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HIGH POWER PULSED FIBER LASER DEVELOPMENT FOR CO2 SPACE BASED DIAL SYSTEM

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Abstract— **High energy fiber lasers emitting around 1579nm is seen as a possible technology for the laser unit of a spaceborn CO_2 DIAL system. We are developing an all fiber system with the following expected performances: pulse energy of 260μJ, pulse duration 150ns, beam quality $M^2<2$, pulse linewidth <60 MHz, laser stability 200 kHz. One of our main concerns has been the radiation induced attenuation mitigation. Various fiber compositions have been investigated.**

I.   INTRODUCTION

Several LIDAR transmitters technologies are currently being developed for CO2 monitoring. Most systems under studies are based on high energy low pulse repetition frequency (PRF) systems based on solid state lasers emitting mainly around 2050nm [1]. Today fiber lasers with reduced pulse energy and higher PRF are being investigated. Both continuous-wave and pulsed lasers can be used [2, 3]. High energy fiber lasers emitting around 1579nm is seen as a possible technology for the laser unit of a spaceborn CO_2 DIAL system. For pulsed operation fiber technology has to demonstrate two major improvements: maximum pulse energy and reliability. Indeed when propagating in fibers, the peak power is quickly limited by non-linearities due to the small core size and the large fiber length [4]. Moreover erbium doped fibers are known to be very sensitive to radiations [5]. The resulting radiation induced attenuation (RIA) will quickly reduce the transmitter performances. We are developing an all fiber system with the following expected performances: pulse energy of 260μJ, pulse duration 150ns, beam quality $M^2<2$, pulse linewidth <60 MHz, laser stability 200 kHz. In this paper we present our results on fiber test and developments and the laser architecture.

II.   GENERAL ARCHITECTURE OF THE HIGH POWER FIBER TRANSMITTER

Fig.1 shows the laser system architecture which is a three stage fiber master oscillator power amplifier (MOPFA) seeded by three stabilized oscillators. These seed lasers are telecom DFB laser diodes that are stabilized by a master/slave architectures. The spectral linewidth of the amplified lidar signal is driven by the natural linewidth of seed lasers. At the output of the stabilized oscillator, 2 mW peak power of low noise power are available with a time pattern composed of 'ON' and 'OFF' pulses controlled by an optical switch. The pattern pulse repetition frequency is 2 kHz. Amplification of single frequency DFB lasers at high peak power leads to Stimulated Brillouin Scattering (SBS). The threshold for this nonlinear effect is of the order of 80W per meter of fiber in standard singlemode fibers. To reach the high peak power of about 2kW in the third stage of amplification, we use the simultaneous implementation of various well-known techniques, such as the use of large mode area fibers, fiber core composition tuning, and strain gradient generation along the fiber.
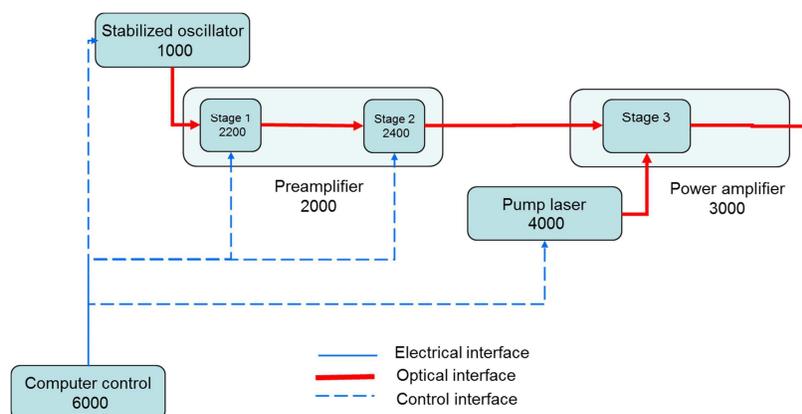
Fig. 1. General architecture of the high power fiber transmitter

