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James Edmunds

Jihan Farzana

Marios Kechagias

Leontios Stampoulidis

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MID-POWER PM BOOSTER AND OPTICAL FIBER PRE-AMPLIFIER FOR 1.55 um SATELLITE LASER COMMUNICATIONS

James Edmunds, Jihan Farzana, Marios Kechagias, Leontios Stampoulidis, and Efstratios Kehayas
Gooch and Housego, Systems Technology Group
Broomhill Way, Torquay, Devon, TQ2 7QL, United Kingdom

I. INTRODUCTION

Laser communications 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 lasercomm. On-board lasercomm systems typically employ Erbium-doped optical fibre amplifier (EDFA) sub-units on the transmit and receive sides to boost signal power and pre-amplify optical signals before photo-detection.

For this application, ESA and OLC terminal equipment suppliers have identified requirements related to mid-power polarization maintaining (PM) fiber amplifiers as well as low noise, high gain pre-amplifiers. In order to develop these units, ESA has launched the programme "Space validation of rad-hard erbium optical fiber amplifier at 1.55 um" as part of the European Components Initiative (ECI) framework, dedicated to the radiation validation and manufacturing of mid-power PM booster and pre-amplifier EDFAs. Gooch and Housego, the European supplier of high-rel space photonic components and units, has taken part into this study and has performed radiation evaluation tests as well as the assembly, integration and test of fiber amplifier units to meet the requirements of space agencies and primes.

In this paper we present highlights of this study. The radiation validation campaign includes gamma radiation tests at 20 kRAD and 100 kRAD TID on Erbium doped fibers to cover typical TID levels found in LEO and GEO satellite missions respectively. PM-booster fiber amplifiers deliver >19 dBm saturated optical power demonstrating <2.7 dB radiation-induced absorption (RIA) gain drop at TIDs as high as 100 krad. The fiber pre-amplifier can deliver >35 dB gain over the full C-band and >40dB around 1550 nm with <1.87 dB RIA induced gain drop at 100 krad TID. When noise management is employed the typical (at 1550 nm) the gain increases to 50 dB and the amplifier delivers more than 40 dB gain across the complete C-band. The post irradiation noise figure measured is in the range of 4 dB at 20 krad and 4.5 dB at 100 krad within the entire C-band.

In terms of unit development, we present the assembly, integration and functional test of Engineering Model (EM) PM booster and pre-amplifier EDFAs. The EM units deploy Gooch and Housego, high-rel fused components which are developed for the demanding sub-marine market (25 years undersea lifetime and 0.1 FIT) and have been qualified and deployed in several satellite missions [4]. In addition, they deploy pump laser diodes manufactured in-house by Gooch and Housego which have been qualified for and deployed in space missions (classified mission information). The functional test results demonstrate stable operation over a wide EDFA case temperature range of which validates the unit thermal design. The low heat rise of the pump laser diodes with respect to the case temperature indicates that the amplifiers can operate at hot operating temperatures exceeding 40 degC.

II. RADIATION TESTS

Radiation tests have been conducted in collaboration with 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. The Erbium doped fibers have been passively irradiated, i.e. they were not pumped / photo-beached during irradiation. As such the radiation results correspond to the worst case expected radiation induced (RIA) gain drop.

PM-booster amplifiers

The target optical specification for the PM booster amplifier is to achieve >18 dBm output power and a noise figure (NF) in the range of 6 dB at 1550 nm. A total of 10 fiber amplifier engines have been assembled with irradiated fibers and tested. The figure below illustrates typical pre-irradiation results including gain, NF and polarization extinction ratio (PER) at BOL pump power, EOL pump power and pump power at maximum de-rated driving current of the pump laser diodes.

