Results in Physics 12 (2019) 1805–1808

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.elsevier.com/locate/rinp

Modeling degraded performance metrics of optical amplifiers under radiation

A.J.R. Lopez-Arreguin[a,*], E. Stoll[a], Jürgen Letschnik[b]

[a] Institute of Space Systems, TU-Braunschweig, Hermann-Blenk-Strasse 23, Braunschweig 38108, Germany
[b] Institute of Astronautics, TU-München, Boltzmannstrasse 15, Garching 85748, Germany

ARTICLE INFO

Keywords:
Radiation
EDFA
Noise
Figure
Gain
Power

ABSTRACT

Gain, noise figure (NF), and output power are considered the common performance metrics of an optical fiber amplifier. With an increasing interest of space industry in developing technologies for satellite-ground and intersatellite communication in the optical band, the EDFA (erbium doped fiber amplifier) is needed as power amplifier in space to compensate attenuation and insertion losses between the building blocks of the architecture. There is very little research on modeling the degradation mechanisms of typical commercial fibers, specifically on the NF and output power metrics, that requires knownledge of the insertion losses at the entrance of the fiber for both the pump and the signal wavelengths λ_p and λ_s. In this brief report we propose that the noise figure and output power trends can be extrapolated from a semi-empirical model for the insertion losses proved at high and low dose rates at two different temperatures. The results show reasonable trends that a common off-the shelf EDFA can present in co-propagating configuration on the NF and output power under several doses at low and high rates. The radiation losses using non-hardened fiber show sustainable attenuation levels in dB that can possibly allow employing this off-the shelf fibers in CubeSats or small satellites without the need of special radiation insulation. It is further supported with theoretical data that the temperature factor can affect more the EDFA degradation in space than the radiation itself, imposing limits on the temperature control of commercial satellites using this photonics.

Introduction

The technological assessment of high data rate laser link modulators in space was initiated by ESA in 1977 [1]. As optical space communications is on the verge of becoming a reality in small satellites [1], the restricted volumetric dimensions impose system requirements for optical pre-amplifiers (as erbium doped fiber amplifiers, or EDFAs) that are difficult to meet in space. In particular, radiation and thermal cycling are two effects that requires assessment of the degradation over the amplifier performance. The following paragraph presents an introduction to the topic.

On EDFA optical amplifiers

In the state of the art of erbium-doped fibers, several authors have performed studies of EDFAs under radiation environment (e.g. see [2–7]). The general consensus is that the EDFA as a silica fiber attributes formation of color centers due to radiation exposure increasing the absorption losses in the near-infrared and visible regions [8,9]. This leads to insertion losses at the pump and signal wavelenghts that are quantified reducing the amplified power at the final end of the fiber [10,11]. However, exposure of the EDFA to ionizing radiation affect the amplifier performance in several types of forms depending on the fiber composition, temperature of operation and radiation dose and rate of dose [9]. A significant amount of research in the field of photonics has been done to explore approaches for decrease the degradation the amplifier presents when the fiber is exposed to the harsh radiation and thermal cycling. Many of those approaches are summarized in different studies [12–16], proposing manufacture of radiation hardened fibers that do not follow classical fabrication techniques from typical ones (e.g. [17–21]). The characterization of this hardened fibers show good compromises in their gain, noise figure and output power performances in radiation environment of covering typical TID (Total Ionizing Doses) of LEO or GEO, and ongoing research is devoted to unit developments of engineering models of pre-amplifier EDFAs to meet requirements of potential space contractors [21].

In the other hand, in the search of methods for reducing radiation-induced losses on off-the shelf EDFAs, different efforts spread in the last

---

[*] Corresponding author.
E-mail address: amenosis.lopez@tu-braunschweig.de (A.J.R. Lopez-Arreguin).

https://doi.org/10.1016/j.rinp.2019.01.051
Received 12 October 2018; Received in revised form 27 December 2018; Accepted 20 January 2019

years have been developed to model the dependence of the gain of EDFAs with radiation [9,22,7,5,12]. From this work we concluded that there are almost no insights on how to model the amplifier's noise figure profile taking into account temperature and radiation effects. However, from the different studies conducted in hard and non-hard radiation fibers, it is clear that the NF increases while the gain decreases as result of a ionizing environment. The purpose of this paper is to propose a simple methodology to obtain the NF in a ionizing environment standing on a verified model for the radiation losses in dB/m, allowing to employ simple numerical integration of the EDFA propagation equations for the laser power. Given the radiation losses are temperature and dose rate dependent, the results presented here allow to observe the metric decay when the temperature changes or when the dose rate is very high, and draw some conclusions.

