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Radiation tolerant frequency comb fiber laser for space applications

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ABSTRACT

A radiation tolerant Erbium fiber based optical frequency comb has been developed and environmentally tested. The system remained operable after an accumulated dose of 1 kGy*. The underlying femtosecond fiber oscillator and Erbium fiber amplifiers have been manufactured from speciality doped fibers. The fiber optic system has been assembled and packaged using low outgassing components in a flight representative package before it was irradiated under active operation in two stages a 500 kGy. The accelerated ageing with dose rates of 10 mGy/s in water was tested using the calibrated Cobalt 60 source of the ESA-ESTEC facilities. The comb laser remained fully functional while the oscillator lost up to 30% of output power after the full exposure to the accumulated dose of 1 kGy. The fiber amplifiers lost 5-7% of output power.

Keywords: frequency comb, radiation hard, erbium doped fiber laser

1. INTRODUCTION

Since its invention the optical frequency comb (OFC) has become the Swiss-knife to synthesize and measure precision optical frequencies, paving the way to advanced optical clocks and quantum sensors.[1] Presently there exists a growing demand for such systems being space qualified, covering diverse applications ranging from precision atomic clocks, ranging, LIDAR, gravitational sensing, and possibly fundamental physics missions based on ultra-precise timing comparisons. Since 2010 Menlo Systems has advanced their comb technology in this direction, aiming for reduced size, weight and power (SWAP), and hardness against space environmental effects. Several sounding rocket missions of compact, low power and automated combs have been launched by now, demonstrating the feasibility of combs in space.[2,3] Since the beginning of such activities the radiation hardness of the doped fibers involved has been a major concern. The radiation sensitivity of optical fibers is usually classified into different types:[4] (a) radiation sensitive, (b) radiation tolerant, and (c) radiation hardened. Fiber lasers based on rare earth doped fibers using Yb and Er are known to be generally radiation sensitive. A recent paper thoroughly reviews the degradation of such fibers caused by energetic particles.[5] In short, the radiation damage to fibers is quite complex and depends on numerous material parameters. Intrinsic ones are mainly related to fiber chemical composition and fiber guiding properties, but also extrinsic parameters exist, like the type of radiation, the accumulated dose, the dose rate, the temperature, the operating wavelength, and the optical power in the fiber core.

The energetic radiation in space can lead to the generation of point defects in the fiber core, increasing the loss of light at pump and lasing wavelengths. Fortunately, such point defects are often unstable and decay or can be annealed by elevated temperatures or light absorption. As a consequence, the ratio of the dose rate of energetic radiation in combination with the laser operation at its nominal power influence the forward-backward reaction between the generation and the annealing of such defects. A higher core temperature favors accelerated

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*The accumulated dose D is expressed in Gray, 1 Gy corresponds to absorption of 1 J/kg, or 100 Rad. The dose rate dD/dt is the dose absorbed per time unit and expressed in Gy/s annealing, and an increased optical pump power in the fiber can be assumed to have a similar effect. This is of particular importance to active fibers pumped in the visible or near infrared wavelength range, as various radiation induced color centers are known to exist in this wavelength region. In the present case we have studied fiber combs under active operation to take such effects into account.

With respect to radiation damage Er doped fibers are at particular risk.[6] Energetic radiation causes radiation induced absorption (RIA) at both the pump and the signal wavelength.[7] The result is a decreased amplification efficiency nearly independent of the type of the ionizing particle.[8] An empirical model allows us to estimate the RIA dependence from a steady-state radiation:[9] It can reasonably be reproduced by a power law function $A(D) = C_0 D^{\beta}$, where $A(D)$ is the RIA, D is the accumulated dose, and β and C_0 are constants depending on fiber properties and operating wavelength.