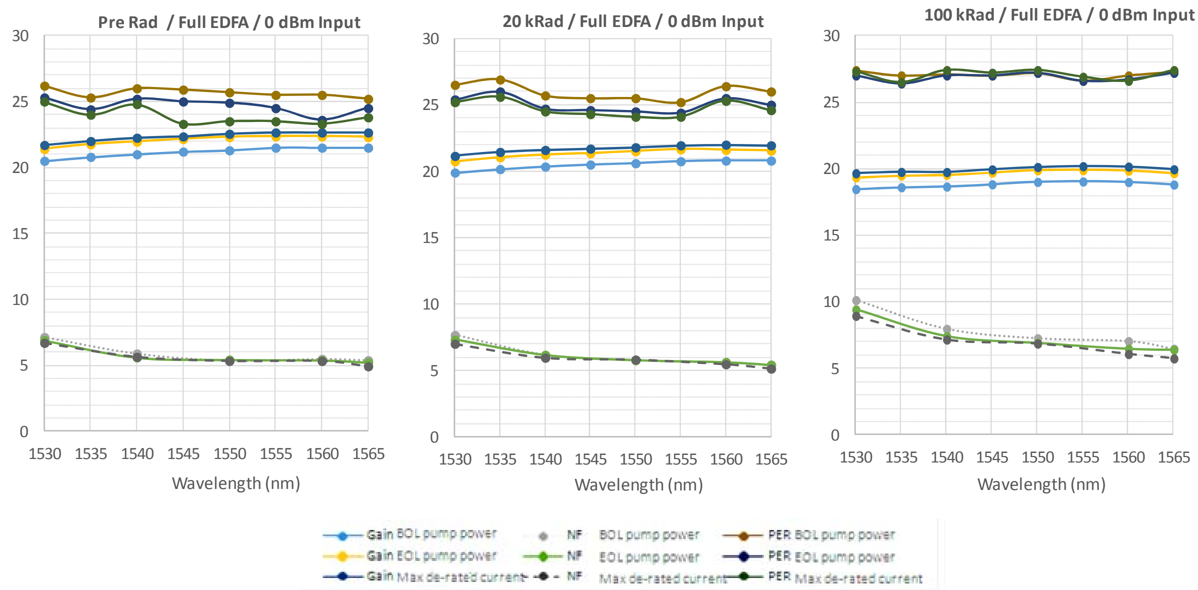

Fig. 1. Gain, noise figure and PER vs. wavelength for the PM EDFA using 0 dBm input. (left) pre-irradiation, (middle) post 20 krad and (right) post 100krad TID. Results are shown for BOL pump power, EOL pump power and pump power at maximum de-rated pump driving current

Over the C band, the PM EDFA gain is between 20.5 < G < 21.5 dB at BOL pump power. Noise figure is between 5.39 < NF < 7.14 dB. Over the 1540 nm to 1565 nm band, performance improves to 21 < G < 21.5 dB and 5.39 < NF < 5.90 dB. The PER is > 23.3 dB.

Fig. 1 (middle) illustrates the post-radiation results of the best performing PM EDFA configuration at 20 krad TID. Over the C band, the PM EDFA gain is between 19.9 < G < 20.8 dB at BOL pump power. Noise figure is between 5.41 < NF < 7.67 dB. Over the 1540 nm to 1565 nm band, performance improves to 20.35 < G < 20.8 dB and 5.41 < NF < 6.18 dB. The PER is > 24.1 dB for all pump powers.

Fig. 1 (right) illustrates the post-radiation results of the best performing fiber amplifier configuration at 100 krad TID. Over the C band, PM EDFA gain is between 18.46 < G < 19 dB at BOL pump power. Noise figure is between 10.1 < NF < 6.46 dB. Over the 1540 nm to 1565 nm band, performance improves to 18.65 < G < 19 dB and 6.46 < NF < 7.96 dB. The PER is > 26.4 dB for all pump powers.

Fig. 2 below shows the optical spectrum analyzer (OSA) traces for 1530 to 1565 nm band with a step of 5 nm for pre-irradiation (left) and post 100 krad (right) irradiation at BOL pump power. Graphs indicate a negligible impact on the EDFA OSNR performance.

