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RADIATION-HARD MID-POWER BOOSTER OPTICAL FIBER AMPLIFIERS FOR HIGH-SPEED DIGITAL AND ANALOGUE SATELLITE LASER COMMUNICATION LINKS

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I. INTRODUCTION

Optical laser communications (OLC) has been identified as the technology to enable high-data rate, secure links between and within satellites, as well as between satellites and ground stations with decreased mass, size, and electrical power compared to traditional RF technology. Recent [1] and planned [2, 3] demonstration missions have focused on utilizing the eye-safe 1.55 um telecom wavelength window for short and long range OLC. Operating at 1.55 um provides inherent capability to boost data rates through the use of field-proven terrestrial high-bandwidth photonic components, including electro-optic modulators and photo-receivers, as well as enabling the scaling of aggregate link capacities through Wavelength Division Multiplexed (WDM) technology. On-board OLC systems typically employ Erbium-doped optical fibre amplifier (EDFA) sub-units on the transmit and on the receive sides to boost signal power and pre-amplify low power optical signals before photo-detection. These EDFA sub-units are categorized - depending on the operating input / output power range - into low noise pre-amplifiers, mid-power booster~~s~~ amplifiers and high-power amplifiers.

Mid-power booster EDFAs delivering output powers in the range of 16-23 dBm can be used in diverse mission scenarios. To date, the wide application range of mid-power boosters in OLC includes short-range LEO to Ground downlinks, long range GEO / gateway optical feeder links and intra-satellite analogue links. In high speed LEO-to-Ground links the booster EDFAs are used to amplify the output of a directly or externally modulated transmitter laser and enable free space transmission over a typical 900 km to 2000 km distance. In long range GEO links (or even deep space links) the mid-power booster EDFA is typically part of an amplifier chain, pre-amplifying the transmitter signal to saturate a cascaded Watt-level high power amplifier and enable free space transmission over >30.000 km. Finally, in future photonics-enabled multi-beam analogue repeaters, booster EDFAs are expected to be used to compensate losses of microwave photonic mixers and optical switches which convert and route RF signals in the optical domain.

The design and development of such space mid-power booster EDFAs represent a number of challenges and performance trade-offs compared to conventional terrestrial fiber amplifiers. Firstly, the well documented susceptibility of Erbium doped fibers to ionizing radiation requires that gamma radiation effects are taken into account during amplifier design and definition of the amplifier optimum parameters (pump power, doped fiber length) in order to optimize End-of-Life (EOL) amplification performance. In the specific case of booster amplifiers, this requirement is critical due to the amplifier operation under low population inversion levels. This operation regime is often chosen in mid-power booster EDFAs to improve power conversion efficiency (PCE), but can also lead to a pronounced impact of radiation effects.

Secondly, the design of the space mid-power booster EDFAs has to comply with the spacecraft electrical power resource specifications and component de-rating requirements. Given that satellite resources are typically well defined and restricted, the space EDFA design has to enable a high PCE through optimization of the amplifier topology and pumping configuration. Again the EDFA EOL performance has to be carefully defined in the context of the mission environmental constraints as well as the mission operational specifications. Finally, the booster EDFA topology has to be engineered according to the OLC link specifications such as wavelength channel plan and noise performance to achieve optimum performance trade-off between optical performance and electrical power requirements.

In this paper we present progress on the design and development of radiation-hard 1.55 um mid-power booster EDFAs for OLC satellite terminals. Specifically, we present the design and experimental testing of two different EDFA mid-power booster designs optimized for low-dose LEO-to-Ground downlink and high-dose telecom satellite applications. The EDFA designs are tailored in the sense that they meet different OLC link EOL

