Compact radiation resistant, high-gain optical fiber preamplifier for small 1.55 um laser-com terminals

Leontios Stampoulidis
LEO Space Photonics
Athens, Greece
ls@leo-sprd.eu

Ahmed Osman
LEO Space Photonics
Athens, Greece
ao@leo-sprd.eu

James Edmunds
Gooch & Housego
Torquay, UK
jedmunds@gandh.com

Clive Palmer
Gooch & Housego
Torquay, UK
cpalmer@gandh.com

Keith Simpson
Gooch & Housego
Torquay, UK
ksimpson@gandh.com

Anaelle Maho
Thales Alenia Space
Toulouse, France
anaelle.maho@thalesaleniaspace.com

Michel Sotom
Thales Alenia Space
Toulouse, France
michel.sotom@thalesaleniaspace.com

***Abstract*—We present the development of a radiation resistant erbium doped fiber pre-amplifier suitable for integration in small satellite laser communication terminals. The work has been performed within the frames of EU H2020-SPACE-ORIONAS project.**

***Keywords*—Erbium doped fiber amplifier, free space optical communications, laser communication terminal, reduced clad fibers**

I. Introduction

The reduction of system size and mass is critical for the wide deployment of laser communications within small satellite platforms. Laser communication terminals (LCTs) targeting LEO satellite constellations are specified to weigh <10 kg, whereas CubeSat LCTs feature 10 times smaller mass and sub-1U volumes. As such the photonic devices used in the lasercom modems must be designed to fit fiber optic and opto-electronic elements into very small form factor (SFF) modules. One of these devices is the optical pre-amplifier which is used on the receive side of an optical inter-satellite link (OISL). High gain and low noise optical pre-amplifiers rely on Erbium doped fibers (EDFs) as the gain medium and deploy a number of passive and active fiber optic components. The use of multi-stage topologies as well as the deployment of redundancies within the module to enhance reliability, increase the component count and hence the mass of hi-rel optical amplifiers. Apart from the bill-of-material (BoM), the main driving factor for the module size and weight is the bend radius of the active and passive optical fibers. Standard 250 um cladding diameter fibers feature a minimum bend radius of 25 mm which directly affects component placement and hence the module footprint. Reduced clad Erbium doped fibers (RC-EDF) and hi-rel SFF components can be exploited to reduce significantly the amplifier size and weight by allowing tight fiber bending and coiling within the module. In such case RC-EDFs have to be evaluated against radiation effects due to the EDF sensitivity to ionizing radiation as well as due to the fact that radiation hard RC-EDFs are not commercially available.

In this paper we present the development of a SFF radiation resistant optical pre-amplifier suitable for compact laser communication terminals carried out within the framework of the ORIONAS H2020-SPACE project [1]. The device compactness is enabled by the use of hi-rel SFF components developed for gyroscope applications and an active fiber that has been selected following gamma radiation testing of COTS RC-EDFs. By selecting a radiation resistant RC-EDF we demonstrate high gain optical pre-amplification with radiation induced gain drop (RIGD) in the range of 2.75 dB at 40 krad. The device mass is as small as 100 grams and has a footprint of 48.6 cm^2.

The paper is organized as follows. Section II reports the radiation evaluation of the COTS RC-EDFs. Section III reports the development of an optical pre-amplifier bread-board model (BBM) assembled for functional verification testing of the amplifier topology. Section IV reports the development of the compact optical pre-amplifier engineering model (EM) which is form fit and function (FFF) equivalent of a qualification model (QM) with the exception of using a commercial-grade printed circuit board assembly and COTS electronic parts. Finally, Section IV reports the functional testing of the BBM and EM in optical transmission experiments with 25 Gb/s OOK and DPSK signals. A receiver sensitivity of -42.5 dBm at BER 10^{-3} for 25 Gb/s DPSK format is achieved when using the BBM optical pre-amplifier, with 2 dB sensitivity penalty recorded for the EM module which is attributed to bend induced losses. Receiver sensitivity penalties can be further improved for the EM model by optimizing the module packaging and adjusting the signal wavelength.