2. EXPERIMENTAL

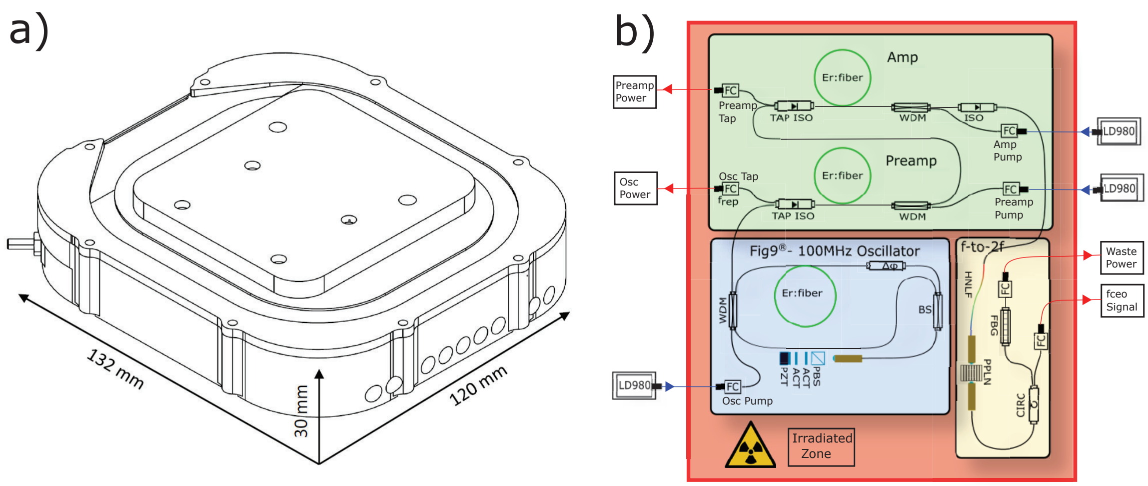

Figure 1. a) Fiber box used for the irradiation experiments. The box contains the complete fiber optical comb in fiber layout as sketched on the right panel. b) Fiber layout for the fiber optical comb system used for irradiation experiments. The systems consists of a 100 MHz Fig-9 NALM oscillator, followed by a split amplifier consisting of a pre-amplifier and a main amplifier, non-linear broadening in a highly non-linear fiber, and a cross phase interferometer (XPS) based on a PPLN waveguide and subsequent FBG filtering. In the experiment only the optics module was irradiated. Electronics, pump diodes, and photodetectors were situated outside of the irradiation zone and connected with fibers to the system.

For several years iXblue has developed and commercialized radiation tolerant rare-earth doped speciality fibers. A comprehensive overview on the present state of the art of design, simulation, and testing of such fibers for space applications has been provided by Ladaci.[10] Based on his work it was possible to develop fast-track two advanced gain fibers in the project matching a goal that has been twofold: (a) reduced radiation sensitivity at an increased dopant concentration and (b) matching the fiber dispersion to comparably narrow fiber laser requirements. Besides the reduction of RIA, which reduces also the radiation induced gain variation (RIGV), we have also reported earlier on the influence of laser activity on the accelerated ageing.[11] Such measurements where performed at the irradiation facility of affiliation c and used fiber laser breadboards with similar laser oscillator and amplifier settings, but without the actors and the PPLN necessary to build a fiber comb.

Fiber breadboards, fiber oscillators[12] and fiber amplifiers have been manufactured with increasing complexity in our irradiation damage studies, with the final fiber layout corresponding to the requirements for a fully operable fiber comb, quite comparable to previous OFC sounding rocket campaigns.[3] The fiber comb laser manufactured here includes all optical elements required for a long-term stabilization of the two fundamental frequencies of the OFC.[1] The stabilization of both frequencies based on such actors has been demonstrated earlier, here we have simply verified that all built-in actors were operating correctly.[13]