III.   SEED LASER TESTS

The seed lasers are 3 identical DFB Telecom laser diodes. Beatnote comparison between oscillators shows a linewidth around 0.5MHz. According to our design the master laser will eventually be locked on the top of an absorption line of CO_2 at low pressure in a multipass cell using modulation/lock-in amplifier loop. Slave oscillators will be locked using beatnote offset scheme using the master laser. The master laser will thus confer long term stability and exactitude to all slave oscillators. We performed short term stability of the beatnote of two free running DFB lasers using a high speed counter. A stability of ~ 220 kHz @ 10 s is measured for the beatnote (fig. 2). Assuming an identical stability for both diodes, the convolution width (220 kHz) can be divided by $\sqrt{2}$ to obtain the stability of a single diode. This yields a value of around 155 kHz assuming identical diodes. Measurements with a wavemeter and a spectrum analyzer measurements are respectively limited at 2 and 0.8 MHz/Hz$^{1/2}$, due to own white noise.
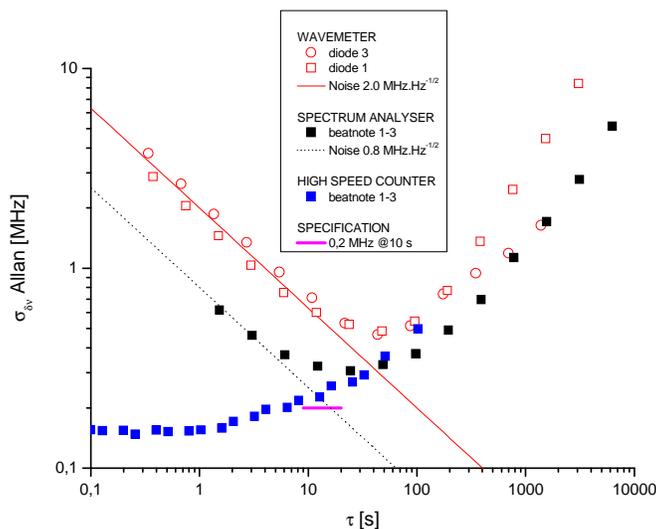
Fig. 2. Allan variance of the seed lasers.

We also measured the spectral purity of the seed lasers using a high resolution OSA for the broadband measurement (fig 3a) and heterodyning on an electrical spectrum analyzer for the high resolution measurement (fig 3b). Spectral purity was measured > 99.95% within 1 GHz.
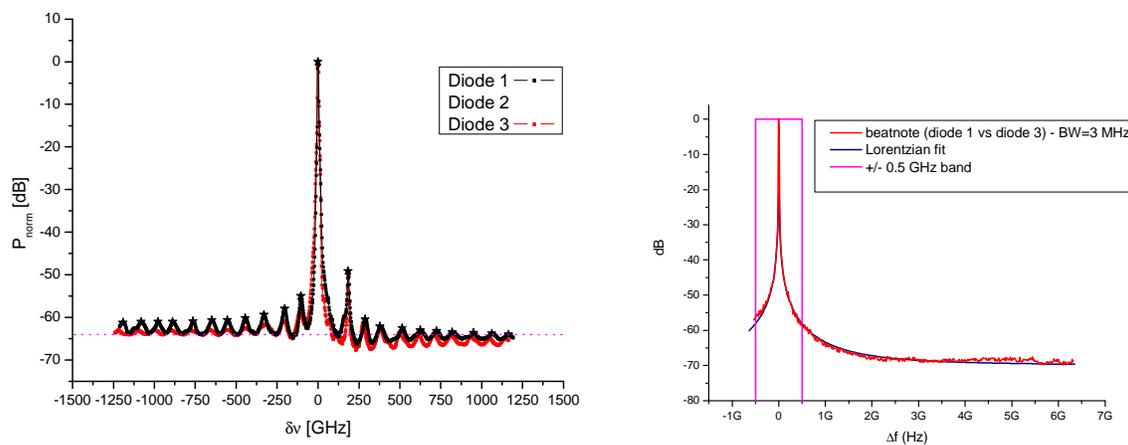
Fig. 3. Emission spectrum of the seed laser measured with OSA (a) ; beating of two seed lasers measured with ESA (b).