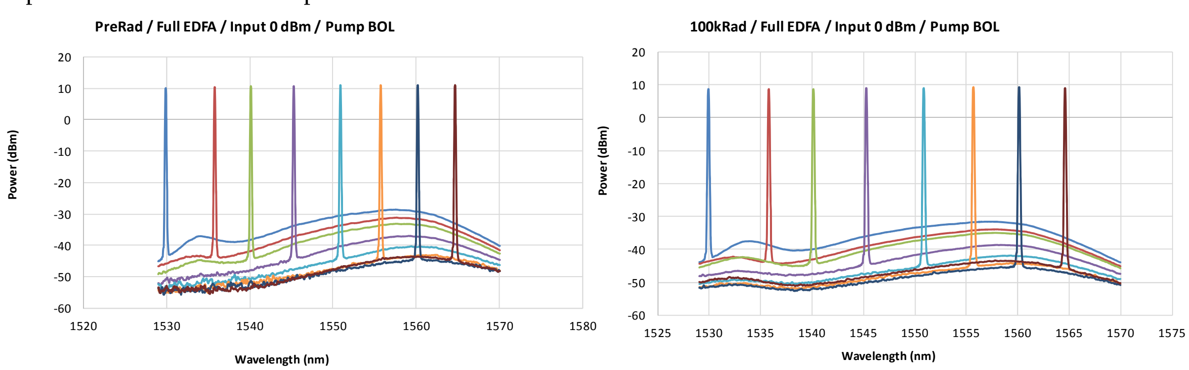

Fig. 2. Amplified signal OSA traces (left) pre-irradiation (right) post-irradiation 100 krad

The tables below summarize the RIA induced gain and NF degradation experienced at 20 and 100 krad TID. With 1550 nm wavelength as reference, measurements reveal a gain drop of 0.7 dB and NF increase of 0.41 dB at 20 krad TID. The corresponding values at 100 krad TID are 2.3 dB and 1.88 dB.

INPUT (dBm)	WL (nm)	Gain 0 (dB)	Gain 20 (dB)	Gain 100 (dB)	DG0-20	DG0-100
BOL pump						
0	1530	20.5	19.9	18.46	0.6	2.04
0	1535	20.8	20.16	18.6	0.64	2.2
0	1540	21	20.35	18.65	0.65	2.35
0	1545	21.2	20.5	18.82	0.7	2.38
0	1550	21.3	20.6	19	0.7	2.3
0	1555	21.5	20.75	19.03	0.75	2.47
0	1560	21.5	20.8	18.99	0.7	2.51
0	1565	21.5	20.8	18.8	0.7	2.7

INPUT (dBm)	WL (nm)	NF 0 dB	NF 20 dB	NF 100 dB	DNF0-20 dB	DNF0-100 dB
BOL pump						
0	1530	7.141	7.668	10.119	0.527	2.978
0	1540	5.895	6.18	7.958	0.285	2.063
0	1550	5.364	5.775	7.248	0.411	1.884
0	1560	5.482	5.587	7.034	0.105	1.552
0	1565	5.385	5.411	6.459	0.026	1.074

Table 1. (left) Gain degradation recorded at 0 dBm input and BOL pump power. (right) NF degradation at the same conditions.

The table below illustrates the RIA induced gain drop recovery as a function of pump driving current at 1550 nm reference wavelength.

	Gain (@ 1550nm) (dB)		
Pump Powers	G_0	G_{20}	G_{100}
BOL	21.3	20.6	19
EOL	22.3	21.5	19.87
@ Max. De-rated current	22.55	21.8	20.12

Table 2. Gain recovery of irradiated PM EDFA after increase of pump power.

The results indicate that the increase of pump power from BOL to EOL value is sufficient to recover fully the gain drop at 20 krad. At 100 krad, the residual gain drop that is not recovered by a BOL to EOL pump power increase is 1.43 dB, but still the amplifier is capable to deliver a gain just below 20 dB. The gain values are also presented for the case where the pumps are driven at maximum de-rated current. The result indicates that a further recovery of the gain degradation is possible.

Pre-amplifiers

The target optical specification for the pre-amplifiers is to achieve >45 dB gain and noise figure (NF) in the range of 4 dB in a wavelength range of 1540 to 1560 nm. A total of 8 fiber amplifier engines have been assembled with irradiated fibers and tested.

The figures below illustrate typical pre-irradiation results including gain and NF at BOL pump power and EOL pump power. Fig. 3 (left) shows gain and NF performance without any noise management and Fig. 3 (right) shows gain and NF performance with noise management which is implemented with the employment of a 0.8 nm band-pass filter.