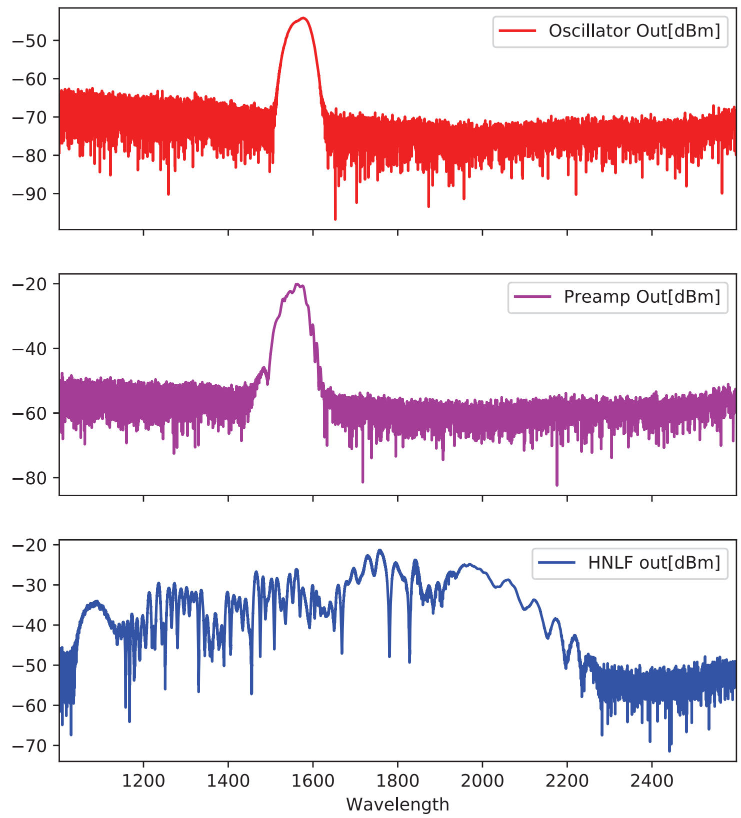

Figure 2. Spectral data at different positions of the fiber optical set-up. Upper panel shows the oscillator spectrum seeded into the preamplifier. The seed spectral bandwidth is about 44 nm, centered around 1575 nm. The middle panel (magenta) shows the spectrum after the preamplifier. The spectral bandwidth is about 41 nm centered around 1560 nm. The third panel shows the octave spanning spectrum achieved after further amplification in the main amplifier and injection into a highly non-linear fiber (HNLF, blue). The spectrum extends from 1050ńm to 2200ńm.

The laser was assembled in a compact fiber box made from aluminum. The box, its drawing shown in figure 1 a) contains all optics elements of the oscillator, the actors for repetition rate and offset frequency, the preamplifier, the amplifier, the spectral broadening in an HNLF, and the cross phase interference using a PPLN waveguide, and some subsequent filtering at 1064 nm. The comb demonstrated operation, providing an offset beat of up to 45dB at 100 kHz RBW, as shown in figure 3. Optical spectra of the laser system taken at different positions in the set-up are shown in figure 2. The comb set-up has then been irradiated at ESTEC with 10 mGy/s standardized to water from a Co-60 gamma ray source, providing photons at 1.172 MeV und 1.332 MeV. The aluminum lid of the fiber box was taken into account by calibration of the irradiation strength behind a 2 mm thick aluminum sheet. The experiment is sketched in figure 1 b). The gamma ray flux was continuously monitored by a gamma ray probe situated close to the device under test. To achieve this comparably high flux the optical system has been centrally positioned at about 20 cm from the Co-60 source, a distance where a homogeneous irradiation over all fibers and fiber components can be assumed. Both, pump and diagnostic light were provided through 6 m long 3 mm buffered polarization maintaining patch-cords. Pump light was provided by low-noise home-built laser driver units and for laser power measurements calibrated commercial power meters have been used. The repetition rate and the offset beat frequency have been acquired by heterodyning light after the PPLN waveguide on a commercial grade photodiode with an integrated RF amplifier and DC filter. The RF frequencies have been monitored and stored with commercial calibrated RF spectrum analyzer. The comb laser operation and all power meters have been controlled and read out by a remotely controlled industry PC, located outside the radiation chamber. In sum, only the fiber optics system was subject to intense Gamma irradiation, and all control and driver electronics was well protected in a shielded area outside the irradiation chamber.