IV.   PRELIMINARY VERSION OF THE HIGH POWER FIBER TRANSMITTER

In order to assess the pulsed performances of our architecture we have built a preliminary version of the setup. A 30mW single frequency 1579nm DFB diode is connected to an AOM used to generate a gaussian pulse shape with pulse duration 150 ns at 4 kHz pulse repetition frequency. The pulses enter a double pass preamplifier built using a standard single mode L-band fiber core pumped at 1480nm. The amplified pulses enter a second stage of amplification built using a 12µm core Erbium doped fiber core pumped at 1480nm. After spectral filtering to remove the ASE, the 31W peak power pulses enter the power amplifier stage. It is built using a 40µm core nLight Er60-40 LMA fiber. It is core pumped in copropagating configuration through a single mode wavelength multiplexer using a 4W Raman fiber laser. Fig. 5 shows the pulse energy and peak power as a function of pump power. As it can be seen, the peak power is quickly limited by SBS to 550 W peak power. To investigate the SBS spectrum of the amplifying fiber, the backpropagating Stokes light has been mixed with the seed laser to produce an electrical spectrum proportional to the SBS spectrum (shown in black on Fig. 6). The SBS spectrum showed a lorentzian lineshape with FWHM equal to 45 MHz (corresponding to 100 MHz in spontaneous regime).
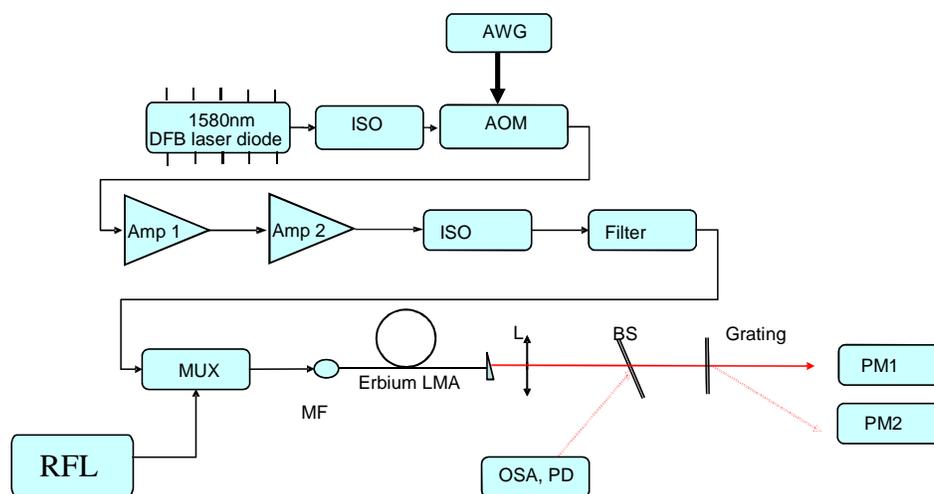
Fig. 4. Set up of the preliminary version of the high power fiber transmitter. ISO: isolator; AOM: acousto-optic modulator; AWG: arbitrary wavefunction generator, MUX: wavelength multiplexer; RFL: Raman Fiber Laser; OSA: optical spectrum analyser; PD: photodiode; PM: powermeter

It is known that the central frequency of the lorentzian Brillouin gain curve can be shifted by applying strain to the fiber. Applying an optimal strain distribution for a given signal distribution in the fiber will result in a flat Brillouin spectrum and a larger threshold [6]. We have shown that a triangular distribution can be used. In a second experiment we then coil the fiber applying a triangular strain distribution with 0.7% maximum strain. The Stokes light spectrum is measured and is broadened and reasonably flat (in red on Fig. 6). With this set up we obtain up to 260 µJ per pulse corresponding to 1.7 kW peak power. The application of strain thus results in an increase of the peak power by a factor almost 4. The slope efficiency also slightly increases to 25%. The output power is now only limited by the available pump power. It should be noted that the slope efficiency would be larger at higher PRF. We have performed an estimation of the fiber lifetime, as it is known that applying stress to an optical fiber reduces its reliability. With much more stringent proof testing than the standard one (250 kpsi instead of 100 kpsi) the estimated lifetime is longer than 7 years which is the mission lifetime.