II. Radiation evaluation of RC-EDF

A. Pre-irradiation testing

Four RC-EDFs, referred to below as samples A1, A2, A3 and A4, were procured from 3 different suppliers. The fibers exhibit a RC diameter of 80 um which would allow tight bending below 10 mm radius depending on target lifetime and proof test levels used during assembly. The fibers were spliced into four 2-stage amplifier fiber optic sub-assemblies (FOSA) for pre-irradiation testing, using co-propagating pumping for stage-1 and counter-propagating pumping for stage-2.

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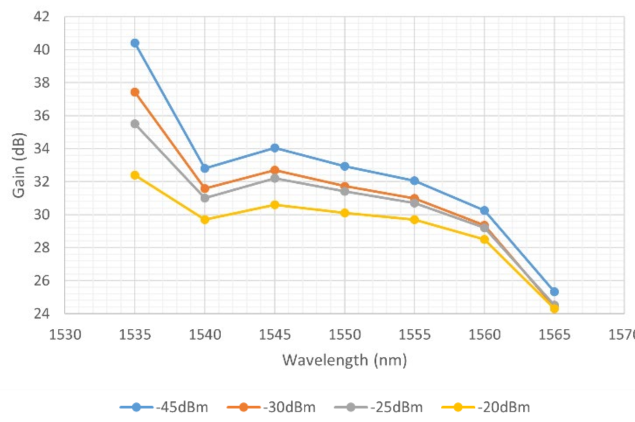

Fig. 1. Stage-1 pre-irradiation optical gain as a function of wavelength and input power for FOSA deploying sample A1.

The EDFs exhibited different pump absorption levels and their lengths have been adjusted to provide similar optical gain at a fixed pump power. RC-RDF lengths were optimized to deliver ~34 dB of optical gain in the first stage and a combined amplifier gain of >50 dB at 1550 nm and -45 dBm input power. Figures 1 and 2 show the plots of the optical gain as a function of wavelength and input power at the output of stage-1 (Fig. 1) and at the output of the FOSA (Fig. 2) that was built with A1 RC-EDF sample. Similar gain curves were obtained by the FOSAs built using A2, A3 and A4 RC-EDF samples.

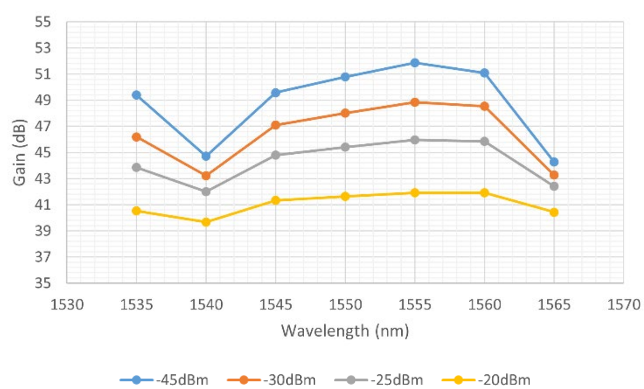

Fig. 2. Stage-1+2 pre-irradiation optical gain as a function of wavelength and input power for FOSA deploying sample A1.

B. Post-irradiation testing

RC-EDF samples were delivered for gamma irradiation up to 40 krad TID. The dose rate that was used was 22.46 Gy/h. The TID test was carried out in the Náyade installation of CIEMAT (Centro de Investigación Energética Medioambiental y Tecnologica) in collaboration with ALTER. The fibers were irradiated passively, i.e there was no light injection during the test – this represents the worst case scenario as there is no photo-bleaching taking place during irradiation.