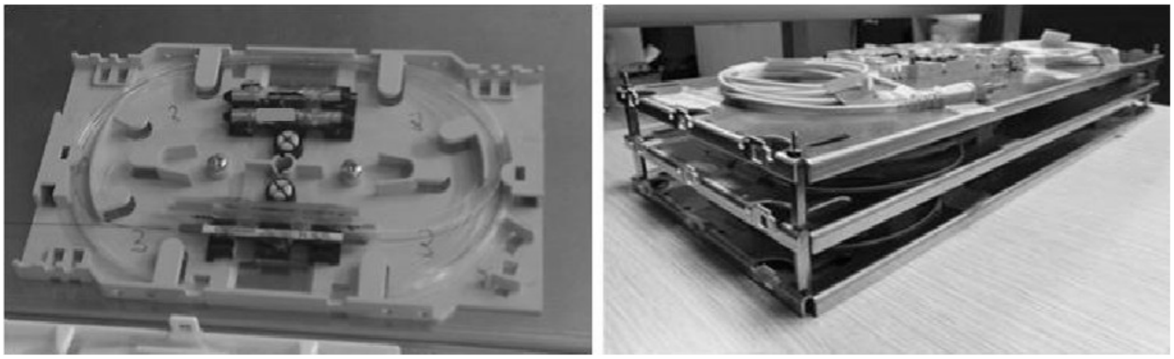

Fig. 1. Assembled EDFA optical engine under test (left) and EDFA optical engines mounted on Aluminum chassis suitable for transportation to the test-house (right)

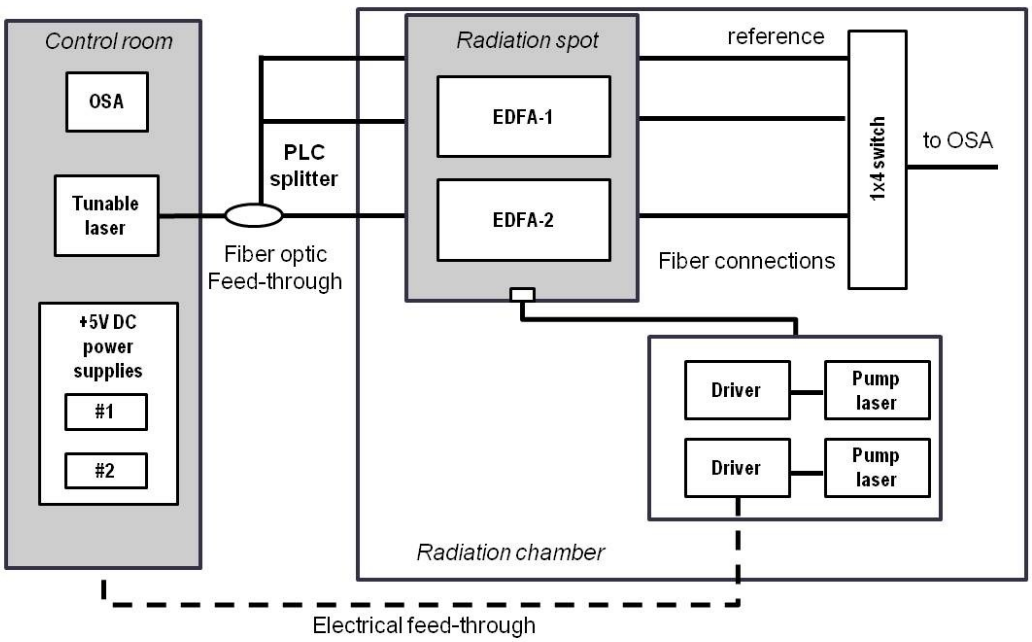

Fig. 2. Radiation test set-up

performance specifications, which are defined within different Total Ionizing Dose (TID) levels and different duty cycle operation.

EDFA optical engines were assembled, irradiated with gamma radiation up to 100 krad TID and monitored in-situ in terms of gain and noise figure (NF). For the LEO-to-Ground downlink application, we demonstrate a booster EDFA with an EOL output power of +20 dBm over the C-band and a radiation-induced gain drop and noise figure increase of <0.55 dB and <0.21 dB respectively under 10 kRad TID. For the telecom satellite application, we demonstrate a booster EDFA with an output power of +18 dBm over the C-band and a gain drop and noise figure increase of <3.12 dB and 0.35 dB respectively at 100 kRad TID.