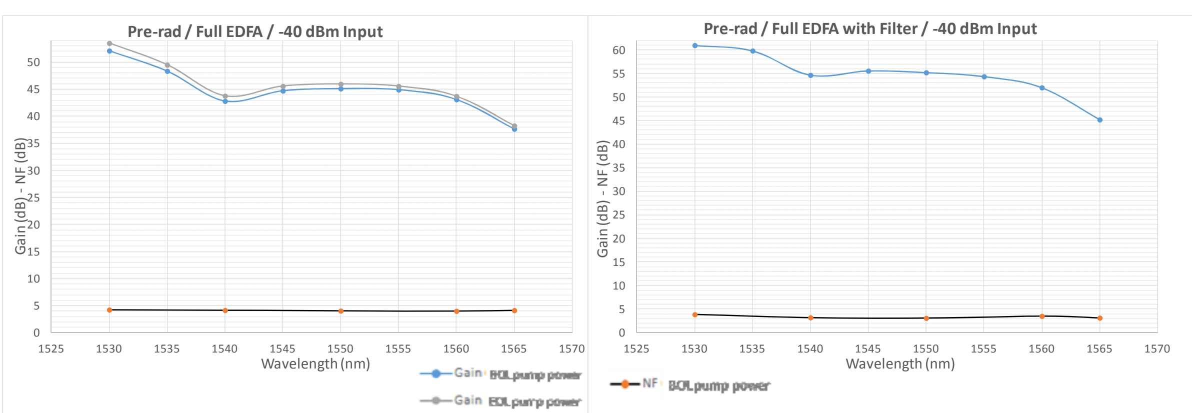

Fig. 3. Pre-irradiation gain and noise figure vs. wavelength for the pre-amplifier at -40 dBm input optical power. Results are shown for BOL pump power and EOL pump power: (left) with no noise management (right) with noise management.

Over the C band, the gain of the pre-amplifier is between 37.65 < G < 52.1 dB at BOL pump power. Noise figure is between 4.02 < NF < 4.25 dB. Over the 1540 nm to 1560 nm band, gain is G > 42.8 dB and NF < 4.17 dB. The inclusion of noise management increases the gain to between 45.2 < G < 60.97 dB for the entire C-band and the gain is G > 52 dB for the 1540 - 1560 nm range.

The figures below illustrate the post-radiation results of the best performing fiber amplifier configuration at 20 krad TID. Over the C band, the gain of the pre-amplifier is between 36.75 < G < 52.15 dB at BOL pump power. Noise figure is between 3.95 < NF < 4.3. Over the 1540 nm to 1565 nm band, gain is G > 42.25 dB.

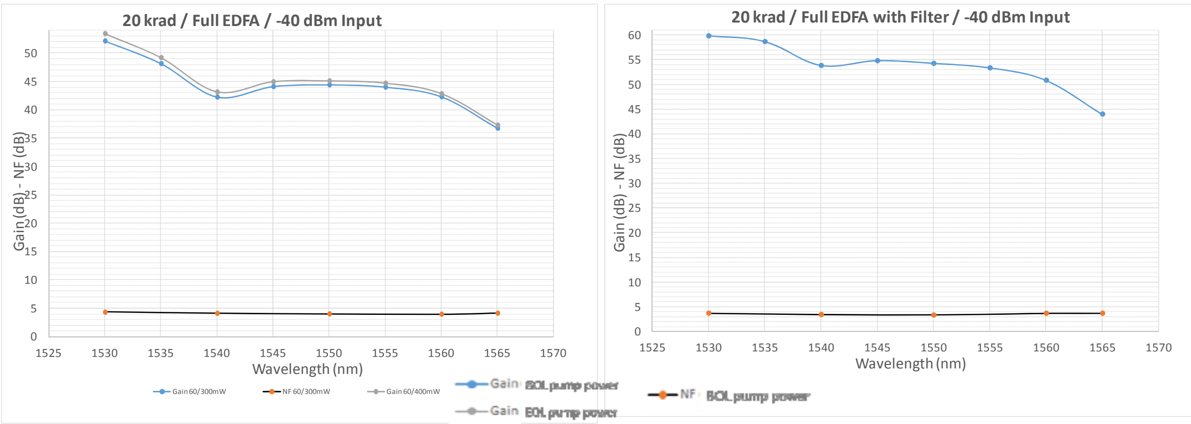

Fig. 4. Post-irradiation gain and noise figure vs. wavelength for the pre-amplifier at -40 dBm input. Results are shown for BOL pump power, EOL pump power: (left) with no noise management (right) with noise management.