Modeling

The general definition of gain is established in terms of the ratio of the output signal power to input signal power, measured over a fiber of lenght z as the following:

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

Normally the amount of Erbium ions in the core of the fiber limit the gain of the amplifier, and above the point all ions are excited the amplifier cannot produce more gain and saturation occurs. Thus, operating in the saturation regime, the signal variation as a function of the lenght z of the fiber $P_s(z)$ is established by a simplified model of Giles-Desurvire for copropagating 980-nm pumped amplifiers as the following:

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

$$\frac{dP_p(z)}{dz} = (\alpha_p + \alpha_p' + \alpha_{pRAD})(N_2(z) - 1)P_p(z) - (\alpha_p + \alpha_{pRAD})N_2(z)P_p(z) \tag{3}$$

Notice the introduction of the pump power $P_p(z)$ in the previous model representing the physical description of the fiber. N_2 is the normalized metastable population given by [23]:

$$N_2(z) = \frac{\frac{\alpha_p P_p}{v_p} + \frac{\alpha s P s}{v_s}}{\frac{\alpha_p}{v_p}P_p + \frac{\alpha_s + g_s}{v_s}P_s} \tag{4}$$

In Eqs. (2) and (4), the radiation-induced losses for signal and pump are α_{sRAD} and α_{pRAD}, g_s is the pre-irradiation gain coefficient of an EDFA, 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. The losses α_{sRAD} and α_{pRAD} are modeled by the following Lorentzian tail following the approach of Bern et al. [5]:

$$\alpha(\lambda)_{RAD} = c\Phi^{1-f}D^f\frac{(1310 - \lambda_0)^2}{(\lambda - \lambda_0)^2} \tag{5}$$

where the total deposited dose is given by D, Φ is the irradiation dose rate, f and c temperature-dependent parameters. The absorption bands are expressed by λ_0. Furthermore, in non-radiative conditions NF of the EDFA can be estimated though [23]:

$$NF = \frac{2g_k}{G}\int_{z=0}^{z=L} N_2(z)\frac{P_s(L)}{P_s(z)}dz + \frac{1}{G} \tag{6}$$

In a former study, the team of Rose et al. [7] established the boundary conditions to determine the NF increase by defining thee insertion losses parameters over a set of high gain and low gain regimes. Such parameters (in our definition) are equivalent to α'_s and α'_p and are held as constants in the radiation experiment. Rose established a computational code based on conventional EDFA equations to compute the radiation induced losses at the pump and signal wavelenghts, α_{sRAD} and α_{pRAD}. However, such authors leaves inconclusive how such degradation losses were assigned. In another study, Williams [8] used an equivalent model with radiation induced losses at the pump and signal wavelenghts that were set as constant values obtained in a post-irradiation experiment. Thus, in past models the latter insertion losses were directly measured to achieve simulations, while the proposition in this paper is based in [5] to use directly Eq. (5).

Simulation results

Low radiation doses

Now we expand the theory to satellite applications. Earth-bounded orbits can be classified in general form according their altitude: Low Earth Orbits (LEO) featuring typical altitudes of 400–1000 km (ISS flyes in a 440 km circular orbit). These type of orbits can present dose rates Φ in the range of 3.7×10^{-4}Gy/h and total doses of up to $D = 16$ Gy (we reference all dose and dose rates according [5]). Medium Earth Orbits (MEO) with altitudes ranging 1000 km up to 35,000 km, with $\Phi = 1.8 \times 10^{-3}$ Gy/h and $D = 78$ Gy. Finally, Geostationary Orbits (GEO) at 35,790 km with $\Phi = 7.8 \times 10^{-4}$ Gy/h and $D = 137$ Gy. Typically, to achieve large Earth coverage communication satellites are placed in GEO orbits, while most of the small satellite programs devoted to Earth remote sensing applications are linked to LEO or MEO orbits. Because radiation doses around Earth are found in very low rates, they seem to affect the gain performance of an EDFA very little over a typical mission lifetime (much less than 1 dB according [5]). However, perfomance on NF and output power an EDFA placed in a satellite could experience is yet to be seen and will be the focus of our study. Table 1 presents the different constant values that were introduced in our previous model, and Table 2 refers to the degradation monitored. A fifth-order Dormand-Price-Kutta method was used to integrate numerically Eqs. (2) and (6) of the EDFA with an adaptive step size algorithm.