II. RADIATION TEST: SAMPLES, SET-UP and CONDITIONS

Fig. 1 illustrates the EDFA test modules to be irradiated. Optical fiber amplifier engines were assembled within fiber-optic enclosures that facilitate component placement and fiber routing. The test samples include the passive EDFA fiber optic components, which are Telcordia qualified fiber optic isolators and WDM signal / pump combiners spliced to the doped fiber. The fiber optic isolators are high-rel components used in high-end terrestrial network applications. The WDM signal / pump combiners are developed in-house by G&H and are fabricated with high-reliability fused coupler technology which is proven for space flight demonstration [4]. Similar G&H fused fiber optic components have passed space evaluation tests and are flying on-board the ESA SMOS mission.

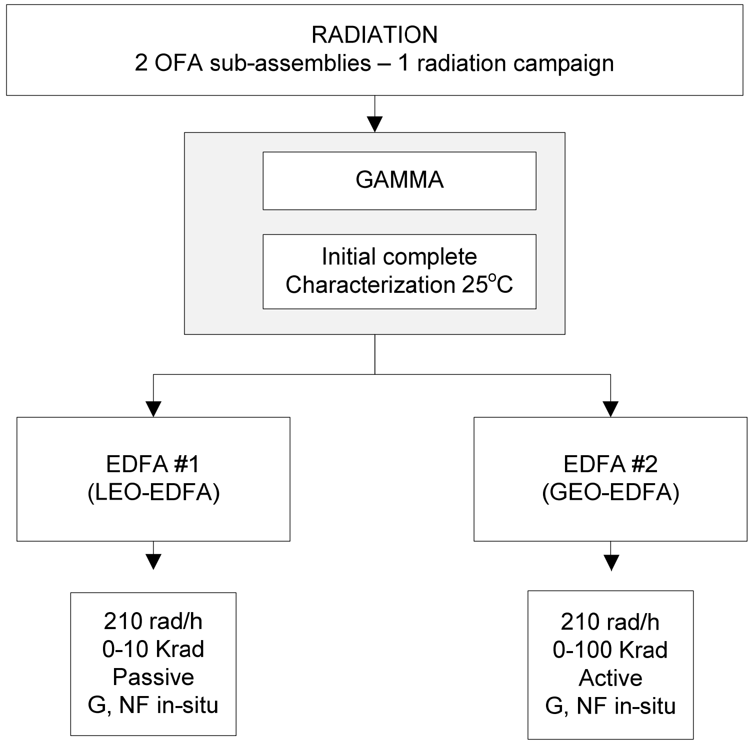

Fig. 3. Radiation test flow and conditions

In this sample-under-test configuration radiation-induced losses affect the whole EDFA fiber optic sub-assembly. By performing post-irradiation functional tests on the individual EDFA passive components, any sources of degradation additional to the RIA in the doped fiber can be identified.

Radiation tests have been conducted in collaboration with the ALTER test house in CNA (Centro Nacional de Aceleradores) Gamma Facility in Seville, Spain. The gamma irradiation test was performed at room temperature using CNA ^{60}Co source at a dose rate of 210 rad/h. Fig. 2 illustrates the test set-up. The EDFA sub-assemblies were mounted on the radiation spot whereas the pump lasers were placed within the radiation chamber but outside the radiation spot. Finally, the seed laser and all test and measurement equipment (Optical Spectrum Analyzer, optical power meter, electrical power supplies) were placed in the facility control room.