The figure below illustrates the post-radiation results of the best performing fiber amplifier configuration at 100 krad TID.

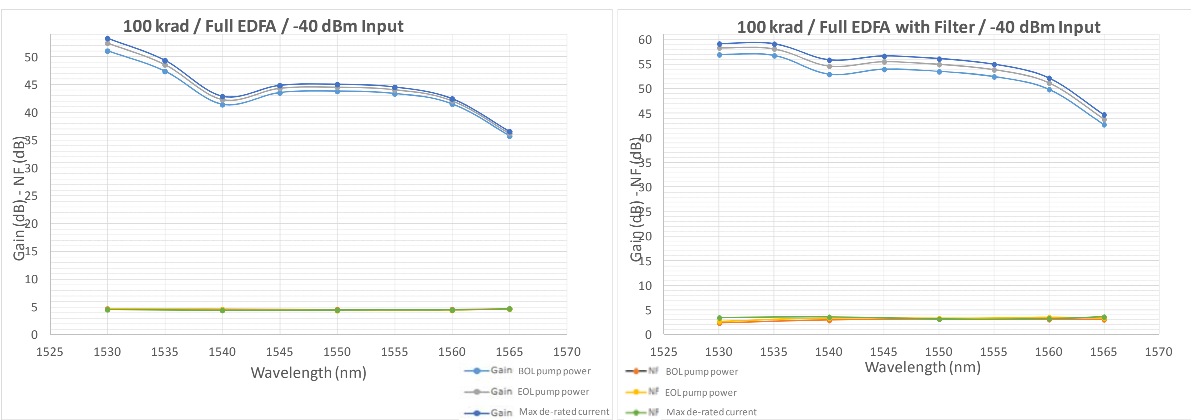

Fig. 5. Post-irradiation gain and noise figure vs. wavelength for the pre-amplifier at -40 dBm input. Results are shown for BOL pump power EOL pump power and pump power at maximum de-rated driving current of the pump diode: (left) with no noise management (right) with noise management.

Over the C band, the gain of the pre-amplifier is between 35.78 < G < 51.1 dB at BOL pump power. Noise figure is between 4.57 < NF < 4.68 dB. Over the 1540 nm to 1560 nm band, gain is G > 41.44 dB and NF < 4.57 dB. The inclusion of noise management increases the gain to between 42.74 < G < 56.95 dB for the entire C-band and the gain is G > 49.88 dB for the 1540 - 1560 nm range.

The tables below illustrate the gain and NF degradation for the best performing LEO (20 krad) and GEO (100 krad) pre-amplifier. With 1550 nm wavelength as reference the gain drop of the amplifier is limited to 0.7 dB at 20 krad TID with no impact on NF. At 100 krad the gain degradation (at 1550 nm) is 1.38 dB and NF degrades by 0.47 dB. The results indicate that the fiber amplifier can sustain a gain of >41.54 dB in the 1540 to 1560 nm range even at 100 krad incident on the fiber and without assuming: 1) any increase of pump power from BOL to EOL and 2) any shielding from spacecraft and the amplifier unit that would reduce the TID level incident on the fiber.

INPUT (dBm)	WL (nm)	Gain 0 (dB)	Gain 20 (dB)	DG0-20
Pump BOL				
-40	1530	52.1	52.15	-0.05
-40	1535	48.35	48.15	0.2
-40	1540	42.8	42.25	0.55
-40	1545	44.7	44.1	0.6
-40	1550	45.1	44.4	0.7
-40	1555	44.9	44	0.9
-40	1560	43.1	42.3	0.8
-40	1565	37.65	36.75	0.9

INPUT (dBm)	WL (nm)	NF 0	NF 20	DNF0-20
Pump BOL				
-40	1530	4.254	4.298	0.044
-40	1540	4.17	4.099	-0.071
-40	1550	4.059	3.998	-0.061
-40	1560	4.02	3.945	-0.075
-40	1565	4.151	4.119	-0.032