High dose rates

The extrapolation of Eq. (5) to high dose rates (much larger than satellites around Earth) has been proved experimentally for the gain in [5]. Thus, the numerical integration of Eq. (2) and (6) will demonstrate the possible degradation of the NF under such environment constraints. This is presented in Figs. 1 and 2. Notice that pre-irradiation ($t = t_0$), the total dose equals $D = 0$ and the metrics for both temperatures tested from the model are very similar each other. Fig. 1 displays the EDFA degradation for 32 Gy/h of dose rate. The general trend seems to be the greater temperature the larger the degradation. The radiation-induced parasitic losses is the dominant factor affecting the amplifier performance, resulting in a gain and output power decay according the total ionizing dose. This is linked to an increasing trend on the NF value for

Table 1
Constant values for EDFA radiation simulation [5].

Parameter[unit]	Value	Symbol
Signal Power [mW]	1.2	$P_s(0)$
Pump Power [mW]	240	$P_p(0)$
Lenght[m]	24	L
Erbium absoption[dB/m]	1.3; 2.9	$\alpha_s;\alpha_p$
Background losses[dB/m*]	4×10^{-3};25×10^{-3}	α_s', α_p'
Gain coefficient[dB/m]	1.314	g_s
Temperature coefficients	0.77, 1.9×10^{-4}, 3×10^{-4}	f, c_{23C}, c_{73C}
Absorption band [nm]	326	λ_0

* at 1310 nm

Table 2
Results of degradation of the EDFA under radiation constraints.

Orbit	*Time*[*] [years]	ΔNF[**] ($\times 10^{-4}$ dB)	$\Delta P_S(L)$[**] ($\times 10^{-2}$ dBm)	ΔNF[#] ($\times 10^{-4}$ dB)
LEO	5	9.5	−7	5
MEO	5	45	−34	26
GEO	20	58 −43	33	

[#] where $\Delta NF = NF_{T=73\,°\mathrm{C}} - NF_{T=22\,°\mathrm{C}}$
[*] where timeframe $t = t_f - t_0$ is D/Φ
[**] where $\Delta(X) = X_{t_f} - X_{t_0}$ at $T = 73$ °C

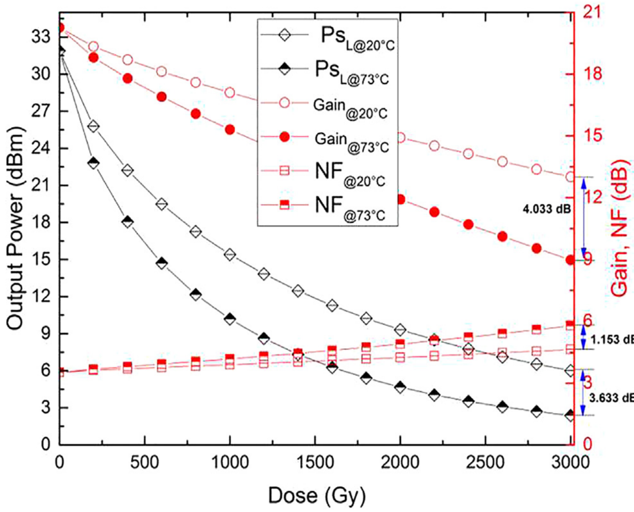

Fig. 1. Simulation of EDFA performance at 32 Gy/h, with a total dose $D = 3000$ Gy equivalent to $t \approx 4$ days of irradiation at constant rate.

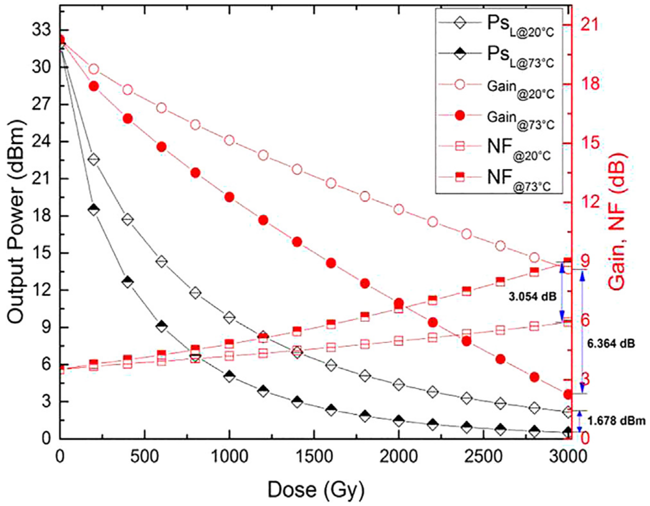

Fig. 2. Simulation of EDFA performance at 269 Gy/h, with $t \approx 11$ days at constant dose rate.

