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MULTI-CORE FIBER AMPLIFIER ARRAYS FOR INTRA-SATELLITE LINKS

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I. INTRODUCTION

In this paper we present erbium doped fibre (EDF) aimed at signal amplification within satellite photonic payload systems operating in C telecommunication band. In such volume-hungry applications, the use of advanced optical transmission techniques such as space division multiplexing (SDM) can be advantageous to reduce the component and cable count. In a variant of optical SDM, multi-core fibers (MCFs) are used to carry multiple signals from transmitter to receiver side reducing the number of optical fibers and as such the mass and volume of the transmission line. In multi-beam satellite payloads these MCFs can be deployed to carry optical signals from the antenna elements (following E/O conversions) to the satellite platform reducing drastically the mass and volume of the harness which dominate the overall system size. In such systems optical amplification can also be realized with SDM techniques helping to reduce further the system size on the equipment level. This requires the development of specialty MC doped fibers that can amplify optical signals and compensate losses within the photonic payload. Among the requirements are resistance to ionizing radiation, which implies negligible level of Radiation Induced Attenuation (RIA), smallest possible mass and volume, as well as high, flat gain characteristics in C band and low noise figure.

A promising response to all those requirements, currently being researched within the EU Beacon project (http://www.space-beacon.eu/), is a novel 7-core radiation hardened MC-EDF. It consists of 7 cores distributed in a hexagonal arrangement, ensuring low manufacturing complexity, and embedded in a common glass cladding. The core diameter is chosen so that the core is single mode for both signal and pump wavelengths. The crosstalk between the cores at 1310 nm is smaller than -35 dB, ensuring that signals in each core do not interfere with each other. This is due to the air holes of an appropriate diameter that surround each core. The diameter of air holes is a compromise between supporting undesirable cladding modes (occurs when air-holes are large) and large crosstalk value (for small air-holes diameter). Also, due to the air holes, coiling the fibre does not affect the gain value, what is advantageous in the terms of efficient packaging of a fiber amplifier.

The use of MC architecture allows for reduction of the optical fibre cable count whilst ensuring the same optical paths in each of the seven cores resulting in capability to maintain phase relations between the signals transmitted in different cores. In the end, the outer fibre diameter is the same as the one of the standard transmission fibre used in telecommunication, i.e. ~125μm. A single core variant of this fiber was radiation tested to define its radiation resistance in terms of radiation induced gain drop (RIGD) in a typical single stage, 20-dB gain amplifier configuration. The fiber sample was irradiated to 20 krad TID and the RIGD was found to be <0.62 dB across the C-band. The result confirms that the fiber composition is suitable for providing radiation resistance against ionizing radiation effects.

II. FIBER FABRICATION AND OPTICAL TESTNG

The figure below illustrates the fabricated doped fibers. Fig. 1 (left) shows the SEM image of a single core erbium doped fibre comprising of a basic cell of 7-core fibre. Since propagation in each core of multi-core fibre is independent, features as absorption, gain or bending loss should be measured only for a single core. Such approach allowed obtaining feedback on the active properties of core and implementing corrections, if needed. Fig. 1 (right) shows the SEM image of the 7-core MC EDF fiber. The number of cores, core pitch as well as the core and air hole diameters are chosen to achieve the following: a) negligible crosstalk between the cores, b) core single mode operation for pump wavelength (980 nm) and c) amplification of signals in the range of 1528 nm -1565 nm (C telecommunication band).