There was some concern that strain could modify the mode repartition in the LMA fiber. However, we have measured an excellent beam quality with M^2<1.2. We have also monitored the fluctuations of the beam centroid position δy and the beam radius ω. We found that $\delta y/\omega$<0.25, which is compliant with the specifications.
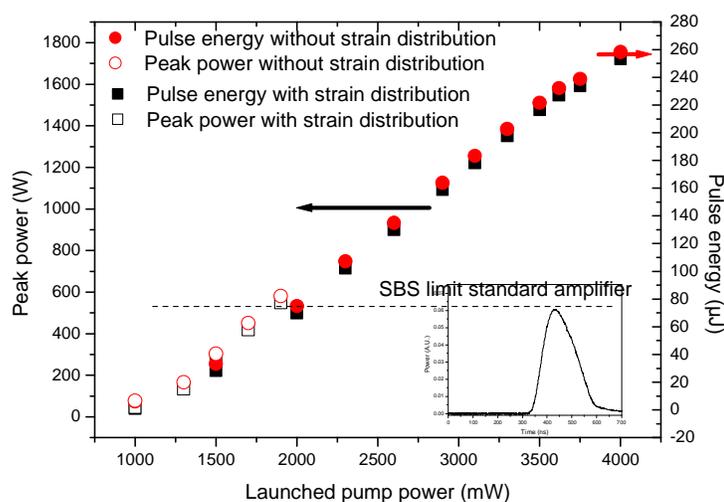
Fig. 5. Peak power and pulse energy as a function of the launched pump power. Without strain distribution (circles) the power is quickly limited. With strain distribution (squares) the pulse energy is pump limited.
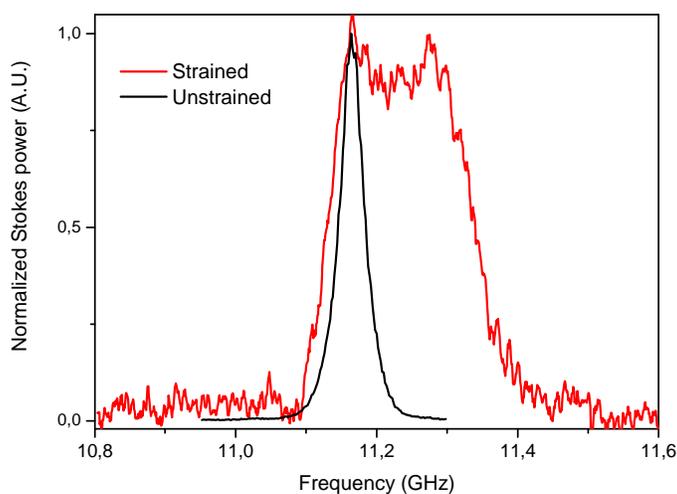
Fig. 6. Electrical spectrum (proportional to the Brillouin gain) of the beating between the Stokes light and the seed laser.

Although the fiber selected is particularly well suited for 1579nm amplification it is very sensitive to radiation. Indeed the fiber glass is rich is alumina and RIA is known to increase with the Al concentration. We thus made exploration on more suitable fiber compositions for the power amplifications stage.

V. COMPARISON OF LARGE MODE AREA FIBERS FOR THE POWER AMPLIFIER

The standard process to prepare doped fibers is solution doping MCVD. In order to reach high gain at 1579nm where the cross-sections are small, large Er concertation are required. This can only be achieved with large quantity of Alumina (Al) in the core glass. However in this process, the maximum Al concentration is limited by crystallization. Moreover high energy fiber systems require LMA fibers with low NA while large Al concentration increases NA. However, simultaneous incorporation of phosphorus (P) and Al (phosphoaluminosilicate composition) has been shown to mitigate this NA increase. Indeed, equimolar addition of alumina and phosphorous reduces the glass refractive index [7, 8].