Fig. 3 illustrates the test flow. The two sub-assemblies, denoted as EDFA-1 and EDFA-2, are tested under different TID and pump configuration to resemble the different mission operation modes. EDFA-1 is tested for 10 kRad TID to simulate the total dose expected within a LEO mission scenario. In this case, the duty cycle operation of the EDFA is low since the on-board terminal obtains line-of-sight and communicates with the ground station for a limited amount of time over the entire mission lifetime. The low duty cycle operation represents an opportunity for energy saving and satellite system providers typically consider that the equipment will remain idle (i.e. switched-off) during the non-contact periods. As such, EDFA-1 is tested in passive mode, i.e. the pump signal is kept in "OFF" state until reaching the 10 krad TID, simulating the worst case scenario where the on-board EDFA is switched once during the mission lifetime. EDFA-2 is tested for 100 kRad in order to assess the performance of the amplifier in a typical telecom satellite mission. Due to the GEO orbit and the application context, on-board photonic systems are expected to operate continuously. As such EDFA-2 is tested under active pumping, i.e. the pump signal is kept in "ON" state for the whole test duration (0-100 kRad).

III. RADIATION TEST RESULTS: LEO-EDFA APPLICATION

EDFA-1 is designed to comply with the EOL optical, electrical and environmental specifications listed in table 1. The EDFA critical parameters, including pump power and doped fiber length are selected considering mission EOL performance. An output power of +20 dBm is considered typically sufficient for such low-orbit communications.

Parameter (EOL)	Specification	Unit
Saturated Output Power	+20	dBm
Wavelength Range	1540 – 1565	nm
Signal Gain (0 dBm input)	>20	dB
Noise Figure (typ.)	<7	dB
Power Consumption	<3.5	Watt
Ionizing Radiation (TID)	<10	kRad

Table 1. EDFA-1 Basic opto-electronic and environmental specifications

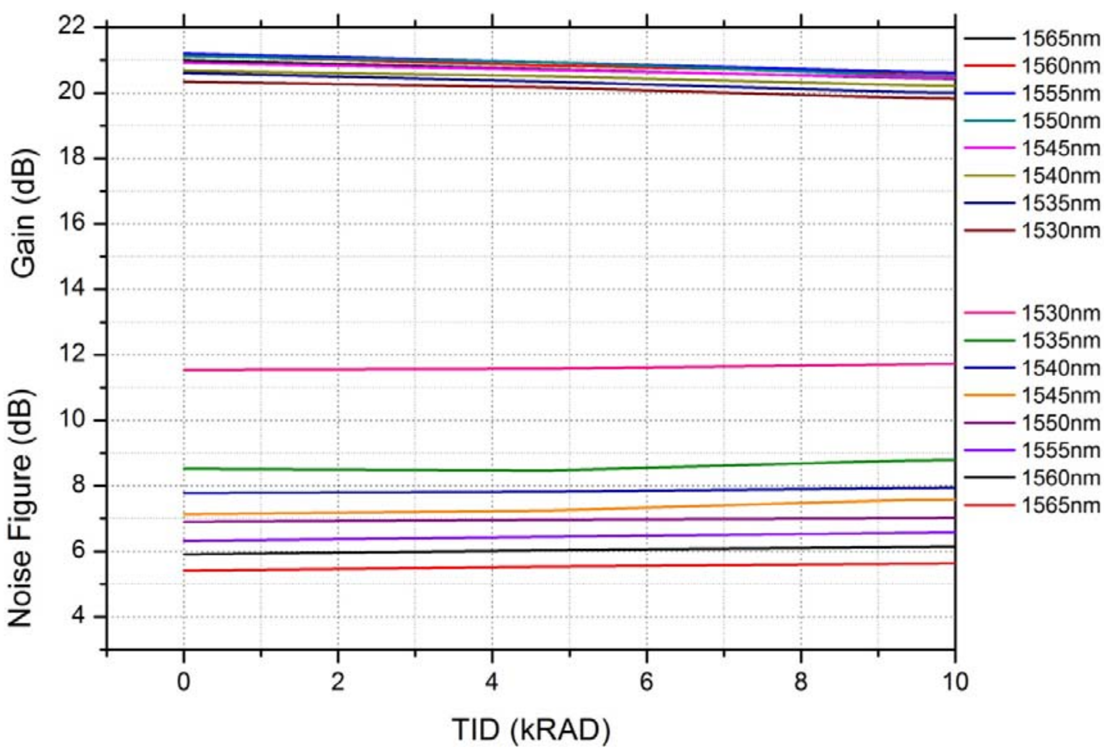

Fig. 4. EDFA-1 radiation test results: Gain and NF performance for 0-10 kRad TID.