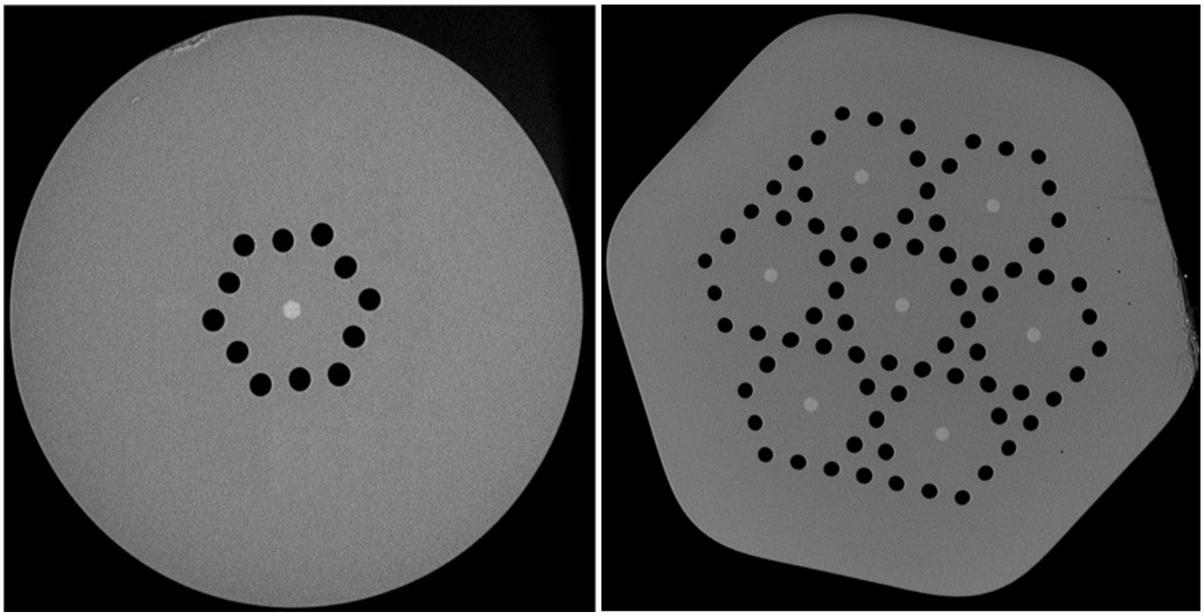

Fig. 1. SEM image of (left) elementary cell (single core EDF) and b) 7-core EDF.

The figure below illustrates numerical simulations of modes propagation in the elementary cell of 7-core EDF conducted in Mode Solutions programme from Lumerical. Propagation of pump wavelength (980 nm) and signal wavelength (1550 nm) has been examined for dimensions of actual fibre. In both cases only fundamental mode propagates in the core. At the same time, the structure of the air holes supports one higher order mode. However, the confinement loss of this mode is large and equals to approx. 7 dB/m and 27 dB/m, respectively, for the wavelength of 980 nm and 1550 nm. In the figure below mode field distributions for the wavelength of 980 nm and 1550 nm are shown.

