a power of 10 µW, whereas the pump at 975 nm, coming from a laser diode, was injected in a contra-propagative way with a power of 150 mW. With this configuration, the measured EDFA gains before irradiation were of \(\approx 29.3\), \(\approx 32.4\), and \(\approx 31.5\) at \(-40\) °C, RT, and 120 °C, respectively. The output signal had been monitored due to an optical spectrum analyzer (OSA) from Yokogawa. After the

| Table 1. Optical fiber characteristics of the considered EDFA. |
| --- |
| Core diameter | Cladding diameter | Core dopants | Length | Core–cladding refractive index difference |
| 2.8 µm | 125 µm | Al and Ce | 6.9 m | 2.5 \(\times\) 10\(^{-2}\) |
irradiation ends, the gain evolution remained monitored during the recovery phase. The experimental setup is shown in Figure 2.

To investigate the radiation induced losses at both the signal and the pump wavelengths, about 80 cm of the same EDF had been irradiated under the same conditions using the experimental setup shown in Figure 3. To approach the same pumping conditions of the gain measurements, the pump had been injected in the fiber 80% of a 15 min lasting measurement cycle. During the remaining 20%, the light from an EQ-99X-FC White Light Source from ENERGETIQ was injected in the fiber to acquire the RIA spectra. This 80% pumping allowed us to reproduce as well as possible the photobleaching impact on the EDF response but might lead to RIA overestimation. The amplified signal was monitored due to the same OSA used in the previous experiment.

With the aim to characterize the sole temperature effects on the fiber, we recorded the changes in its transmission spectrum while it was treated at −40 °C, RT, and 120 °C. Figure 4 shows the used setup. A white light source (WLS) was injected in the fiber placed in the oven and the transmitted spectra were monitored due to the OSA. The steps of temperatures lasted 20 min.

4. Experimental Input Parameters

4.1. RIA at Different Temperatures

To reproduce the gain response of an EDFA under irradiation, the numerical model requires input parameters to be implemented beforehand. Some of these are quite easily measurable or calculated from measurable parameters, such as the absorption and emission cross sections or the radiation-induced losses. The other parameters are already known as the geometry of the fiber and its composition, and finally, the spectroscopic parameters are optimized due to the PSO algorithm.

Figure 5 gives the spectral RIA in dB/m measured for the fiber after being exposed to a dose of 300 krad at the three temperatures of irradiation. RIAs were calculated as follows

\[
RIA(\lambda, T) = -10 \log \left( \frac{I_{300 \text{ krad}}(\lambda, T)}{I_{\text{pristine}}(\lambda, T)} \right)
\]  

where \( L \) is the length of the irradiated sample; \( I_{\text{pristine}} \) and \( I_{300 \text{ krad}} \) are the transmitted spectral intensities before and after irradiation, respectively. The obtained RIA results are typical of aluminosilicate glass matrix: at lower wavelengths, the RIA around 975 nm is caused by the Al-OHC (aluminum oxygen hole centers) and another contributor, not yet identified.\(^{28}\) The RIA at the pump wavelength appears to be significantly influenced by the irradiation temperature: the higher the temperature, the higher the RIA level. In contrast, the RIA at the signal wavelength, for which the defects at its origin still need to be identified, seems more slightly temperature dependent. The different effect of the temperature on the RIA in the two spectral domains can be explained by the fact that the point defects at the origin of the RIA differ in both cases\(^{28}\) as well as the temperature dependence of their generation or bleaching rates.
4.2. Thermo-Optic Modeling

The temperature is known to change the properties of the glass, as its refractive index. In our case, we apply an external thermal load that leads to a slight refractive index change $\Delta n(T)$ that we evaluated as this variation impacts the overlapping factor between the propagating mode and the rare-earth ions distribution. To calculate $\Delta n(T)$, we have to consider the exact fiber composition, made mainly in our tested sample of silica (SiO$_2$), alumina (Al$_2$O$_3$), and germania (GeO$_2$) in the core and pure silica in the cladding. First, the volume percentage ($f$) of each dopant has to be determined as follows:

$$f_{\text{dopant}} = \frac{M_{\text{dopant}} \text{mol}_{\text{dopant}} \% \rho_{\text{SiO}_2}}{\rho_{\text{SiO}_2} \rho_{\text{dopant}} + \text{mol}_{\text{dopant}} \% (M_{\text{dopant}} \rho_{\text{SiO}_2} - M_{\text{SiO}_2} \rho_{\text{dopant}})}$$

(18)

with $M$ the molar mass, and mol$_{\text{dopant}}$% the molar percentage of the dopants in the fiber and $\rho$ their densities. The thermo-optic coefficient of the fiber is defined as

$$\frac{\partial n_{\text{SiO}_2/\text{dopant}}}{\partial T} = \sum f_{\text{dopant}} \frac{\partial n_{\text{dopant}}}{\partial T} + \left(1 - \sum f_{\text{dopant}}\right) \frac{\partial n_{\text{SiO}_2}}{\partial T}$$

(19)

where $\partial n_{\text{SiO}_2/\text{dopant}}/\partial T$ is the thermo-optic coefficient of the different types of glasses. All the data concerning the different dopants are reported in Table 2.