An operating wavelength range of 1540 - 1565 nm is defined to be compatible with CWDM technology which is expected to be used in LEO applications. A typical (at 1550 nm) NF of 7 is specified. EDFA-1 is tested under 10 kRad which is the typical TID in LEO orbit assuming standard equipment shielding.

Fig. 4 illustrates the Gain and NF performance over the entire C-band (1530 - 1565 nm) for 0 to 10 kRad TID with 0 dBm input power for EDFA-1 using the in-situ monitor set-up. The Gain and NF values obtained for the different wavelengths confirm that the EDFA has been designed and optimized to provide high Gain and low NF values for the specified operating wavelength band of 1540 - 1565 nm. The results also indicate that the EDFA is capable ~~to~~ of maintaining the +20 dBm output power at 10 kRad even when operated in passive mode and with an electrical power consumption of 3.5 W, which takes into account opto-electronic and electronic component de-rating. The typical NF (1550 nm) at 10 kRad is 7 dB, which is compliant to the EDFA EOL

Parameter		Wavelength (nm)	
		1540	**1565**
Gain @ 0 dBm input	Gain pre-irradiation (dB)	20.68	21
	Gain @ 10 krad (db)	20.23	20.45
	Gain drop (dB)	**0.45**	**0.55**
Noise Figure	NF pre-irradiation (dB)	7.78	5.41
	NF @ 10 krad (dB)	7.94	5.62
	NF variation (dB)	**0.16**	**0.21**