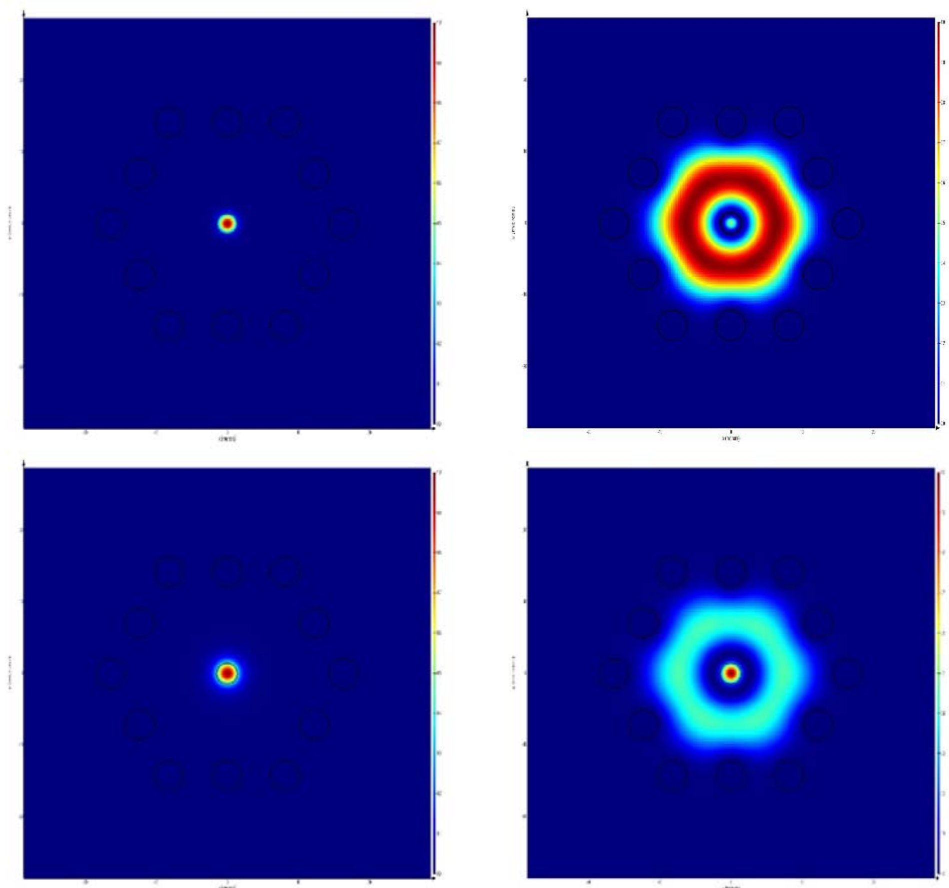

Fig. 2. Cross sections of modes propagating in the elementary cell of the seven core fibre. (top) Cross section for 980 nm and (bottom) Cross section for 1550 nm

The absorption spectrum has been evaluated with the use of cut-back method. The figure below shows a typical absorption spectrum in the 900 - 1700 nm region. The fiber exhibits an absorption of ~10 dB/m at 980 nm. The result is in accordance with standard erbium ions absorption spectrum in silica glass.

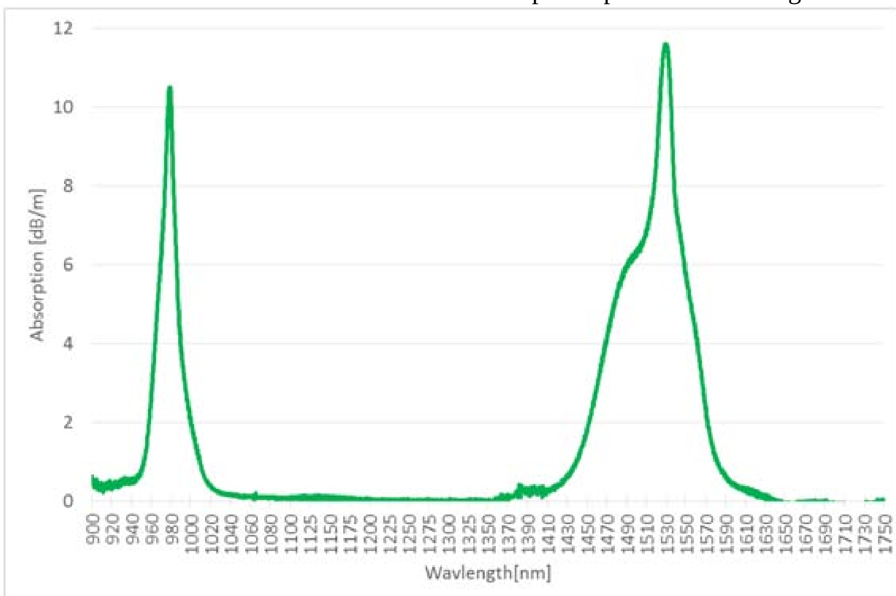

Fig. 3.: Absorption spectrum of manufactured EDF fiber.

The figure below shows the experimental set-up used to measure the core-to-core crosstalk cross-talk in the 7-core EDF.