about 0.5 dB larger than the measured pre-irradiation at 20 °C, and about 1.2 dB more than pre-irradiation at 73 °C. As the radiation-induced losses are dependent on the dose rates, the EDFA is more susceptible to larger degradation at 269 Gy/h as observed in Fig. 2. Post-irradiation values are larger for up to 2 dB for 20 °C and up to 5 dB at 73 °C. This confirms the fiber sensitivity increases with dose rate and temperature variation, in a very similar form as presented by previous studies [7]. The loss in gain and increase in NF monitored by Ma et al. [19] on commercial erbium-ytterbium co-doped fibers (EYDF) was 25.08 dB and 3.84 dB after exposure to 1440 Gy/h dose rates for up to 50 krad of ionizing dose (or 500 Gy). This represents respectively a decrease six times and five times larger for the gain and NF here reported at 269 Gy/hr ($T = 73$ °C), after 500 Gy. That seems to be because the larger dose rates the more performance degradation is experienced by commercial EDFAs, and further the deterioration characteristics of EYDFA are much bigger than EDFA's under the same radiation conditions [19].

Conclusions

An equation is complemented to a model to achieve full characterization of the EDFA performance in radiation conditions. The noise figure of a commercial EDFA under characterization has been estimated theoretically by dose breakpoint using a numerical integration scheme with good compromise in computation time. The results presented in this study, complementing the model of Berne et al. [5], suggest that a typical commercial fiber could endure radiation conditions in space under a temperature-controlled environment (e.g. a CubeSat), with minimum degradation to be actually monitored. However, because the EDFA contains isolators and multiplexers that are also sensitive to radiation, achieve a general global model for the degradation will require modeling of the contribution of such elements on the total noise figure increase. Thus, neglecting the remaining losses from other than fiber components the proposed method here could be a reliable estimator, since the general trend of increase of NF according dose has been observed and documented in several studies before, but never modelled. The coupled term dependent on the insertion losses of the rest of the elements of the EDFA can be added to the fiber-dependent value established in Eq. (5).

Acknowledgment

The main author thank to the Institute of Space Systems whom provided the computational resources to perform the simulations presented in this paper.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttps://doi.org/10.1016/j.rinp.2019.01.051.

References

[1] Sodnik Z, Lutz H, Furch B, Meyer R, Optical satellite communications in europe. In: Free-Space Laser Communication Technologies XXII; vol. 7587. International Society for Optics and Photonics; 2010, p. 758705.
[2] Taylor EW, McKinney SJ, Sanchez AD, Paxton AH, Craig DM, Winter JE, et al. Gamma-ray-induced effects in erbium-doped fiber optic amplifiers. In: Proc. SPIE; vol. 3440. 1998, p. 16–23. DOI: 10.1117/12.326691.
[3] Caussanel M, Signoret P, Gilard O, Sotom M, Touboul A, Gasiot J. Assessing space radiation environment effects on erbium-doped fiber amplifier. RADECS 2003. Proceedings of the 7th European Conference on Radiation and Its Effects on Components and Systems. 2003. p. 533–6.
[4] Caussanel M, Signoret P, Gasiot J, Gilard O, Sotom M. Extrapolation of radiation-induced edfa gain degradation at space dose rate. Electron Lett 2005;41(4):168–70. https://doi.org/10.1049/el:20057704.
[5] Berne O, Caussanel M, Gilard O. A model for the prediction of edfa gain in a space radiation environment. IEEE Photonics Technol Lett 2004;16(10):2227–9. https://doi.org/10.1109/LPT.2004.833877.
[6] Li M, Ma J, Zhang X, Song Y, Du W. Investigation of black box model for erbium-doped fiber amplifiers in space radiation environment. J Lightwave Technol 2012;30(23):3667–71. URL: http://jlt.osa.org/abstract.cfm?URI=jlt-30-23-3667.
[7] Rose TS, Gunn D, Valley GC. Gamma and proton radiation effects in erbium-doped fiber amplifiers: active and passive measurements. J Lightwave Technol 2001;19(12):1918.
[8] Williams GM, Putnam MA, Askins CG, Gingerich ME, Friebele EJ. Radiation effects in erbium-doped optical fibres. Electron Lett 1992;28(19):1816–8. https://doi.org/10.1049/el:19921158.
[9] Williams GM, Putnam M, Askins CG, Gingerich ME, Friebele EJ. Radiation-induced coloring of erbium-doped fiber optical fibers. Greenwell RA, Paul DK, editors. Optical Materials Reliability and Testins: Benign and Adverse Environments, vol. 1791. 1993.