In order to evaluate this possible technology, we have tested large mode area fibers based on this phosphoaluminosilicate glass produced by ORC using the solution doping MCVD process (cf. table 1).

A.   Fibers properties

Table 1. Fiber properties of aluminophosphosilicate fibers and commercial aluminosilicate fibers.

Fibre	Glass composition	Core diameter/ NA	Note
A	Aluminophosphosilicate	30 µm/0.1	LMA
B	Aluminophosphosilicate	30 µm/0.12	LMA
C	Aluminophosphosilicate	11µm/0.12	Singlemode version of fibre B
L1	Aluminosilicate	4µm	Singlemode Er40-4/125
L2	Aluminosilicate	40 µm/0.09	LMA Er60-40/250
EY	Phosphosilicate	10µm/0.14	

Figure 7 left shows the electronic dispersion spectroscopy (EDS) measurement on fiber A. P concentration was kept larger than Al concentration to avoid crystallization issues. We added Yb as a screening agent in order to reduce the Er clustering. Indeed, Er ions tend to cluster at high concentration and Yb helps mitigating this effect. The Erbium concentration reaches an average value of 420 ppm mol in agreement with the measured peak absorption of 45 dB/m. Figure 7 right shows the index profile of the fiber measured on the preform. Despite the presence of a central dip, due to evaporation of the phosphorous during the soot collapse, tapering the fiber input allows to keep a relatively good beam quality. The refractive index profile compares well with the profile computed using the non-additive relation and the RE contribution [8].
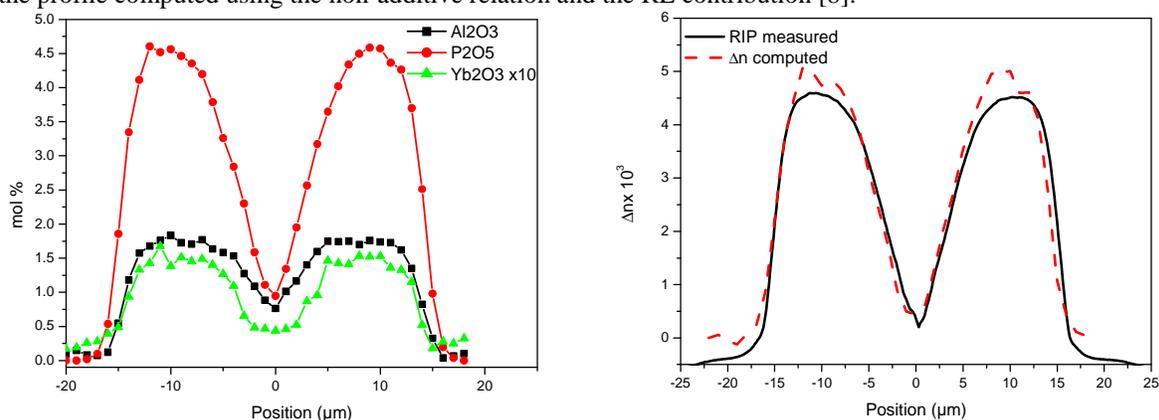
Fig. 7. Left: Chemical analysis of fiber A by EDS. Right: Measured refractive index on the preform (solide line) and calculated using the EDS concentration (dashed line).