Table 2. EDFA-1 Gain and NF radiation test results

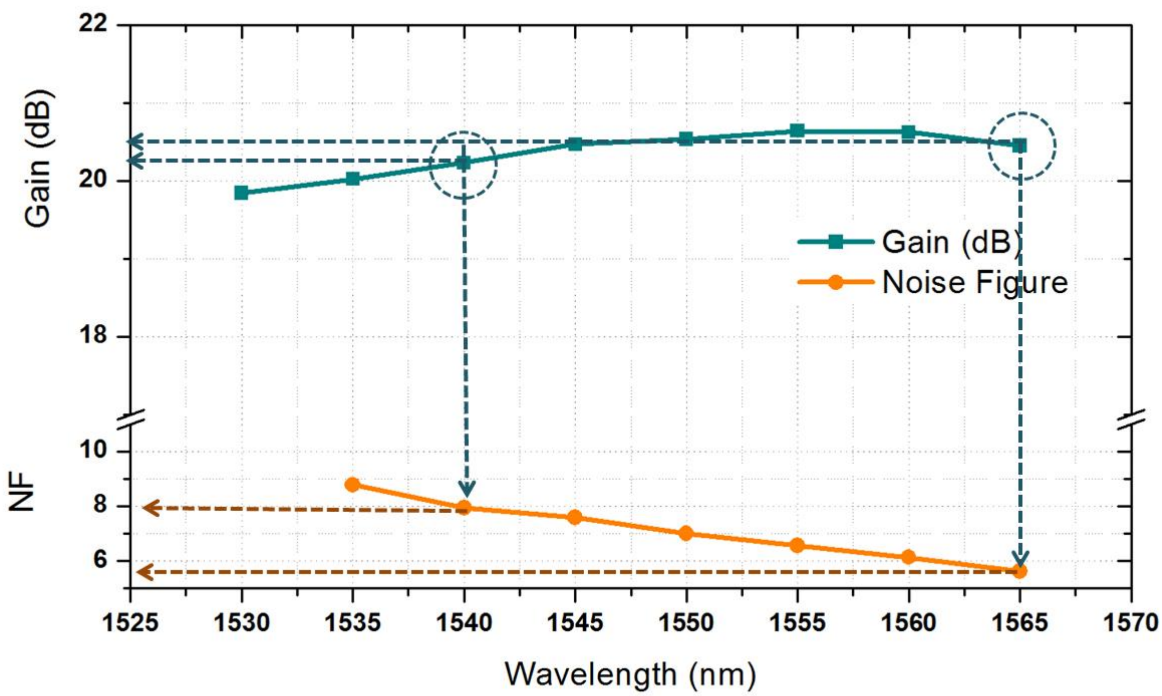

Fig. 5. EDFA-1 Gain and NF performance at 10 kRad TID with 0 dBm input power

operation. Table 2 illustrates the Gain drop and NF increase at 1540 nm and 1565 nm wavelengths. The maximum gain drop is 0.55 dB and the maximum NF increase is 0.21 dB both obtained for 1565 nm wavelength channel. Fig. 5 presents the amplifier performance results at 10 kRad TID over the specified operating wavelength range of 1540 to 1565 nm.

IV. RADIATION TEST RESULTS: GEO-EDFA APPLICATION

According to the GEO telecom satellite mission scenario, the EDFA-2 is designed to comply with the EOL optical, electrical and environmental specifications listed table 3. Similarly to the previous case, the EDFA critical parameters are selected considering mission EOL performance requirements.

An output power of +18 dBm is considered typically sufficient for use as pre-amplifying booster or loss compensator in a telecom payload. An operating wavelength range of 1530 - 1565 nm is defined. The broader wavelength range is required in this case due to the potential extended use of DWDM technology, for scaling the aggregate capacity of telecom intra-satellite or satellite to ground links. As such EDFA-2 is specifically

Parameter (EOL)	Specification	Unit
Saturated Output Power	+18	dBm
Wavelength Range	1530 – 1565	nm
Signal Gain (0 dBm input)	>18	dB
Noise Figure (typ.)	<6	dB
Power Consumption	<3.5	Watt
Ionizing Radiation (TID)	<100	kRad