INPUT (dBm)	WL (nm)	Gain 0 (dB)	Gain 100 (dB)	DG0-100
Pump BOL				
-40	1530	51.7	51.1	0.6
-40	1535	48.45	47.42	1.03
-40	1540	42.9	41.44	1.46
-40	1545	45	43.56	1.44
-40	1550	45.2	43.82	1.38
-40	1555	44.9	43.39	1.51
-40	1560	43.15	41.54	1.61
-40	1565	37.65	35.78	1.87

INPUT (dBm)	WL (nm)	NF 0	NF 100	DNF0-100
Pump BOL				
-40	1530	4.485	4.677	0.192
-40	1540	4.278	4.58	0.302
-40	1550	4.096	4.574	0.478
-40	1560	4.064	4.572	0.508
-40	1565	4.289	4.665	0.376

Table 3. (top) Gain and NF degradation recorded at -40 dBm input and BOL pump power for 20 krad TID. (bottom) Gain and NF degradation at the same conditions for 100 krad TID.

The table below illustrates how the RIA induced gain drop recovery as a function of pump driving current at 1550 nm reference wavelength for the LEO (left) and GEO (right) pre-amplifier.

	Gain (@ 1550nm) (dB)	
Pump Powers	**G_0**	**G_{20}**
BOL	45.1	44.4
EOL	45.95	44.99
@ max de-rated current	-	-

	Gain (@1550nm) (dB)	
Pump Powers	**G_0**	**G_{100}**
BOL	45.2	43.82
EOL	45.95	44.56
@ max de-rated current	-	45.06

Table 4. Gain recovery of irradiated PM EDFA after increase of pump power.

The results indicate that the increase of pump power from BOL to EOL value is sufficient to recover fully the gain drop at 20 krad. At 100 krad, the residual gain drop that is not recovered by a BOL to EOL pump power increase is 0.64 dB, but still the amplifier is capable to deliver a gain >44.5 dB. The gain values are also presented for the case where the pumps are driven at maximum de-rated current for 100 krad. The result indicates that almost a full recovery of the gain degradation is possible.

III. UNIT ASSEMBLY, INTEGRATION AND TEST

Two engineering model (EM) amplifiers have been build and tested. The opto-electronic components employed in the EM units are the same type as the components that would be deployed in an EQM or FM unit, which means that they are Form-Fit-Function (FFF) equivalent and fabricated with the same fabrication process and the same material as the EQM/FM parts. The same applies to the fused fiber optic components. As such the optical performance of the EM units is expected to be representative to the performance of the higher TRL/grade units. All the fused components are manufactured in-house by Gooch and Housego according to high-rel and space compliant processes. The pump diodes deployed are also manufactured in-house using Gooch and Housego laser welding assembly process which delivers fully hermetic and high-rel opto-electronic modules. These components have been evaluated successfully against mechanical, thermal vacuum and radiation environmental constraints and have space mission deployment heritage.

The figure below illustrates the CAD drawing and the finished unit which is identical for both the PM-booster and pre-amplifier. The mechanical layout is representative of the EQM/FM unit. The unit mass is 560 grams and the dimensions are (L) 159.5 mm x (W) 146 mm x (H) 27.5 mm (length and width excluding the mounting flanges). The optical interface is MiniAVIM and the electrical interface is 44-pin high density D-sub. The unit design accommodates pump laser diode redundancy and can host 2 fiber amplifiers in the same housing. In terms of monitor and control functions, the unit accommodates input and output optical power monitors, pump driving current and temperature monitors as well as pump enable / disable function and loss-of-input function. In terms of electronics interface, the unit has a digital interface with LVDS transceivers and ADC/DAC converters, as well as an on board DCDC converter. With the digital interface, the unit offer various advantages including lowest external and internal I/O requirements, known standard at the interface requiring no additional qualification, lowest BOM cost on the system level and least amount of real estate required within the pump diode circuit. Finally, the unit includes an internal thermistor mounted on the unit case reference point to provide monitoring of the unit temperature. In the EM model shown below the electronic circuitry is developed with COTS components. A design with space-grade EEE parts has been completed and implemented by Gooch and Housego. As such an EQM/FM design and implementation is readily available.