Fibre B has a similar composition as fiber A with [Yb] increased by 30% and [Al] increased by 25% and was drawn with a core diameter of 30µm and core NA 0.12. Fiber C has the same composition as fiber B but was drawn to 11µm core diameter for singlemode operation. Radial profiles for fiber B is expected to be close to fiber A. A length of 10m of fiber C was γ-irradiated using a ⁶⁰Co-source at room temperature to measure the RIA. Using the same protocol aluminosilicate fiber L1 with 427 ppm Erbium was also irradiated. The radiation induced attenuation reaches a maximum of 0.15 dB/m for fiber C and 0.68 dB/m for fiber L1 around 1500 nm for a dose equal to 10 kRad (cf. fig. 8). This reduction of RIA in the aluminophosphosilicate host confirms recent results [9].
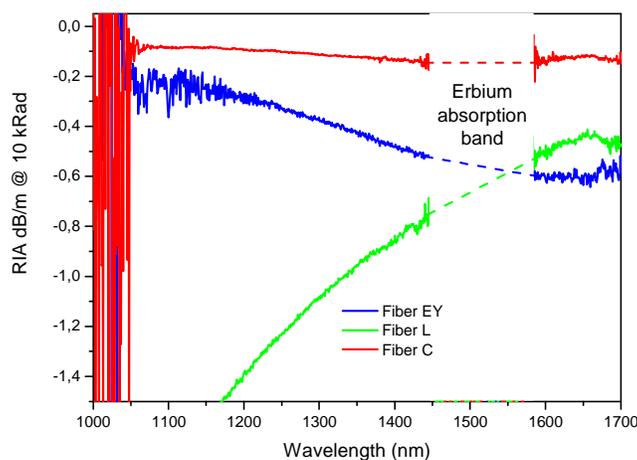
Fig. 8. RIA spectrum of various fibers tested during the project at 10 kRad

Normalized absorption spectrum for the fibers C, L1 and EY have been measured and shown on fig. 9. Fiber C presents a strong reduction of the cross-sections around 1579nm. From this observation a strong reduction of gain in fiber B/C can be expected compared to aluminosilicate fibers.
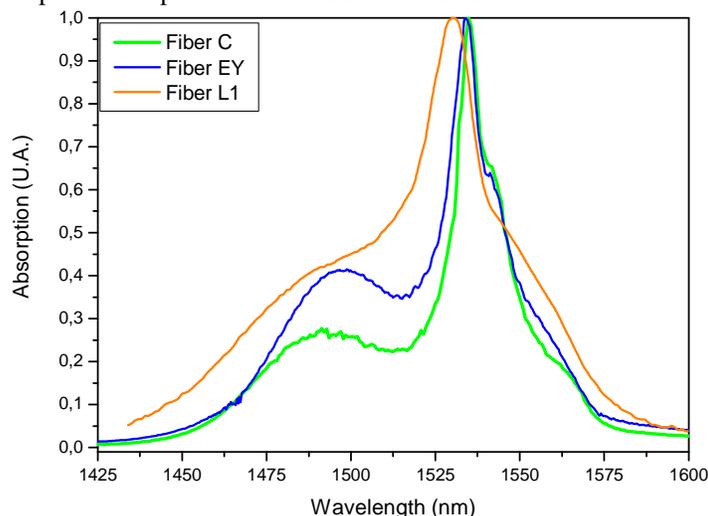
Fig. 9. Comparison of the normalized absorption spectrum zoomed around 1580nm of relevant fibers.

A. Amplification experiments

A CW amplifier was built to assess fiber B/C slope efficiency at 1565nm (expected to be the maximum of efficiency) and at 1579nm. Seed lasers emitting at 1565 nm or 1579nm are spliced to a fiber multiplexer to couple a 1532nm pump fiber laser to a piece of fiber B or C. The output power and spectrum are recorded for various input powers. Figure 10 left shows results for 9m of fiber C. With 120 mW input power at 1565nm, the output power increases steadily. At 1579nm, fiber C is not saturated and the output power quickly saturates even for 225 mW input power due to ASE amplification around 1565nm. Before saturation efficiency is only 30%. Figure 10 right shows results for 9m of fiber B. The efficiency is even lower around 13% at 1579nm. The presence of clusters and the low cross sections at 1579nm explain these results.