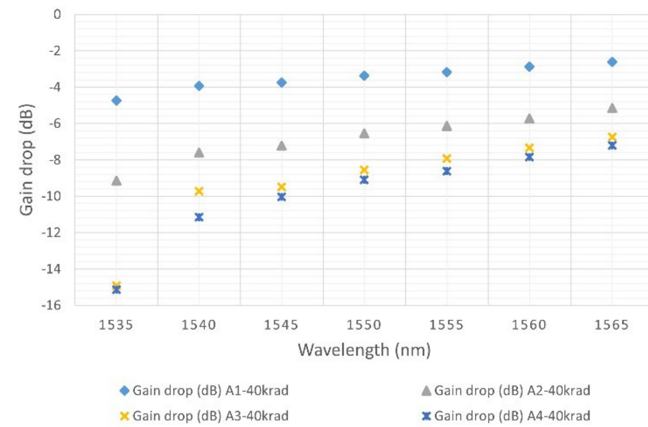

Fig. 3. Stage-1 post-irradiation optical gain drop as a function of wavelength for -45 dBm input power.

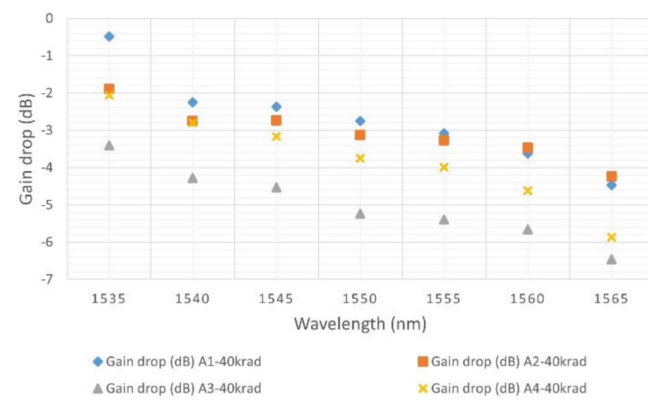

Fig. 4. Stage-1+2 post-irradiation optical gain drop as a function of wavelength for -45 dBm input power.

Following irradiation, the RC-EDF samples were used to re-build the FOSAs for post-radiation testing. Fig. 3 shows the stage-1 radiation-induced optical gain drop obtained using the four irradiated RC-EDFs. The comparison between pre and post radiation gain (reference wavelength 1550 nm) shows that RC-EDF A1 demonstrated a radiation induced gain drop (RIGD) of 3.37 dB, which is approximately 2 times lower than A2 (6.54 dB) and ~4 times lower than A3 (8.55 dB) and A4 (9.1 dB). Fig. 4 shows the RIGD measured at the output of each FOSA at 40 krad. At 1550 nm, the amplifier built with sample A1 exhibited a RIGD of 2.75 dB whereas A2, A3 and A4 exhibited RIGD of 3.13 dB, 5.24 dB and 3.75 dB respectively.

III. BBM Assembly, Integration and Test

A BBM optical pre-amplifier unit was assembled and integrated using RC-EDF A1. The optical circuit topology was modified compared to the FOSA assemblies with the aim to enhance the radiation resistance. Fig. 5 (top) shows the assembled BBM which relies on G&H proto-flight EDFA heritage unit [2]. The BBM was developed as a gain module, deploying commercial-grade fiber optic components and pump lasers. The pump lasers were driven by OEM laser drivers externally to the unit. The unit dimensions (L x W x H) are 169.6 x 159.5 x 24.5 mm, including the mounting fixtures. The

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BBM provides optical access between the two amplifier stages to enable the use of an optical filter. Fig. 5 (middle) shows the optical gain measurements as a function of wavelength and input power when a 0.8 nm mid-stage optical bandpass filter is used. The unit delivers ~62 dB small signal gain at 1550 nm and -45 dBm optical input power. The gain compresses to 47 dB at -25 dBm corresponding to +22 dBm saturated output power. Fig. 5 (bottom) shows the evolution of NF as a function of input signal wavelength for -45 dBm input power. The NF ranges between 4.76 and 4.05 dB and is measured at 4.15 dB for a typical wavelength of 1550 nm. The inset shows typical optical spectra which indicate an OSNR of ~10 dB for 1540 to 1565 nm wavelength range.

