Theoretical study of the space radiation effects in an EDFA for an small satellite mission

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NIMPH (Nanosatellite to Investigate Microwave Photonic Hardware) is a 3U Cube-Sat[1] project devoted to accomplish a qualification process of Microwave-Photonics (MWP) technology operating in space. With an advanced concept of MWP payload including an Erbium-doped fiber amplifier (EDFA), the nanosatellite will be launched in 2019 to measure at Low Earth Orbit(LEO) the effects of space radiation over the fiber, monitoring their critical performance parameters: gain, output power and noise figure (NF). Standing on a well verified model for the gain of an EDFA in radiative constraints, here we present a pre-study of the radiation effects in the amplifier within the context of NIMPH mission, when the fiber is operated in space at temperatures between 20 and 73°C within a set of predefined orbits of 355-1447 km altitude, and pumped in copropagating configuration at 980 nm. Also, a simple model is proposed to estimate the NF growth of an EDFA in an ionizing environment, determining the possible variation of noise at typical space dose rates.

Keywords: NIMPH, Microwave-Photonics, Erbium Doped Fiber Amplifier (EDFA), Noise Figure, Radiation Dose, Output Power, Gain.

I. INTRODUCTION

Microwave-Photonics is an interdisciplinary area that studies the interaction between microwave and optical signals[2] and joins together the worlds of radio-frequency engineering and optoelectronics[3]. The major functions of Microwave Photonics systems include photonic generation, processing, control and distribution of microwave and millimeter-wave signals[2], and many research findings have been reported in the last years as an effort to find new techniques for different applications, such as enabling technologies for advanced payload concepts with the aim to explore new communication bands for future telecommunication satellites[4]. However, Microwave-Photonics (MWP)hardware need to meet further specifications requirements for space applications than current commercial ground equipment. Also, optical fibers and erbium-doped fibers, which are often part of the equipment for transmission hardware, are sensitive to radiation[5–11], and the main effect in space is the overall degradation of their gain performance and noise figure[7,12–14] (NF).

Within the framework of the space validation of photonic technology for the next generation of communication satellites, the Cube-Sat NIMPH will test an MWP equipment including two different erbium-doped fiber technologies. This in-flight experiment will lead a comparison between radiation-hardened and common telecommunication doped fibers, through the measurement of Gain and NF within a LEO orbit with a typical dose profile of 200 Gray of radiation at least. The EDFA is currently the most efficient optical amplifier in the 1550 nm range[15], that have become an essential component in terrestrial telecommunication networks based on optic fiber[16]. This device also plays a crucial role in the emerging laser technology for inter-satellite communication[13], and represent an important component for the actual development of ground-satellite optical communication systems[11,17–19]. In all devices constituting the terminal links in space, sensitivity to hard radiation is an important issue that needs to be addressed mainly for optical fibers[20]. In consequence, further implications of testing and qualifying in space the EDFA integrated in a payload are very wide in the telecommunication field.

In the state of the art of erbium-doped fibers, a large number of groups have made focus on testing the EDFA in radiation constraints[5–14,19,21–29]. Those effects are well quantified[6,7,11,13,21,25] , and the result of exposure to ionizing radiation could potentially affect the amplifier performance in a number of different ways[6], depending on the dose, dose rate, temperature or fiber composition. Usually, radiation induced damage is attributed primary to the formation of color centers in Er-doped silica fibers[5,6], increasing the absorption losses in the near-infrared and visible regions. This phenomena leads the parasitic losses at pump and signal wavelengths to reduce the amplified power at the output of the fiber[8,10]. Some approaches have been developed to model the de-

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pendence of the gain of EDFAs with radiation[6,21,24,25,30], and researchers began to search methods for reducing radiation-induced losses on fibers. As a result, different radiation-hardened concepts in erbium or Ytterbium -doped fibers have been tested[26,27,31,32]. However, experimental research showing the dependence of the EDFA performance with temperature show a complex process in the degradation of the gain and noise figure profiles[30,33–37], which still needs to be well understood essentially for current space applications of erbium-doped fibers. Few work has been devoted to study the amplifier as a real system gathering both temperature and radiation effects[13,37], and there is not such a model that take into account both measures on the noise figure profile yet. Therefore, here we present the results regarding the performance of the EDFA metrics in context of NIMPH, evaluating the expected degradation in gain of an EDFA representative for the mission, and also proposing a simple methodology to obtain the NF degradation in a ionizing environment.