We can compare these figures with the amplification results obtained with 5m of fiber L2 used in the preliminary high energy setup: maximum power 4W and 37% efficiency for 380 mW injected at 1579nm. LMA fiber L2 thus generates a much higher gain with about 3 times larger efficiency for a twice shorter fiber length (meaning less RIA and higher SBS threshold) than LMA fiber B at 1579nm.
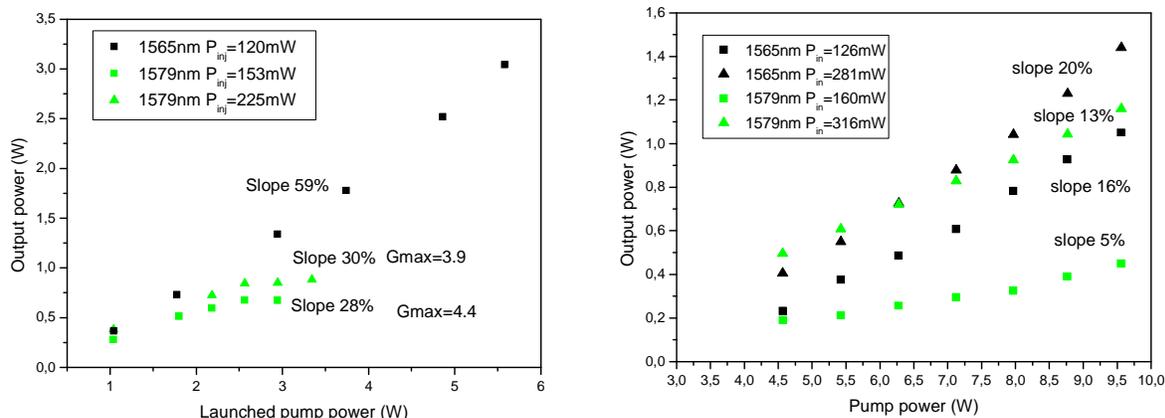
Fig. 10. (Left) amplification of 1565nm and 1579nm signals in fiber C (single mode) pumped at 1532nm; (Right) amplification of 1565nm and 1579nm signals in fiber B (LMA) pumped at 1532nm.

VI. TEST OF A COMMERCIAL RAD HARD FIBER FOR THE PREAMPLIFIER

Along with the Erbium doped fiber of the power amplifier, the system includes several other doped fibers whose sensitivity to radiations need to be minimized. The first stage of amplification must generate a gain of 30 dB. As it is based on a single mode fiber, optimization of the fiber composition is easier. We have tested fiber IXF-RAD-AMP-2-PM from iXFiber. This is a single clad PM Er doped fiber with peak absorption 25.1 dB/m at 1530nm. Using this fiber we have built a double pass amplifier (cf. fig. 11). The fiber is core pumped at 1480nm (this wavelength has less RIA than 980nm). During irradiation the input power is monitored through the tap coupler and output power is monitored after the circulator.
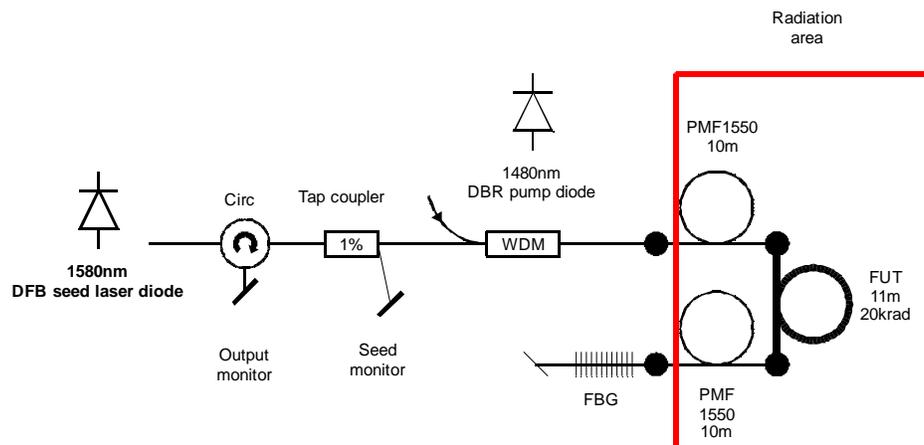
Fig. 11 1580nm double pass amplifier setup during tests. Fiber is 9m rad hard single clad Er doped fiber

The fiber is located closed to a radiating Cobalt 60 source. The laser is coupled to the doped fiber through 10m standard PM1550 transport fibers. The amplified power is being recorded during the whole experiment. The fiber is irradiated with a dose of 185rad/h (total dose 20.7 krad). The amplifier is characterized before irradiation, during irradiation and after irradiation. We set the input power to 4µW at 1579.04nm and pump power to 95 mW. Before irradiation, the output spectrum after the circulator can be seen on Fig. 12 right. The OSNR is -26 dB. The ratio of signal power to total power is 74%. Most of the ASE is concentrated around 1560nm. Total power is measured to be 5.9 mW.