[10] Lewis RBJ, Sikora ESR, Wright JV, West RH, Dowling S. Investigation of effects of gamma radiation on erbium doped fibre amplifiers. Electron Lett 1992;28(17):1589–91. https://doi.org/10.1049/el:19921012.

[11] Fukuda C, Chigusa Y, Kashiwada T, Onishi M, Kanamori H, Okamoto S. Gamma-ray irradiation durability of erbium-doped fibres. Electron Lett 1994;30(16):1342–4. https://doi.org/10.1049/el:19940870.

[12] Li M, Ma J, Tan LY, Zhou YP, Yu SY, Che C. A new simple model for edfa incorporated in the irradiated environment for inter-satellite optical communication. J Russian Laser Res 2008;29(3):262–7. https://doi.org/10.1007/s10946-008-9015-4.

[13] Berkdemir C, Ozsoy S. An investigation on the temperature dependence of the relative population inversion and the gain in EDFAs by the modified rate equations. Opt Commun 2005;254(46):248–55.

[14] Nakaji H, Shibata T, Ohmura M, Inoue A, Shigematsu M, Ishizawa Y. A temperature-insensitive erbium-doped fiber amplifier. Optical Amplifiers and Their Applications Optical Society of America; 2003. https://doi.org/10.1364/OAA.2003.TuD5. p. TuD5.

[15] Lee JH, Park N. Reduction of temperature-dependent multichannel gain distortion using a hybrid erbium-doped fiber cascade. IEEE Photon Technol Lett 1998;10(8):1168–70. https://doi.org/10.1109/68.701539.

[16] Liu Q, Ma J, Tan L, Zhou Y, Yu S. Experimental study of the temperature and electron-irradiation effect on erbium-doped fiber amplifiers. J Russian Laser Res 2013;34(3):226–9. https://doi.org/10.1007/s10946-013-9345-8.

[17] Gusarov A, VanUffelen M, Hotoleanu M, Thienpont H, Berghmans F. Radiation sensitivity of edfas based on highly er-doped fibers. J Lightwave Technol 2009;27(11):1540–5.

[18] Thomas J, Myara M, Troussellier L, Burov E, Pastouret A, Boivin D, et al. Radiation-resistant erbium-doped-nanoparticles optical fiber for space applications. Opt Express 2012;20(3):2435–44. https://doi.org/10.1364/OE.20.002435. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-20-3-2435.

[19] Ma J, Li M, Tan L, Zhou Y, Yu S, Ran Q. Experimental investigation of radiation effect on erbium-ytterbium co-doped fiber amplifier for space optical communication in low-dose radiation environment. Opt Express 2009;17(18):15571–7. https://doi.org/10.1364/OE.17.015571. URL: http://www.opticsexpress.org/abstract.cfm?URI=oe-17-18-15571.

[20] Girard S, Laurent A, Pinsard E, Robin T, Cadier B, Boutillier M, et al. Radiation-hard erbium optical fiber and fiber amplifier for both low- and high-dose space missions. Opt Lett 2014;39(9):2541–4. https://doi.org/10.1364/OL.39.002541. URL: http://ol.osa.org/abstract.cfm?URI=ol-39-9-2541.

[21] Stampoulidis L, Edmunds J, Kechagias M, Stevens G, Farzana J, Welch M, et al. Radiation-resistant optical fiber amplifiers for satellite communications. In: Free-Space Laser Communication and Atmospheric Propagation XXIX; vol. 10096. International Society for Optics and Photonics; 2017, p. 100960H.

[22] Williams GM, Wright BM, Mack WD, Friebele, E.J. Projecting the performance of erbium-doped fiber devices in a space radiation environment. vol. 3848. 1999, p. 271–280. DOI: 10.1117/12.372781.

[23] Movassaghi M, Jackson M. Design and compact modeling of saturated erbium-doped fiber amplifiers with nonconfined doping. Opt Fiber Technol 2001;7(4):312–23. https://doi.org/10.1006/ofte.2000.0354. URL: http://www.sciencedirect.com/science/article/pii/S1068520000903547.