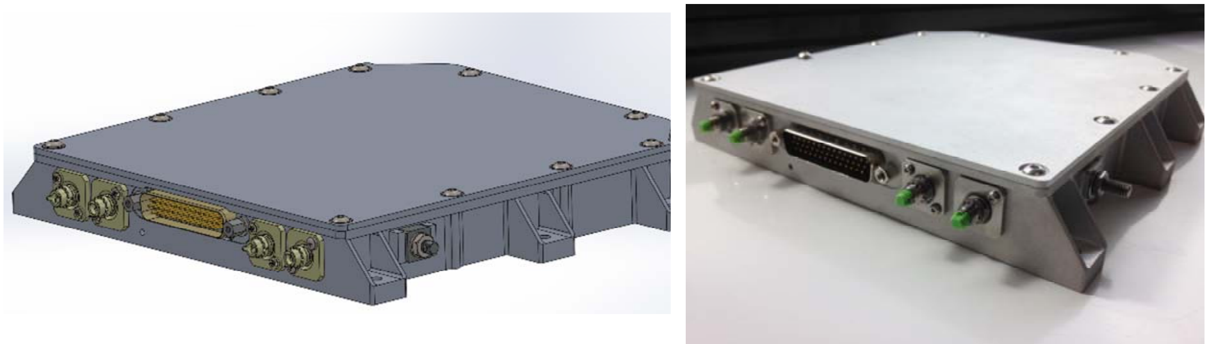

Fig. 6. EM fiber amplifier unit: (left) CAD drawing, (right) assembled unit.

Both units have been installed in a thermal chamber and tested at 21 degC and the qualification cold and hot temperatures of -10 degC and +40 degC.

The figure below illustrates the gain, PER and NF performance of the PM booster EM-EDFA unit over temperature. The PM booster EDFA has been optimized to provide peak gain around 1560 nm region. The results show that at room temperature and -10 dBm input power the amplifier would deliver typically (1550 nm) >20 dBm output power with >25 dB PER and NF ~5 dB. The results indicate that performance is sustained at 40 degC. At -10 degC, there is a drop of gain and NF increase which is attributed to the decrease of PER down to ~12 dB. The decrease in PER is attributed to the performance of the passive fiber optic components which are specified for PER performance >20 dB at >-5 degC. As such a >20 dB PER performance can be guaranteed at cold temperatures >-5 degC.

The temperature of the pumps has been monitored during test through the internal thermistor elements. At the unit case hot temperature of 40 degC, the pump temperature heat rise was ~5.5 degC when the pumps were driven at BOL pump driving current and ~7.5 degC when pumps were driven at maximum de-rated driving current. As such the fiber amplifier can operate at hot temperatures beyond 40 degC, given that the pump laser diodes have a maximum operating case temperature of 75 degC.

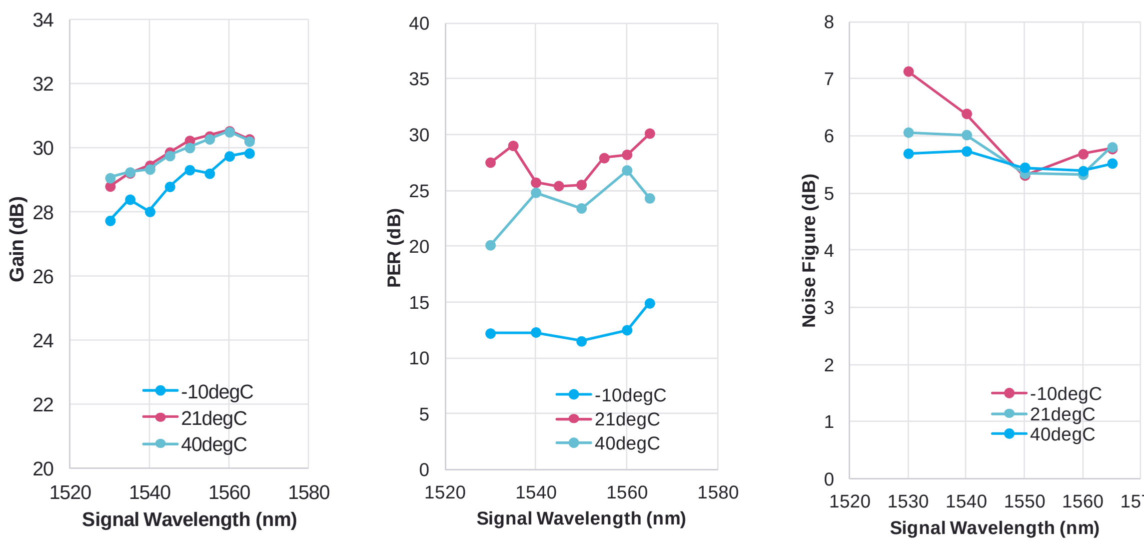

Fig. 7. PM-booster EM-EDFA performance over qualification temperature range: (left) gain, (middle) PER, (right) NF.