II. THEORY

A. Gain radiative model

The gain is considered as the performance metric for fiber amplifiers. The definition of gain G is[16]:

$$G = \frac{P_{s,out}}{P_{s,in}} \tag{1}$$

Where $P_{s,out}$ and $P_{s,in}$ are the output and the input signal power respectively, measured over the length of the fiber. Normally the gain of the EDFA is limited by the finite number of Erbium ions in the core of the fiber. Increasing the pump power beyond the point where all ions are excited cannot produce more gain and thus saturation occurs.

In radiation conditions, gain properties of erbium-doped fiber amplifiers are well represented by a set of experimentally-verified coupled partial differential equations[24], in terms of the signal power $P_s(z)$ and the pump power $P_p(z)$, which generally are integrated numerically:

$$\begin{aligned}\frac{dP_s(z)}{dz} =& (\alpha_s + g_s)N_2(z)P_s(z) \\ & -(\alpha_s + \alpha_s' + \alpha_{sRAD})P_s(z),\end{aligned} \tag{2a}$$

$$\begin{aligned}\frac{dP_p(z)}{dz} =& (\alpha_p + \alpha_p' + \alpha_{pRAD})(N_2(z) - 1)P_p(z) - \\ & (\alpha_p + \alpha_{pRAD})N_2(z)P_p(z)\end{aligned} \tag{2b}$$

Is precisely important to note, that although several assumptions were made in determining the physical description of the fiber represented by Eqs. (2a) and (2b), they are reduced analytic expressions coming from the Giles-Desurvire model simplified for copropagating 980-nm pumped amplifiers[38], that operate in the signal-saturated regime[39]. N_2 is the normalized metastable population given by[24,39]:

$$N_2(z) = \frac{\frac{\alpha_p P_p}{v_p} + \frac{\alpha s P s}{v_s}}{\frac{\alpha_p}{v_p} P_p + \frac{\alpha_s + g_s}{v_s} P_s} \tag{3}$$

In Eqs. (2) and (3), g_s is the gain coefficient of an EDFA estimated in the pre-irradiation characterization[24], constants α_s and α_p are the measured erbium absorption for signal and pump, v_s and v_p the signal and pump frequencies, α_s' and α_p' the background losses for pump and signal, and finally α_{sRAD} and α_{pRAD} the radio-induced losses for signal and pump. In past models, the radiation induced losses were directly measured in dependence of the wavelength, leading to an inaccurate determination if a long fiber is used. However, a methodology have been proposed to model the spectral dependency of α_{sRAD} and α_{pRAD} in the near infrared region based in a power law from the single absorption measurement at 1310 nm. This estimation is in direct dependence of the dose, dose rate and temperature, and experimentally verified for extrapolation to typical space dose rates[14]. The radiation losses thus are model by the following Lorentzian tail in the near-infrared region:

$$\alpha(\lambda)_{RAD} = c\Phi^{1-f} D^f \frac{(1310 - \lambda_0)^2}{(\lambda - \lambda_0)^2} \tag{4}$$

Where Φ is the irradiation dose rate, D the total deposited dose, c and f temperature-dependent parameters. λ_0 is a parameter that gives a rough estimation of absorption bands position. Using Eqs. (2), (3) and (4), we can compute the evolution of the gain of a typical EDFA in space radiation conditions under temperature constraints.

B. Noise Figure derivation

In the other hand, the Noise Figure can be expressed in terms of the Amplified Spontaneous Emission (ASE) power[16] in a bandwidth Δv by:

$$NF = (1 + 2\frac{P_{ASE}}{hv\Delta v})\frac{1}{G} \tag{5}$$

where P_{ASE} is the ASE noise power, h the Planck's constant, v the frequency of the light and Δv the optical measurement bandwidth, and G the the gain.