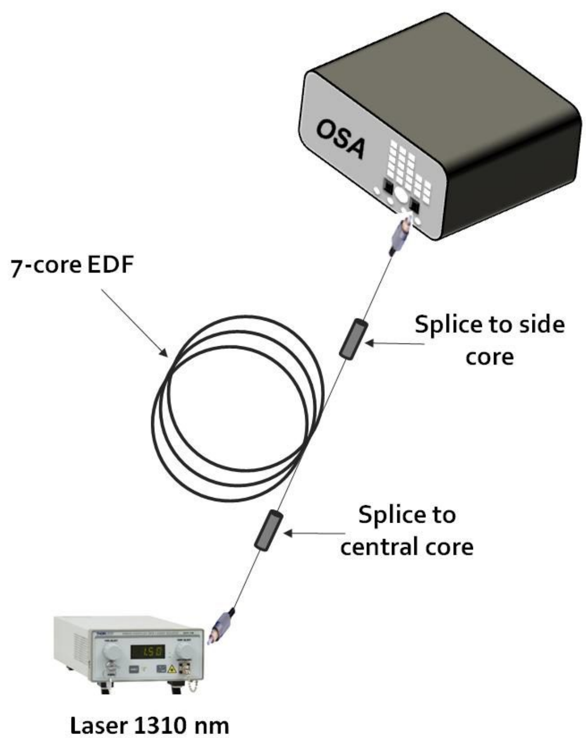

Fig. 4. Set-up for crosstalk evaluation.

A light source operating at the wavelength of 1310 nm is used, since this wavelength is not absorbed by erbium ions. Light is launched into the EDF central core. A side core is connected to the Optical Spectrum Analyzer (OSA) to measure the optical power that is coupled from the central core. Crosstalk, which is defined as power difference between maximal measured signal power and introduced one, is at the very low level of -37 dB, and should not affect the performance of a MC EDFA.

III. FIBER RADIATION TESTING

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 single core EDF have been passively irradiated.

The figure below illustrates pre-irradiation results. A single stage breadboard fiber amplifier has been assembled and 980 nm pumping was used in a configuration to optimize noise performance.
Gain and noise figure measurements over the C-band have been performed to characterize the doped fiber performance.

The table below lists the test conditions:

Input power	-6 dBm
Signal wavelength	1530 to 1565 in 5 nm steps
Pump power	150 to 250 mW in 50 mW steps

Table 2: Test conditions of breadboard amplifier

The figure below illustrates the gain and NF as a function of wavelength. The amplifier delivers >21.9 dB of gain at 150 mW pump power which scales up to >24.4 dB at 250 mW pump power. The NF is <5.1 dB over the C-band.