Table 3. EDFA-2 Basic opto-electronic and environmental specifications

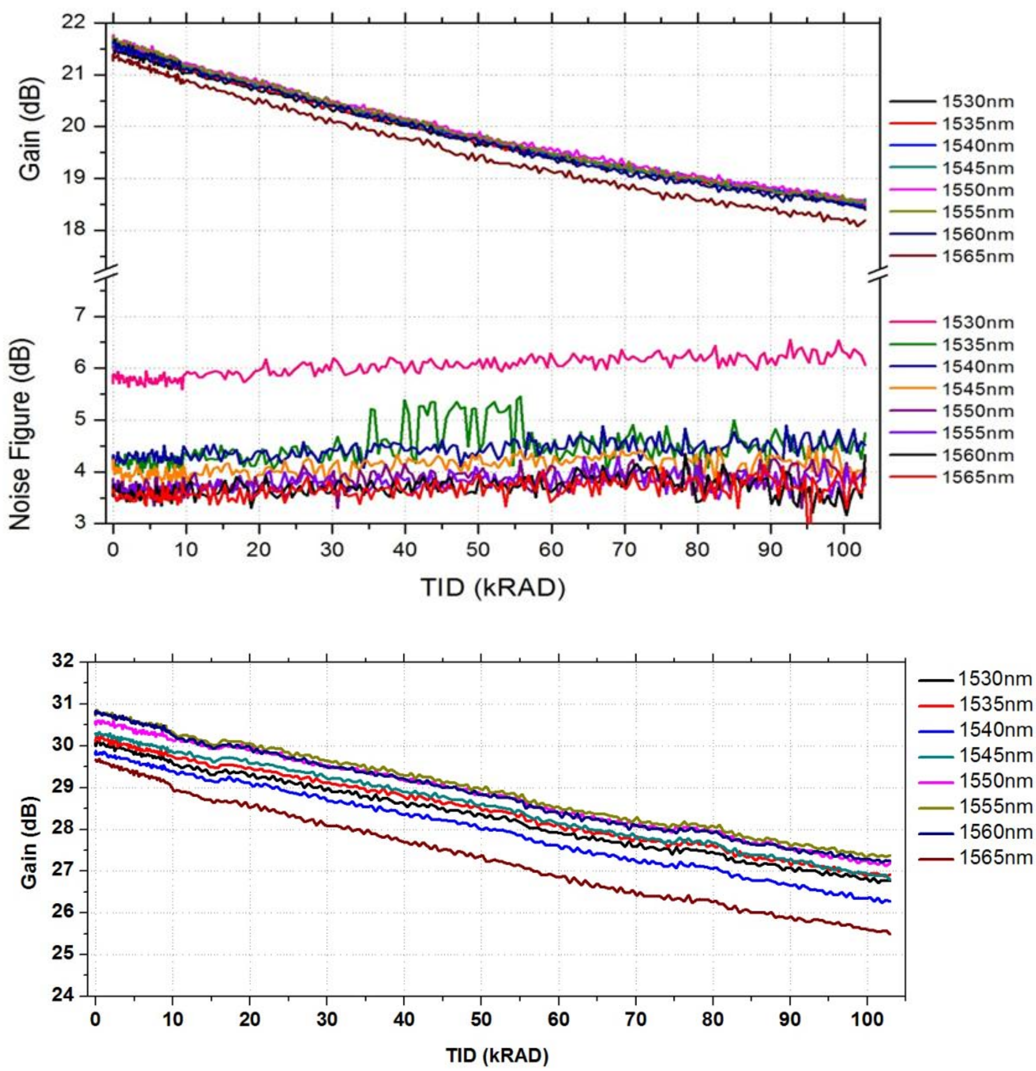

Fig. 6. Gain and NF performance of EDFA-2 from 0-100 kRad with 0 dBm input power (top) and with -10 dBm input power (bottom)

Parameter		**Wavelength (nm)**	
		1530	**1565**
Gain @ 0 dBm input	Gain pre-irradiation (dB)	21.52	21.27
	Gain @ 100 krad (db)	18.4	18.19
	Gain drop (dB)	**3.12**	**3.08**
Noise Figure	NF pre-irradiation (dB)	5.71	3.6
	NF @ 100 krad (dB)	6.06	3.9
	NF variation (dB)	**0.35**	**0.3**