According Ref.[40], the power P_{ASE} emitted from the output of an EDFA at wavelenght λ_k can be obtained by integrating over the whole lenght of the amplifier the spontaneous emission power dP_{sp} from each infinitesimal section of the lenght multiplied by the gain at the same wavelengh $G_k(z, L)$, measured from that infinitesimal section to the end L of the amplifier, in a way that:

$$P_{ASE}(L) = \int_{z=0}^{z=L} dP_{sp} G_k(z, L) \tag{6}$$

with $G_k(z, L) = \frac{P_s(L)}{P_s(z)}$. Moreover, for a single polarization at wavelenght λ_k, emitted in one single direction of the amplifier by a section of lenght dz, the spontaneous emission noise power dP_{sp} is given by[40]:

$$dP_{sp} = g_k N_2(z) \Delta v dz \tag{7}$$

Where g_k is the gain coefficient, and $N_2(z)$ the upper state population. Using Eqs. (5), (6) and (7) we can obtain:

$$NF = \frac{2g_k}{G} \int_{z=0}^{z=L} N_2(z) \frac{P_s(L)}{P_s(z)} dz + \frac{1}{G} \tag{8}$$

The last expression has been validated in non-radiative conditions[39], showing a great accuracy with experimental data. Modeling of the NF in radiation conditions requires knowledge of the insertion losses at pump and signal wavelengths[25], that here are given by $\alpha(\lambda)_{RAD}$, and using Eq. (8) we are able to estimate the Noise Figure according the radiation dose, by integrating the signal power $P_s(z)$ and population of the excited state $N_2(z)$ functions correlated to the radio-induced losses of Eq. (4). Note that this approach leads to estimate the NF by numerical integration of the coupled Eqs. (2) first, to obtain $P_s(z)$ and $N_2(z)$ functions, which are latter implemented in Eq. (8) to obtain the NF by dose breakpoint. The numerical integration scheme to solve both Eqs. (2) and (8) has been chosen in order to get the best compromise between accuracy and computation time.

For evaluating in a more concise way the NF of the EDFA, and because the multiplexers and isolators of the EDFA contain fibers, is important to note that in Eq. (8) the insertion losses due to fiber components different than the Er-doped fiber have been neglected, so the overall NF of EDFA should be higher[39]. However, recent experimental research[13] suggest that the radiation-insertion losses of a WDM coupler vary within 6 dB in the dose range of 0-10 Gray, while the optical isolator remains almost insensitive to radiation with total doses in the same range. Since the radiation effect on those devices cannot be neglected, this lead us to estimate the correct value for the NF with a coupled term dependent of the insertion losses of the multiplexers and isolators:

$$NF_{EDFA} = NF_{EDF} + \mu(D) \tag{9}$$

In the previous equation, NF_{EDF} is the erbium-doped fiber noise figure given by Eq. (8) and $\mu(D)$ represent the remaining losses coming from the other fiber components of the EDFA, that seem to be in direct relation with the dose of radiation[13]. Due to the lack of experimental results for space-low dose rates, we will avoid the extrapolation of Eq. (9) for the calculation of the NF in this simulation. Instead we will use Eq. (8), neglecting the additional insertion losses due to the multiplexer elements and other fiber sources of the EDFA, furthermore even the EDFA's NF should be somewhat higher for each dose breakpoint, is not expected to change the overall expected trend. Consequently this method could be a reliable NF predictor under radiation and temperature conditions and a feasible way to understand proper data coming from real testing conditions in NIMPH mission.

III. SIMULATION RESULTS

A. Assesment of the orbit and radiation profile

Given the values for the radiation-induced losses in erbium-doped fibers, one can model the effect that loss has on amplifier performance[6]. Since the model of EDFA we present in the previous section is mainly dependent of the radiation dose received, then we can extrapolate this model to study the amplifier operating in space at definite dose and dose rates profiles depending on the orbit[14,24]. We investigated five possible Low Earth Orbits (LEO) for NIMPH mission, which are defined in Table I. At such orbits and for an accurate assesment of the radiation reaching the fiber in the inner satellite, we used OMERE-Fastrad software[41] to obtain the received total ionizing dose (TID) expected in the place of the payload board that contains the EDFA (Fig. 1).