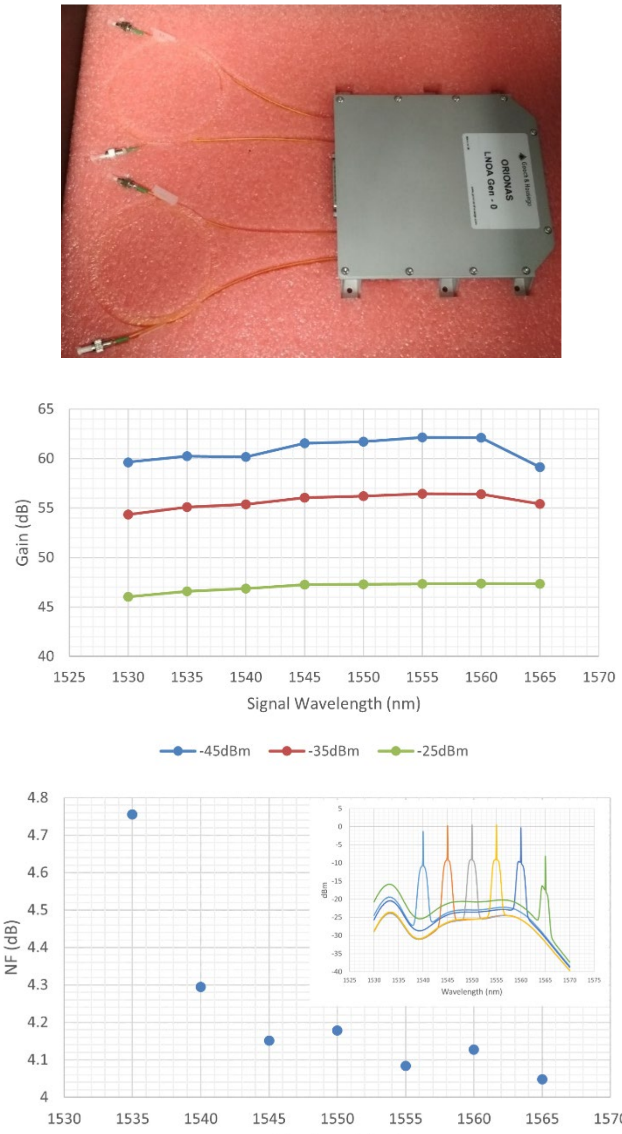

Fig. 5. (top) BBM optical pre-amplifier unit, (middle) optical gain as a function of wavelength and input power at the amplifier output and (bottom) NF as a function of input signal wavelength. The inset shows the optical spectrum trace at the amplifier output for 1540 – 1565 nm wavelength range.

The amplifier measurements were obtained for a pump laser driving current equal to the maximum de-rated current, which is defined as 80% of the laser kink-free current.

IV. EM Assembly, integration and test

Following BBM verification, an engineering model (EM) of the compact radiation resistant optical pre-amplifier was assembled and integrated. In order to demonstrate form factor reduction with respect to the BBM heritage model, sub-miniature fiber components with a reduced diameter (80um) cladding have been used and packaged with a tight fiber bending within the module. All the fused components are manufactured in-house by G&H according to high-rel and space compliant processes. The opto-electronic components employed in the unit are Form-Fit-Function (FFF) equivalent to the ones used in a QM/FM. The same applies to the fused fiber optic components.