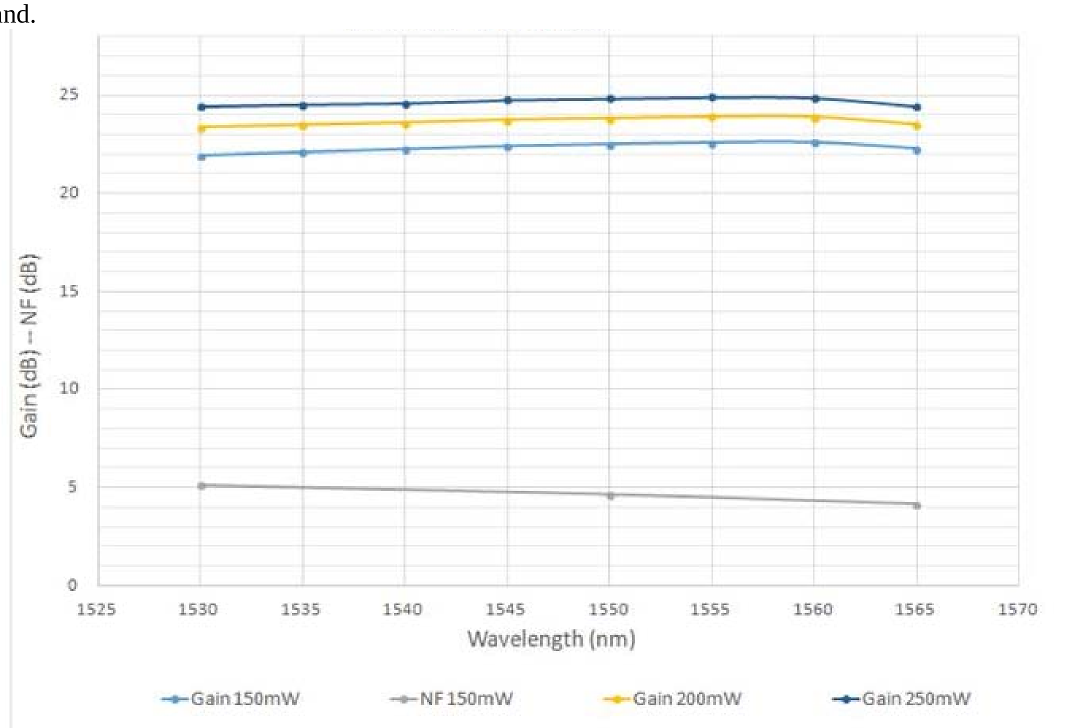

Fig. 5. Pre-irradiation gain and NF performance of BEACON breadboard amplifier

Following irradiation the fiber sample was re-spliced to the breadboard amplifier and was measured. The figure below illustrates the post-irradiation results.

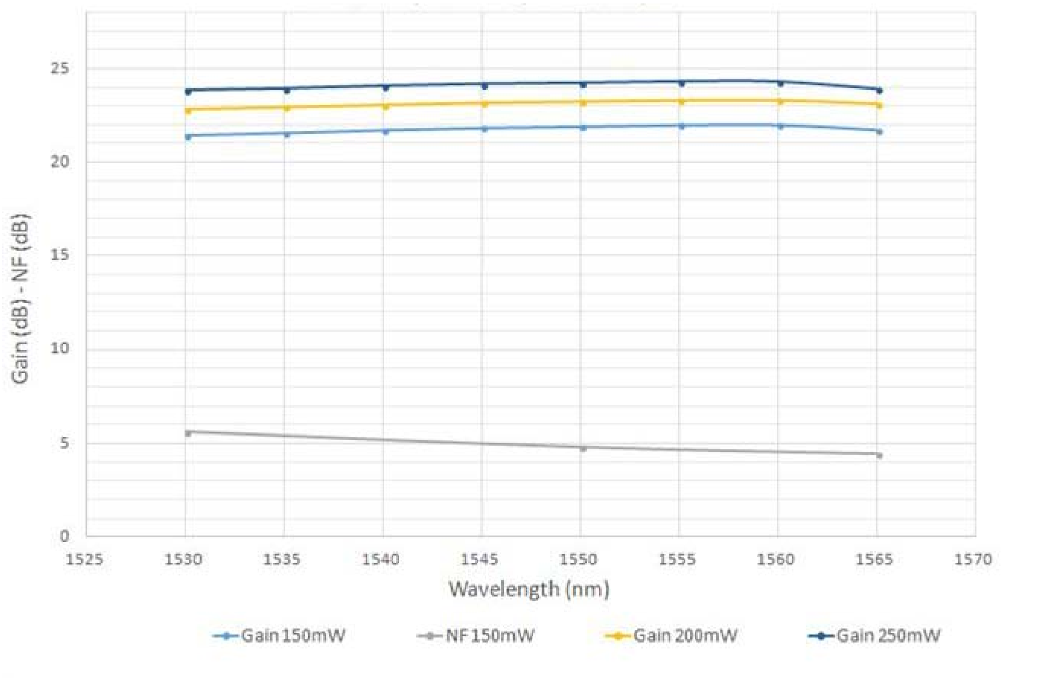

Fig. 6. Post-irradiation gain and NF performance of BEACON breadboard amplifier

The figure below illustrates the amplifier output spectrum which reveals a high OSNR and a flat gain over the C-band.