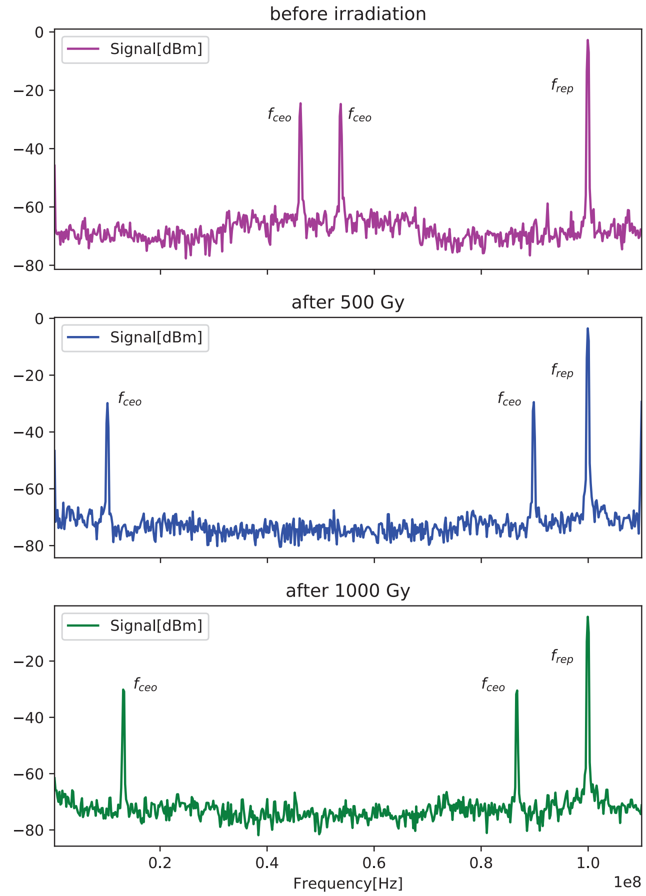

Figure 3. RF spectra of the comb generated from unbalanced heterodyne photo-detection after the cross-phase interferometer of the comb, acquired with 100kHz RBW. The RF spectra before irradiation, in between after 500 Gy and after 1 kGy did not significantly degrade. The typical f_{ceo} beat (the two smaller peaks) strength exceeds 40 dB above noise floor. Shift of the spectral position of the offset beat is normal, the comb was not controlled for the stabilization of the beat frequency. Right large peak is the repetition rate f_{rep} at (100 MHz).

During irradiation the fiber box was thermally stabilized to 26 ± 0.05 degrees using three Peltiers, two NTCs and a commercial grade temperature controller circuitry. During operation of a fiber comb laser its precision temperature control is recommended to avoid strong drift in repetition rate and offset frequencies. At the applied dose rate of 10 mGy/s the accumulation of 1 kGy has been achieved with an accumulated irradiation duration of 27.8 hrs. The irradiation duration has been split into two separate 13.9 hrs phases, with approximately 5 hrs of recovery in between. Between the first and the second irradiation phase the pump diode current of the oscillator was increased from 200 mA to 210 mA to compensate for oscillator losses. Also the amplifier pump current was readjusted from 750 mW to 770 mW for both pre- and main fiber amplifier. The pause between the first and the second irradiation enables also study of the recovery rate of the irradiated system and simulates corrective action for an improved laser operation. During irradiation the system has been operated at 100% duty cycle. We have reported earlier on the duty-cycle dependent radiation damage and annealing effects,[11] demonstrating that active laser operation has a significant positive influence on laser survival under irradiation.