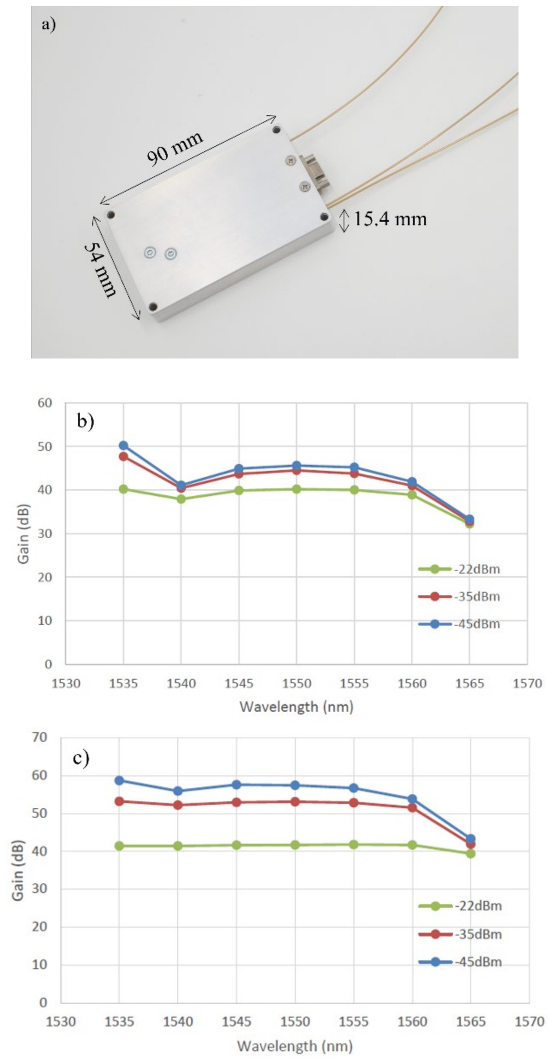

Fig. 6. a) EM optical pre-amplifier module, b) optical gain as a function of wavelength for -45, -35 and -22 dBm input power and c) optical gain as a function of wavelength for -45, -35 and -22 dBm input power when a 0.8 nm mid stage filter is used.

The EM unit also comprised a printed circuit board assembly containing electronic laser drivers as well as control electronics. The electronic components are COTS replaceable by hi-rel parts in the scope of building a higher TRL unit. As such the optical performance of the unit is expected to be representative to the performance of higher TRL grade units. The assembled module is shown in Fig. 6a). The module weighs 103 grams and its dimensions (LxWxH) are 90 mm x 54 mm x 15.4 mm. Optical and electrical interfaces are on one face to minimize the space required for connections. The module is designed to be mechanically mounted to a heat dissipating surface with four bolts. The four mounting bolts also provide additional fastening of the module lid at the corners - this keeps the footprint small by avoiding the need for mounting feet. The module has a 1.5 mm wall thickness providing radiation shielding. Additional local shielding for the RC-EDF is provided within the module. Optical interfacing is via feedthrough pigtails exiting the front of the module (same side as electrical connector). Optical interfaces include input, output and mid-stage access to allow use of an external filter. The exit of the fibre from the housing is protected by PEEK sleeving. The fibre on these pigtails is SMF28e+ or similar with a 125um cladding. In terms of optics, the unit includes pump redundancy on both amplifier stages as well as mid stage and output power monitors. Communication with the module is done through an embedded RS232 interface. Through this interface, the user can control the bias current of the pump diodes, get access to power monitors as well as monitor the internal PCB temperature. The unit supports constant current and constant power modes. The BOL power consumption is in the range of 4W. Fig. 6b) shows the amplifier optical gain as a function of wavelength for three input power levels. At -45 dBm the gain is over 45 dB at a typical wavelength of 1550 nm, whereas the saturated output power is measured at +18 dBm for an input power of -22 dBm. Fig. 6c) shows the results when a 0.8 nm is used as a mid-stage filter. Due to the ASE rejection the optical gain is extended above 55 dB at 1550 nm and above 40 dB at 1565 nm. The NF of the unit at a typical wavelength of 1550 nm is ~5 dB. The increase in NF compared to the BBM is attributed to bend-induced losses and can be further suppressed with optimization of the component placement within the unit.