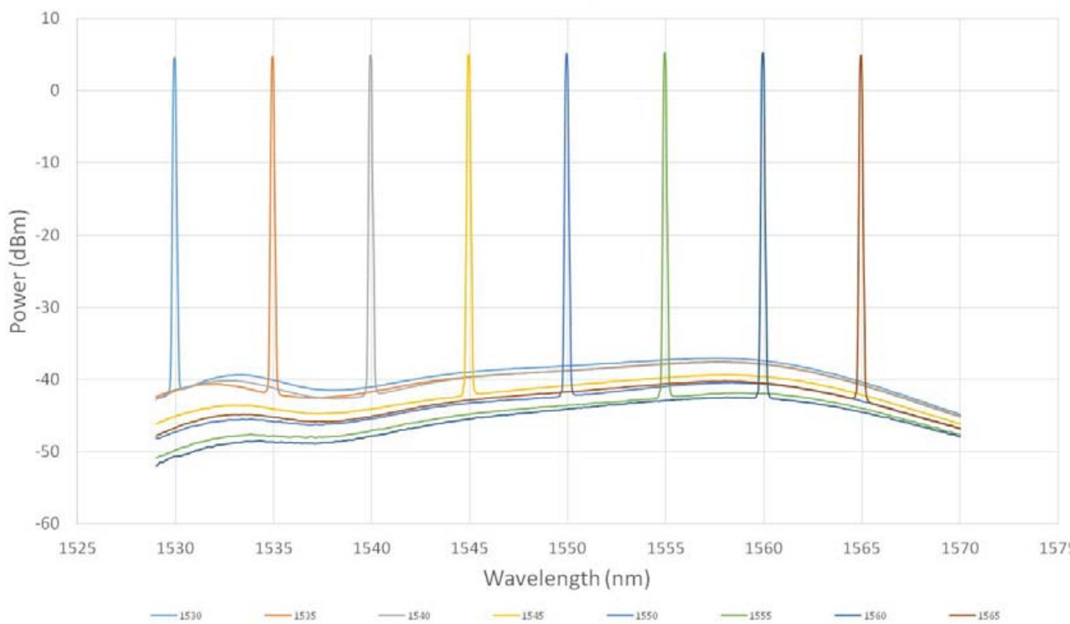

Fig. 7. Post-irradiation BEACON breadboard amplifier spectrum

The table below summarizes the comparison between pre- and post-irradiation performance.

INPUT (dBm)	WL (nm)	G 0 krad	G 20 krad	DG	NF 0 krad	NF 20 krad	DNF
Pump = 150mW Co							
-6	1530	21.96	21.43	0.53	5.148	5.6	0.452
-6	1535	22.13	21.56	0.57			
-6	1540	22.28	21.72	0.56			
-6	1545	22.44	21.84	0.6			
-6	1550	22.54	21.92	0.62	4.681	4.814	0.133
-6	1555	22.62	22	0.62			
-6	1560	22.63	22.01	0.62			
-6	1565	22.32	21.74	0.58	4.2	4.463	0.263

Table 3: Comparison between pre- and post-irradiation performance

The results indicate a RIA gain drop <0.62 dB and a maximum increase in NF of 0.45 dB. The results confirmed that the doped fiber composition is suitable to provide a strong tolerance against radiation effects.

IV. CONCLUSIONS

We have presented the fabrication and testing of a prototype 7-core erbium doped fiber (EDF). The fiber exhibits single mode operation at both signal and pump wavelength as well as core-to-core crosstalk as low as -37 dB. Radiation testing has been performed on a single core variant to validate the fiber composition. Results demonstrate RIA induced gain drop of ~0.6 dB at 20 krad TID. The multi-core structure can help reduce the fiber count in on-board fiber amplifier arrays and lead to compact and cost-efficient packaging. It is also compatible with SDM approaches which can be beneficial for volume hungry applications such as photonic payloads.

V. ACKNOWLEDGMENT

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