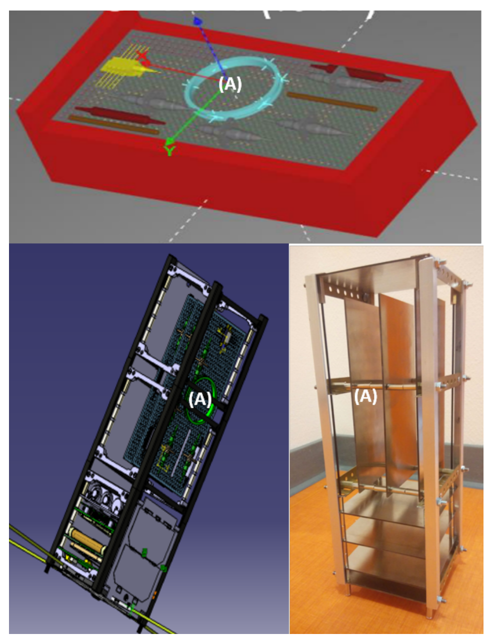

FIG. 1. Different views of the localization of the virtual detector around the fiber(A) in the computarized models (above, left), and estimated ubication in the real payload (right).

The software method consist in setting a virtual silicon detector inside the real system geometry to perform

TABLE I. Orbital Characteristics and typical doses for an EDFA, and radiation induced losses in gain and amplified power, with: i=inclination,L=spacecraft lifetime, r=distance to earth.

Orbit Name	Orbit Characteristics	Total Dose, Dose Rate	Gain Loss [a] ($\times 10^{-2}$dB)	$P_{s,out}$ Loss [a] ($\times 10^{-2}$dBm)	NF Loss[a] ($\times 10^{-3}$dB)
Orbit 1 (Pleiades)	L= 2 yrs, r=698 km, i= 98.2°	104 Gy, 5.9×10^{-3} Gy/hr	7.4	6.4	7
Orbit 2 (Sacred)	L= 2 yrs, r=650 km, i= 65°	104 Gy, 5.9×10^{-3} Gy/hr	7.4	6.4	7
Orbit 3 (Sacred modified)	L= 2 yrs, r=650 km, i=98°	340 Gy, 19.4×10^{-3}Gy/hr	24.1	19.9	24
Orbit 4 (Robusta)	L= 2 yrs, r=340-1450 km, i=71°	313 Gy, 17.8×10^{-3} Gy/hr	22.2	18.4	22
Orbit 5 (LEO)	L= 5 yrs, r=695 km, i= 98.18°	16.4 Gy, 3.7×10^{-4}Gy/hr	0.7	0.7	0.72

[a] Radiation losses when operating the EDFA at fixed temperature of 73°C

TABLE II. Constant values for simulation

Parameter	Symbol	Value[a]
Signal Power	$P_s(0)$	1.2mW
Pump Power	$P_p(0)$	240 mW
Lenght	L	24 m
Erbium absoption	α_s, α_p	1.3dB/m, 2.9dB/m
Background losses(at 1310 nm)	α'_s, α'_p	0.004dB/m,0.025dB/m
Gain coefficient	g_s	1.314 dB/m
Temperature coefficients	f, c_{23C}, c_{73C}	0.77, 1.9×10^{-4}, 3×10^{-4}
Parameter absorp.bands	λ_0	326nm

[a] From Ref.[24]

a sector analysis by ray tracing method, gathering both the TID level and dose depth curve. The total doses and associated dose rates collected placing a detector along the position of the fiber are presented in Table I. Assuming that an EDFA is operating in space as power amplifier, hardest environment constraints in terms of total deposited dose have been identified for the orbit named Sacred modified, that resembles the name from the Sacred Cubesat Orbit[42]. Highest doses are followed by Robusta[43] orbit and Pleiades[44] SSO (Sun-synchronous orbit), that according our simulations it has a total expected dose in the same order of Sacred orbit. In addition, in order to evaluate the efficiency of our EDFA isolated from the rest of the nanosatellite, we attempt to define another LEO orbit, for which the dose profiles were obtained by the virtual detector confined inside an aluminum spherical shield of 10 mm thick[24].