Just after irradiation, the total (signal+ase) output power was 46% of its initial value. 7 days later, the total output power had increased to 63% of its initial value before irradiation. This can result partly from reproducibility of the measurement and partly from fiber self-healing. Indeed by doing the same measurement 54 days after irradiations we found that the power increased somewhat to 78% for the total power and 89% for the signal power. Fig.12 right shows that the spectrum has globally the same shape but with a ~3dB drop.
In an operational system, an increase of the pump power by 20 mW would compensate for this signal drop with a power of 4.2mW (cf. Fig. 12 left).These numbers are consistent with the low measured RIA of only 0.2 dB/m for 20.7 kRad.
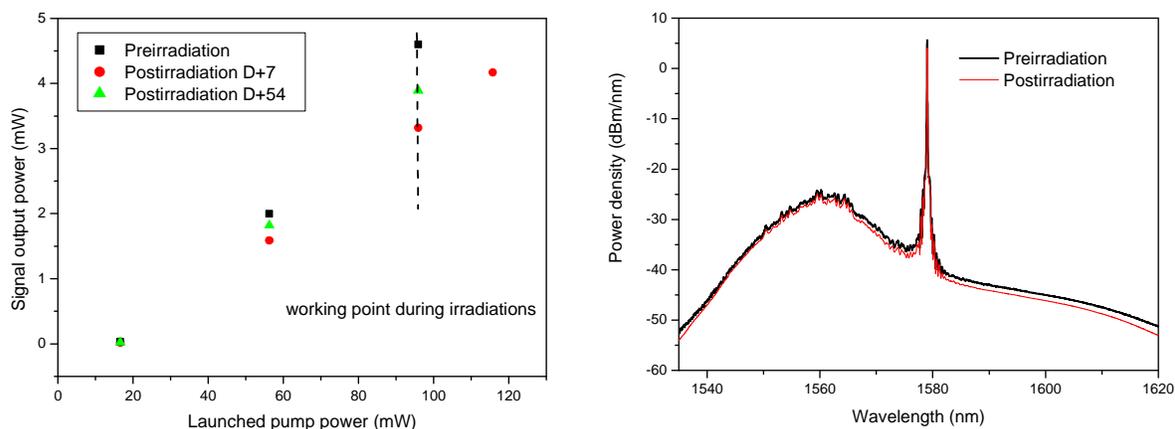
Fig. 12. (Left) Comparison of signal output power for various pump level at 7 days and 54 days after irradiation. (Right) Comparison of preirradiation and postirradiation output spectrum (after the circulator) of the double pass amplifier.

VII.   CONCLUSION

We have designed a three stage all fiber MOPFA to generate 260µJ per pulse of energy around 1579nm. The measurement of short term stability of the free running DFB lasers yields to 155 kHz @ 10 s. Beatnote comparison between oscillators shows a linewidth of around 0.5MHz.

For the amplifying fibers, we have compared RIA and efficiency for phosphoaluminosilicate fibers prepared by ORC and commercial aluminosilicate fibers. The first ones present a 4 times decrease in RIA compared to standard fibers. However the gain decrease around 1579nm is very significant. Therefore we based our design on the LMA aluminosilicate fiber. This fiber is sensitive to radiations and further work will be required on the fiber and shielding. With this design a preliminary setup was tested that demonstrated 260µJ pulse energy for 150ns pulse duration and 4 kHz PRF.

Finally we have also tested a radhard fiber from iXFiber that can be used in the first amplifier in double pass configuration. We have showed that the RIA were as small as 0.2 dB/m for 20 kRad dose and that the double pass amplifier gain could be recovered after 20 kRad by increasing the pump power.

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