Table 4. EDFA-2 Gain and NF radiation test results

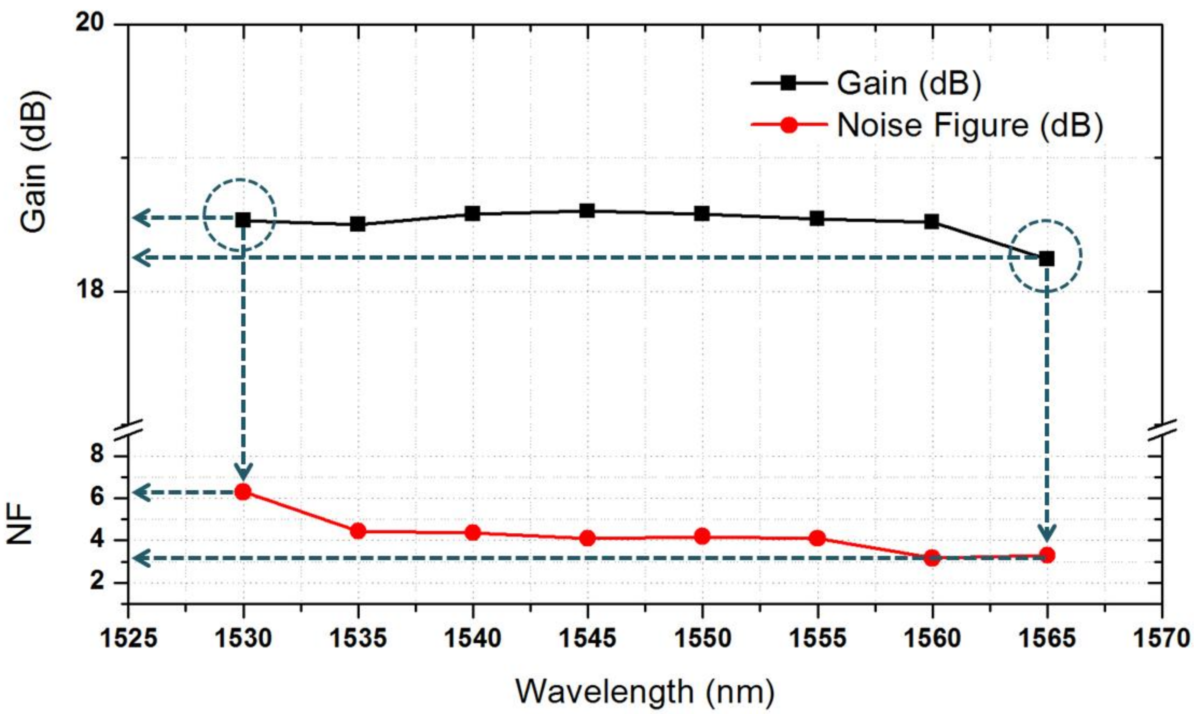

Fig. 7. EDFA-2 Gain and NF performance at 100 kRad TID with 0dBm input power

designed to provide a flat gain spectrum and low noise operation over the entire C-band. EDFA-2 is tested up to 100 kRad, which is the typical radiation level imposed on the equipment within the telecom satellite. Depending on payload architecture and corresponding equipment designs, the TID levels are expected to range between 60 kRad to 100 kRad, assuming equipment shielding.

Fig. 6 shows the evolution of Gain and NF over the 1530 - 1565 nm for 0 kRad to 100 krad TID. The results indicate that this EDFA is operated under a higher inversion level to enable low noise levels over the entire C-band. The EDFA is capable ~~to~~ of maintaining the +18 dBm output power at 100 krad and an output power of +19 dBm at 60 kRad. The typical NF (1550 nm) at 100 kRad is 4 dB which is compliant to the EDFA EOL specifications.

Table 4 illustrates the Gain drop and NF increase at 1530 nm and 1565 nm wavelengths. The maximum gain drop at 100 kRad is 3.12 dB and the maximum NF increase is 0.35 dB, both obtained for 1530 nm wavelength channel. Figure 7 presents the amplifier performance results at 100 kRad TID over the specified operating wavelength range of 1530 to 1565 nm. The results demonstrate that the amplifier is capable ~~to~~ of delivering the +18 dBm specified output power with low noise levels over the entire C-band and at an electrical power consumption of 3.5 W which takes into account EOL operation.

V. CONCLUSIONS

We have demonstrated the development and radiation testing of mid-power booster optical fiber amplifiers applicable to 1.55 um OLC earth observation and telecommunication satellite missions.

Gamma radiation tests on the optical fiber amplifiers were carried out under total irradiation doses found in Low-Earth and Geostationary orbit satellites. The radiation results verify the robustness of the design and the components used, as the recorded radiation induced degradation allows the amplifiers to remain within the stringent End of Life specifications.

Specifically, the EDFA designed for LEO application (10 kRad TID range) delivers +20 dBm output power, which is maintained even at the worst case scenario of passive operation accommodating significant energy savings by using the amplifier in switched-mode, i.e. operating only during contact with the ground station. A NF variation as low as 0.21 dB has been achieved. The EDFA designed for the telecom satellite application (60-100 krad TID range) delivers +18 dBm output power when operated in active mode and achieves low noise performance (NF<6) over the entire C-band enabling the deployment of dense WDM technology to scale telecom link capacities to multi-Gigabit ranges.

The validation of the above EDFA designs facilitates the implementation of the next phase, which is the development of Engineering Qualification Model (EQM) and subsequently Proto-Flight (PFM) and Flight Model (FM) mid-power booster EDFA variants. In parallel, the validation of EDFA designs for low noise optical pre-amplifiers (30 dB to 50 dB gain) and high power boosters (+27 dBm to +40 dBm) is underway, under support of ESA and the EU towards the development of a full family of qualified space EDFAs for diverse 1.55 um OLC missions.

VI. ACKNOWLEDGMENT

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