3. RESULTS AND CONCLUSION

During and after the irradiation the fiber comb was operating very stable. The drift rate of the offset beat was in the order of a few kHz/min, and the free running offset beat showed a line-width of about 30 kHz which

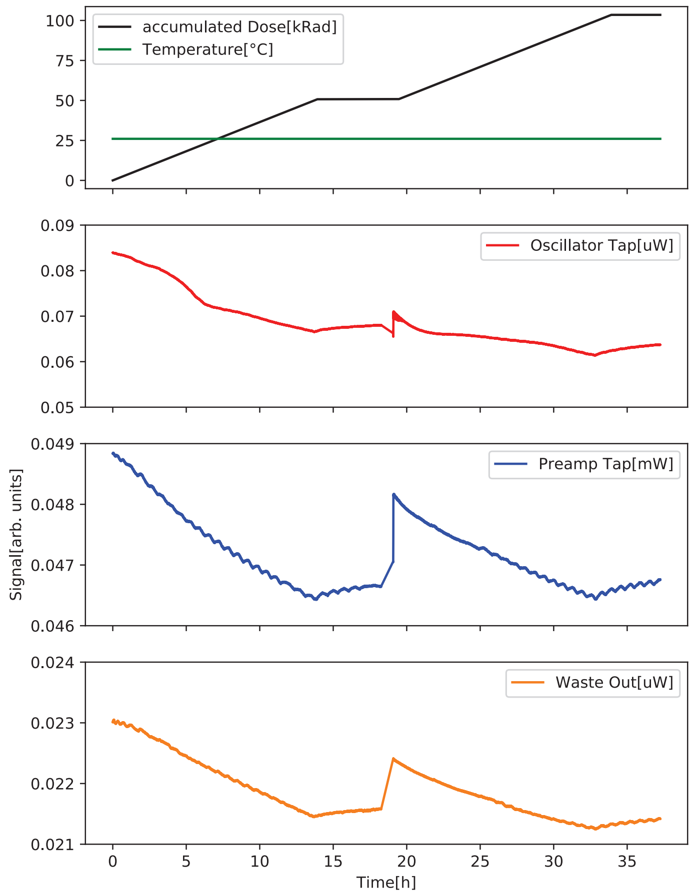

Figure 4. Data from irradiation experiments at ESTEC. Upper panel shows the accumulated dose applied to the system (black). First, 500 Gy have been applied over a period of 13.9 hrs, then the system was allowed to recover for 5hrs. The pump intensity was readjusted after 19hrs before the second 500Gy have been applied over 13.9 hrs, and afterwards a 5 hrs recovery period. The fiber box temperature was stabilized to 26 C. The second panel (red) shows the intensity measured at the oscillator tap out (1%). The third line (blue) shows the power at the preamplifier tap output (50%). The lower panel (orange) shows the laser power of the light remaining at the waste output behind the FBG.

compares well to our present ultra-low noise combs. For the oscillator we have observed a significant loss of laser output intensity at the isolator tap output (-30% at 1 kGy), see figure 4. However, the oscillator repetition rate, and the comb offset beat changed only very slightly and very slowly. Nevertheless, the comb oscillator was able to cope with losses and drifts, which can presumably be compensated by pump laser current adjustments, fiber box temperatures, and feedback actor voltages. Laser amplifiers lost comparably less output power after 1 kGy irradiation, about 6-7% (see figure 4). Moreover, we did not observe any strong laser damage or degradation of fiber laser components used in our set-up. A laser built from standard gain fibers would have lost about 0.125%/Gy. The fiber technology developed here has increased the lifetime for frequency combs in radiation environments by about a factor 10. The performance loss of the radiation tolerant fiber comb used here can be compensated by pump laser light adjustments. It should also be noted that our study simulated rather a worst-case scenario, because: (a) A comb operated at MEO faces a 1:3000 reduced irradiation. This shifts the forward-backward reaction of fiber losses largely towards an increased lifetime. (b) continuous adjustments of pump power during the mission can be applied to compensate continuously for the radiation induced losses of laser power. Here we have applied only a step-wise increase to the pump power after 19 hrs of the experiment, a continuous power regulation can keep the comb continuously at the sweet spot. From our present data we conclude that fiber comb systems build from of-the-shelf components as selected here are able to survive cosmic irradiation for at least 10 yrs at Mid-Earth Orbit (MEO), assuming that these lasers are additionally shielded by about 6 mm Aluminum. This will actually be the case in the space comb design of Menlo Systems that has been recently elaborated for future in-orbit deployments.

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