Table 2. Glass and dopants parameters used for the EDFA modeling.

| Glasses   | Thermo-optic coefficient [10$^{-5}$ C$^{-1}$] | Molar mass [kg m$^{-3}$] | Density [g cm$^{-3}$] | Mol% |
|-----------|---------------------------------------------|--------------------------|----------------------|------|
| SiO$_2$   | 10.6                                       | 60.08                    | 2200                 | 0.0845 |
| Al$_2$O$_3$ | 13.1                                      | 101.96                   | 3950                 | 0.0011 |
| GeO$_2$   | 19.4                                       | 104.61                   | 4250                 | 0.0203 |

4.3. Cross Sections

Figure 6 shows the absorption and emission cross sections $\sigma^\text{a}^{13/2}$ and $\sigma^\text{e}^{13/2}$ of the fiber at the three different temperatures around 1550 nm. The cross sections are obtained by acquiring the absorption spectra $\Delta \text{abs}^{13/2}(\lambda, T)$ of the active fiber at each temperature. The $\sigma^\text{e}^{13/2}$ is then calculated as

$$\sigma^\text{e}^{13/2}(\lambda, T) = \frac{\Delta \text{abs}^{13/2}(\lambda, T)}{10 \log(e) N_{\text{Er}} \Gamma (\lambda, T)}$$

(20)

where $N_{\text{Er}}$ is the erbium concentration. $\Gamma$ is the overlap factor between the propagating modes and the erbium ion distribution, obtained due to Comsol Multiphysics simulations. The $\sigma^\text{e}^{13/2}$ depends on both the wavelength and the temperature. Knowing the absorption cross sections, the emission cross sections was calculated using the McCumber theory:

$$\sigma^\text{e}^{13/2}(\lambda, T) = \sigma^\text{a}^{13/2}(\lambda, T) \exp (E_{\text{ZL}} - h\nu / k T)$$

(21)

The emission cross section depends on the absorption one, $E_{\text{ZL}}$ being the energy difference between the bottom of the $^2I_{13/2}$ manifold and the bottom of the ground state $^4I_{15/2}$. $T$ is the temperature $T$, $h$ and $k$ are the Boltzmann and Planck constants, respectively. However, due to the McCumber theory both...
\[ \sigma(\lambda) \] depend on temperature but in the opposite way. In fact, as
the temperature rises, at shorter wavelengths \( \sigma_{\text{Er}}^a(\lambda, T) \) decreases
whereas \( \sigma_{\text{Er}}^e(\lambda, T) \) increases. At longer wavelengths, \( \sigma_{\text{Er}}^e(\lambda, T) \)
increases with temperature whereas \( \sigma_{\text{Er}}^a(\lambda, T) \) decreases at higher
temperatures. This can be explained by considering that the
energy level population is proportional to the temperature, fol-
lowing the Boltzmann’s law. The heating allows populating
the most energetic stark level manifolds of the erbium ions.
Then, the absorption probability is larger at low energies
(high wavelength photon) to go from the fundamental to the
\( ^4I_{13/2} \) energy level. Inversely, when the
fiber is cooled, the absorp-
tion probability is higher at high energies (a photon at low wave-
length) to go to the \( ^4I_{13/2} \) energy level. Concerning the emission
cross section, the same argument can be applied. At high tem-
perature, more electrons populate the higher stark level mani-
folds, then they will emit photons at higher energy (smaller
wavelength) whereas at lower temperature, electrons are on
lower sublevels, then their emissions correspond to lower
energies (larger wavelengths).

5. Comparison between Experiment and Simulation Results

We used our simulation code to reproduce the measured EDFA
gain degradation when the active fiber is exposed to combined
temperature and radiation effects. Figure 7 compares the experi-
mental and calculated gain degradation kinetics at \(-40^\circ\text{C}, \text{RT}, \text{ and } 120^\circ\text{C}\). The measured gain degradations in dB have been
calculated as
\[
G(\lambda, D) = 10 \log \left( \frac{P_{\text{out}}(\lambda, D)}{P_{\text{in}}(\lambda, D)} \right)
\]
with \( D \) the dose applied on the fiber and \( P_{\text{in}}(\lambda) \) and \( P_{\text{out}}(\lambda, D) \) the
input and output power, respectively, at the chosen wavelength
and dose. The 5% error has been applied on these measure-
ments. The experimental tests show that radiation strongly
affects the EDFA gains at the three temperatures and that glob-
ally the irradiation temperature has a minor effect on this EDFA
architecture vulnerability. Up to 100 krad dose, the gain degrada-
tion remains limited to about 5 dB (20% of the initial gain) but at
the highest dose of 300 krad, the EDFA is no more amplifying the
1550 nm input signal. It can be observed that the simulations at
\(-40^\circ\text{C}\) agree well with the measurement. The one at RT also
globally agrees with the experiment. Indeed, at this temperature,
the simulation kinetic concords with the experiments until
\( \approx 70 \) krad. Then, the difference between them increases with a simu-
lation overestimating the gain degradation from \( \approx 100 \) to \( \approx 250 \)
krad. At higher doses and during the recovery, the simulation
and the experiments match again better. Finally, the simulations
of the gain degradation at \( 120^\circ\text{C} \) behave similarly than at RT, but
the discrepancy is greater and the calculated and measured gains match only for doses up to 70 krad. The simulation error seems to increase with the temperature rise but it can also be related to the fact that the RIA increases at the pump wavelength with the temperature.