V. Evaluation in optical transmission testbed

The BBM and EM units were evaluated in a transmission testbed with 25 Gb/s OOK and DPSK PRBS15 signals. Fig. 7 (top) shows a schematic of the transmission configuration including at the transmitter side a Continuous Wave (CW) Distributed Feedback Laser (DFB) laser, a Mach Zehnder Modulator (MZM) and a High Power Optical Amplifier. At the receiver side, after the low noise optical amplifier (LNOA), the demodulation depends on the chosen optical modulation format either a simple photoreceiver for OOK or a Delay Line Interferometer (DLI) cascaded by a balanced photoreceiver for DPSK. The optical channels were set either at 1542 nm or 1554 nm. Bit Error Ratio (BER) as a function of the optical received power at the input of the LNOA was measured. More details on the testbed configuration are provided in [3]. Fig. 7 (bottom) shows the BER measurements obtained when using the BBM and EM models as the LNOA for OOK and DPSK modulation schemes. With the BBM unit and 1554 nm 25 Gb/s DSK input signal, the measured receiver sensitivity was -40.5 dBm at BER=10^{-4} and -34.8 dBm for BER=10^{-9}. A penalty of 5 dB was measured for OOK signal modulation.

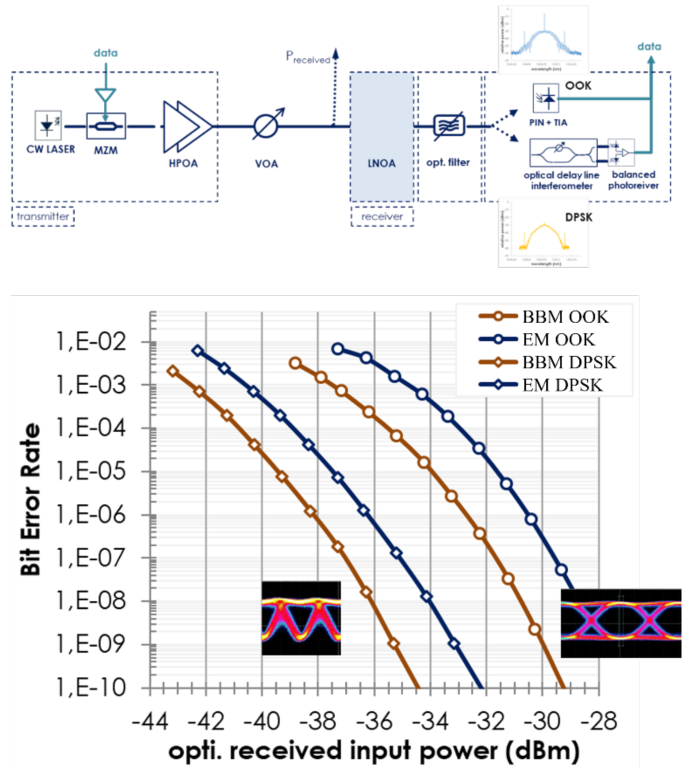

Fig. 7. (top) Schematic of optical transmission testbed, (bottom) BER measurements using the BBM and EM units as the LNOA for OOK and DPSK modulation format

Using the EM unit as the LNOA, a receiver sensitivity penalty of 2 dB was measured compared to the BBM. This is attributed to the higher NF of the EM unit. This penalty was reduced to <1 dB when a shorter wavelength of 1542 nm was used. This is due to the fact that shorter wavelengths exhibit a smaller bend induced loss and as such noise performance is improved.

VI. Conclusion

We have reported the development of a compact radiation resistant optical fiber pre-amplifier applicable to 1.55 um satellite laser communication links. The device features a footprint of 48.6 cm^2 and a volume of 74.8 cm^3 which are 82% and 88.7% smaller than the footprint and volume of a proto-flight optical amplifier heritage model. The amplifier delivers up to 57 dB of optical gain at 1550 nm. The module features RS-232 controllability through an embedded micro-controller, includes optical power and pump laser diode bias monitors and can be switched between constant current and constant power modes. It is designed to operate at hot temperatures of 60°C and has a typical electrical power consumption of <4 W. The device has been tested in transmission experiments enabling a receiver sensitivity of -38.15 dBm (BER 10^-4) for 25 Gb/s DPSK which is improved to -39.95 dBm by adjusting the signal wavelength. The compact form factor of the unit makes it suitable for deployment in laser communication terminals deployed within small satellite platforms.

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