B. Monitoring the radio-induced degradation on the EDFA

For projecting the performance of the EDFA in space, we will stand in the scheme discussed previously by Eqs. (2)-(8). Table II shows the experimental values obtained during the pre-irradiation characterization of an EDFA beamed with ^{60}Co γ-rays up to 3 kGy[24]. Those input values are widely used for modeling the EDFA in different radiation scenarios[45,46] and are also employed in this analysis. Combined with the dose and dose rate profiles set in Table I, we are able solve Eqs. (2) and track the behavior of signal power $P_s(z)$, pump power $P_p(z)$ and consequently evaluate the gain and noise figure of the EDFA operating in NIMPH context. Note that the temperature of operation of the amplifier is fixed at T=73°C in this analysis. The numerical results are presented consecutively in Table I. Worst damage in the EDFA have been found at higher TID doses, as expected[14,24]. However, it is known radiation has few impact on the gain for low-dose rate orbits with less than 200 Gray[13], as in Pleiades and Sacred. The gain decays around 0.22 and 0.24 dB in Robusta and Sacred modified orbits, respectively, with a probable increase of the Noise Figure in the order of 10^{-3} for the latter orbits. This apparent increase in the NF in a ionizing environment have been observed experimentally in other works at higher dose rates[13,25]. Although here we do not discuss what the actual reason for this growth is, no relevant studies have been performed at typical space dose rates, and we may simplify that the observed growth is correct, but yet difficult to reproduce: the increment of the NF starts from an initial value of of 3.52 dB when the dose is null. This amount of noise is challenging to reproduce in experiment, specially when accounting the several elements of the EDFA that contribute to overall observed values. In this case we may adjudge this value to the lack of information about the precise fluctuation of the remaining losses due to the other fiber elements of the EDFA, and their behaviour with radiation. For the isolated EDFA of Orbit 5, we observe a minor decay in the gain and output power, but not redundant for this values being in perfect agreement with Ref.[24]. From our analysis, few conclusions can be set. First, the generally observed small variations in the EDFA performance could be difficult to be monitored in time with the on-board electronics and sensors, and may lead the NIMPH team to redefine the mission orbit inclusive the payload, in the worst case exposing the EDFA directly to space weather to obtain higher dose impacts to be detected. But temperature cycling is a big issue to take in account, specially when experimental studies relating the performance of EDFA in radiation and temperature constraints show an hysteresis behavior in the measured gain in low powered EDFAs[37], complicated to be monitored in the framework of NIMPH mission where only radiation dose effects are contemplated to be tracked. Therein, a further analysis is required in terms of characterizing the influence of temperature in the gain and noise figure metrics at typical space dose rates. Part of this study is presented in the next section. Secondly, since only amplifier an erbium-doped fiber was irradiated to build the model that have been used in this letter, the extent of additional radiation induced damage resulting from the associated EDFA electronics and optical pump sources is required to fully characterize the EDFA responses in radiation environments. As mentioned before, even the extent of disturbance in these components was not reported here, normally the contribution to the total induced degradation is expected to be less that of the induced fiber damage[13], while the overall effect in the total degradation should be higher. Consequently plans to achieve a full characterization of EDFA are underway. According the previous results, in terms of expected TID, we have select the Sacred modified orbit as a feasible orbit for NIMPH.

C. Influence of temperature

Now, we present the results regarding the influence of temperature of the EDFA in the losses. Two different temperatures for the amplifier operation were analyzed, 20 and 73°C. The numerical results are summarized in the following graphs. Fig. 2 shows the performance of the EDFA under radiation and temperature constraints from the orbits of Table I. The impacts on the losses are clearly illustrated, and without regard of the mission and dose profile studied, with rising temperature is observed a greater deterioration in the performance of gain and NF of the EDFA. Something similar have been observed in low-powered EDFAs in a post-irradiation process[37]. Nonetheless, this degradation is also small between the 20 and 73°C temperature gap studied. For the Sacred modified orbit we report 0.15 dB (gain) and 0.014 dB (NF) of difference when operating between one or the other temperature, as the graphs show. In the rest of orbits, is also observed a substantial degradation if the temperature is increased when higher is the TID received, suggesting an influence of temperature in the effect that radiation holds in the EDFA. Beside this evidence, since changes in the operating temperature can degrade the fundamental parameters of the amplifier in space, is important to make emphasis on temperature control inside the nanosatellite to stabilize the internal operation of EDFA. This represents an issue that still needs to be clarified for the NIMPH team, if whether or not to use an active temperature control system due the long exposure to thermal cycling and temperature extremes in space environment.