By investigating in more details through simulation the signal and pump powers distributions along the active fiber length for the various irradiation doses, we observe that the 70–100 krad dose also corresponds to the threshold where the RIA around 975 nm prevents the pump to reach the fiber entrance and then to fully amplify the input signal at 1550 nm. This explains that, at higher doses and higher RIA at 975 nm, we first observe a clear 1550 nm signal decrease up to the fiber length where it starts to be amplified by the remaining pump at 975 nm despite the high RIA levels. This is shown in Figure 8a,b that show the evolution of the signal and the pump powers at 120 °C along the active fiber length for various irradiation conditions. Comparable results have been obtained at the two other temperatures, for which the aforementioned effect is slightly reduced as the RIA at the pump wavelength is lower. From a practical point of view, this analysis also reveals that it will be possible to limit the gain degradation at higher doses by considering in our system an excess pump power that can shift the appearance of this threshold at higher doses than those of interest for future space missions.

A possible explication of the observed difference between the experiments and results at higher doses can be related to the estimation of the fiber exact absorption at the pump and signal wavelength. Indeed, the irradiation temperature can activate new ways to supply the population inversion of the higher levels of the various sublevels associated with these levels. The temperature effect is quite complex and difficult to implement in the current version of the numerical code. A better consideration of these effects in a future version of the models can improve the quality of our predictions for the gain degradation at high dose levels and high temperatures.

Finally, a last possibility that we investigated concerns the impact of a radiation-induced variation of the various other spectroscopic parameters involved in the considered Er³⁺-doped system. We previously illustrated that varying these spectroscopic parameters by ±20% does not influence the EDFA gain significantly. [33, 34] Here again, parametric simulations showed that the EDFA gain is only slightly impacted by changing these parameters and that none of them can explain the observed difference between our experiments and simulations.

6. Conclusion

In this article, we investigate both experimentally and by simulations the combined radiation and temperature effects on the ≈30 dB gain of an EDFA based on a backward pumping scheme. We then compare the measured and simulated gain degradation kinetics of an EDFA as a function of the dose and at different temperatures.
temperatures (−40 °C, RT, and 120 °C). The obtained results are of direct interest for space applications for which those environmental constraints limit the integration of this photonic technology. The temperature does not greatly affect the kinetics of the gain degradation, a very important result as it implies that accelerated tests done at room temperature represents well for the investigated test conditions, the behavior of the system on a larger range of temperature. To model these coupled effects, we developed and exploited a numerical code that solves the differential rate equations pertaining the energy levels of erbium ion system. The spectroscopic parameters have been optimized due to a PSO algorithm. The emission and absorption cross sections have been either measured or calculated at each temperature considering the thermal contribution of the dopants on the refractive index of the fibers and the attenuation of the fiber at each temperature. Through the RIA measurements at the pump and signal wavelengths, it is possible to put into the numerical code those RIA values at the different doses (or times). The code reproduces pretty well the measurements for doses below 70 krad (actual space missions) and less efficiently the observed gain degradation kinetics at larger doses, especially at the higher temperature. This dose threshold has been shown to correspond to the irradiation conditions where the pump starts to be no more able to excite the erbium ions over the whole active fiber length, implying an attenuation of the input signal at 1550 nm before its amplification. This has a strong impact on the EDFA gain and this issue can be partially mitigated at the system level by considering a higher initial pump power, the excess pump allowing to overcome the RIA issue. In more details, the comparison between the simulation and the measured gain shows that when the temperature increases, the kinetics of the simulated gain in this dose range do not really correspond to the experiments after a dose of ≈70 krad. At this stage, our assumption is that the model should be upgraded to consider the thermal influence on the populations of the stark manifolds of the $^4I_{13/2}$ and $^4I_{15/2}$ energy levels affecting the attenuation at both the signal and pump wavelengths. We also performed a parametric simulation evaluation of a possible radiation-induced effects on the other spectroscopic parameters involved in our considered erbium model, none seems able to explain the observed differences.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

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