The figure below illustrates the performance of the pre-amplifier EM-EDFA unit over temperature. Results are shown with noise management. The results show that at room temperature and -40 dBm input power the amplifier would deliver typically (1550 nm) >55 dB gain with NF ~<4 dB. The results indicate that performance is sustained at both cold and hot temperatures of -10 and 40 degC respectively.

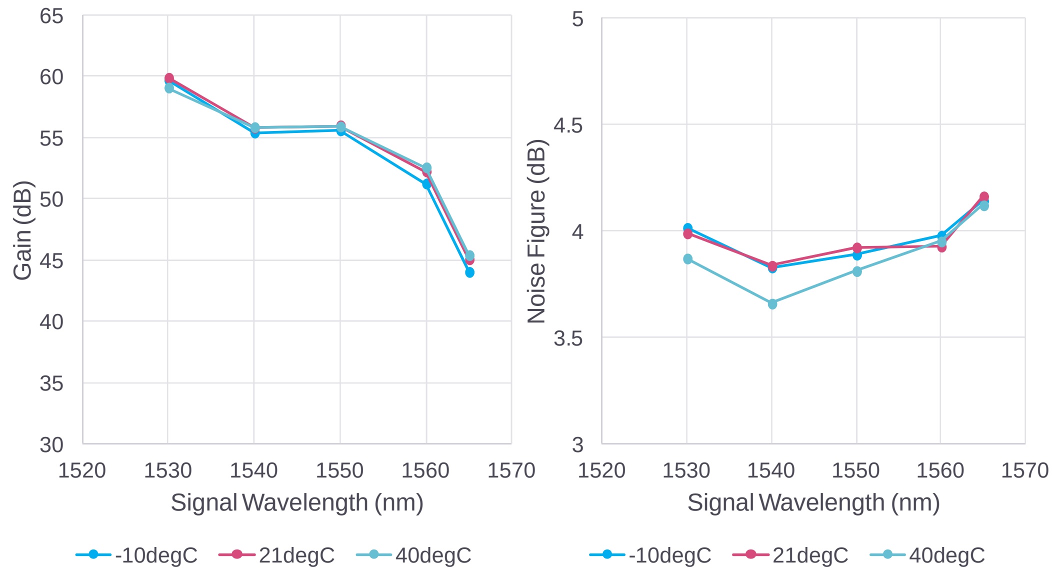

Fig. 8. Pre-amplifier EM-EDFA performance over qualification temperature range: (left) gain, (middle) PER, (right) NF.

IV. CONCLUSIONS

We have demonstrated the radiation validation as well as the assembly, integration and test of PM-booster and pre-amplifier EDFAs. The radiation validation results demonstrate the PM-booster EDFA robust performance against ionizing radiation with a recorded <0.75 dB and <2.7 dB RIA induced gain drop at 20 and 100 krad respectively. The degradation is recoverable through increase of pump power. In terms of optical performance the amplifier is expected to deliver 21.5 dBm saturated output power at 1550 nm for 20 krad TID and at expected EOL pump power. The corresponding EOL performance at 100 krad TID is >19.5 dBm. Both performances are in line with target requirements. Similarly the pre-amp EDFA exhibits a RIA induced gain drop of 0.7 dB at 1550 nm and 1.38 dB respectively. In terms of optical performance ~45 dB of gain is delivered at 20 and 100 krad TID and expected EOL pump powers. We have also demonstrated the assembly of EM units using high rel opto-parts and COTS electronics and results validate the optical, electronics and thermal design. EQM and FM level electronics design with space qualified EEE parts has been completed and realized and unit level qualification testing is underway and is to be completed within Q4 2016.

V. ACKNOWLEDGMENT

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