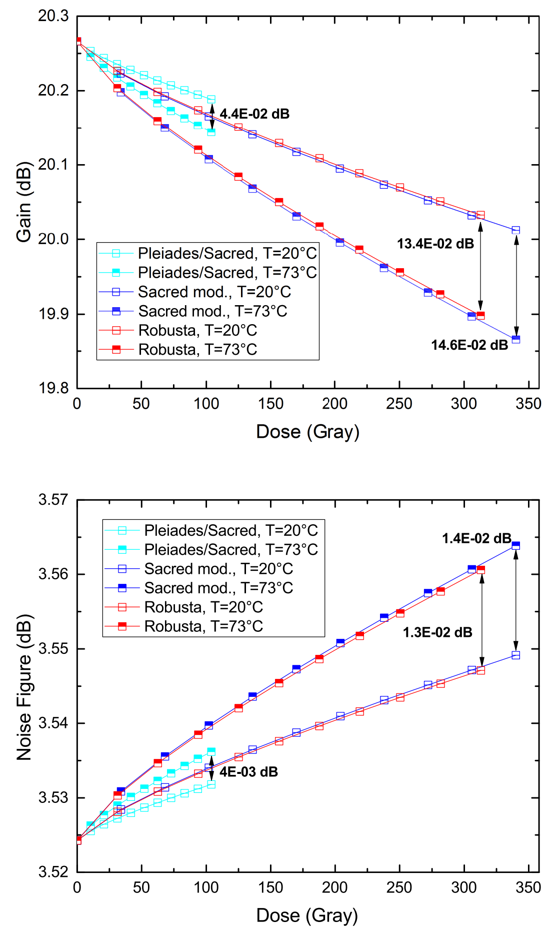

FIG. 2. Monitoring of the radio-induced losses according temperature, for gain (above) and noise figure (below), according the TID for NIMPH pre-defined orbits.

IV. CONCLUSIONS

We review the possible mission scenarios for NIMPH satellite obtaining the deposited doses that will be collected in the location of the fiber during the course of the mission. Highest TID doses up 340 Gray are expected for Sacred-modified orbit, and the consequent radio-induced losses in gain of the 980 nm pumped EDFA are, in the worst case, less than 1 dB. We introduce a proper framework to obtain the NF of the fiber in a ionizing environment by numerical integration of the output power and population of the metastable level functions correlated to the radiation-induced losses of the fiber. Our numerical results show that is expected a minimal degradation on NF as much as 0.02 dB at such typical low-dose rates. In the same way we review some assumptions and practical limitations of the radiative equations when testing the hardware in real space conditions, expecting additional losses and damage factors. Even the present model for the NF is somewhat simplistic, contributions on temperature dependent distortions show a possible limiting factor with the EDFA operating in a temperature uncontrolled environment, even further studies on the dynamics of growth and recovery are needed implementing the thermal annealing process of the induced loss in the fibers. Further work is necessary to address those degradation and regeneration mechanisms of the radiative model of the fiber, since having the amplifier in a pumped operating state will allow continuous photoannealing and recovery to occur, decreasing the amount of degradation.

Moreover, other constraints such as fiber composition and length that are critical for the EDFA need to be adapted to have the best compromise in performance within the goals of the mission, while the team faces the challenge to match the dimensions of the onboard MWP payload to the design parameters of the CubeSat. In addition to the typical EDFA that will be implemented in the payload, and with regard of the present study, the team is realizing whether or not to implement a radiation-hardened fiber in the payload or a more sensitive one.

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