

Environmental testing of active thulium fibers and fiber components for space-based greenhouse gas monitoring

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ABSTRACT

Laser systems for use in space are exposed to different environmental conditions that can affect the performance and reliability of their different components. Mechanical loads during launch, temperature variations, and ionizing radiation can cause optical losses and, subsequently, a degradation of the laser process. Consequently, testing against environmental conditions is an essential step in the development of laser systems for space-based missions. This work presents two of four environmental test campaigns conducted in the course of the Horizon Europe project HALLOA to test its key subsystem – a ns-pulsed Thulium-doped fiber amplifier (TDFA) – against environmental conditions relevant to Low Earth Orbit (LEO) LiDAR missions, including vibration, shock, temperature cycling, and ionizing radiation. We will show our strategy for testing critical fiber components as well as Thulium doped fibers in laser operation with the goal of increasing the TRL of the TDFA module to 5-6.

Keywords: Differential absorption LiDAR, TRL 6 demonstration, Environmental testing, Thulium-doped fiber amplifier

1. INTRODUCTION

Optical fiber components, actively doped fibers, and ultimately all subsystems intended for space-based laser systems must maintain their optical performance under the harsh environmental conditions encountered during their use in space missions. Especially relevant are mainly three conditions. First, the components must tolerate high mechanical loads (vibration and shock). Second, they must typically operate and be stored within a wide temperature range, and third, they must deal with cosmic radiation such as gamma radiation. These loads can lead to increased optical losses, wavelength shifts, reduced output power, or other irreversible degradation of the optical components.

Differential Absorption LiDAR (DIAL) is a reliable technique for monitoring atmospheric CO_2 / H_2O concentrations and profiling horizontal wind speeds. The above mentioned detrimental effects are particularly critical for laser-based DIAL instruments operated from space. A laser system must have certain characteristics in order to be used in a DIAL mission: it must operate in single mode at various wavelengths at about $2\ \mu\text{m}$, have exceptional beam quality ($M^2 < 2$), high spectral purity (99.95 % within 1 GHz), stable wavelength ($< 100\ \text{kHz}$), and high pulse energy ($> 10\ \text{mJ}$).¹ To achieve these parameters, overcome limitations such as Stimulated Brillouin Scattering (SBS), and reduce the complexity of the laser system, a hybrid solution combining the benefits of fiber-based systems and free-space crystal-based laser amplifiers may be a viable choice. Fiber-based laser systems offer several advantages for such hybrid system, including compactness and high optical efficiency. At a wavelength around $2.05\ \mu\text{m}$, Thulium-doped fiber amplifiers are therefore attractive candidates. Nevertheless, their use in space requires the individual fiber components as well as the Thulium fiber itself to be evaluated under corresponding environmental conditions.

For this purpose, the Horizon Europe project HALLOA^{2,3} has been launched to build a hybrid laser architecture designed primarily for space-based DIAL applications. One distinguishing aspect is the use of entirely European Union (EU) optical components and subsystems, which reduces the dependence on non-EU technologies. The investigated components in this work form one of two main subsystems: a $2.05\ \mu\text{m}$ pulsed double stage

Table 1. The four environmental test campaigns in the HALLOA project.

No.	Test campaign	Vibration	Shock	Thermal	Gamma	Proton
#1	Critical fiber components	Passive	Passive	Passive	Passive	
#2	Tm-doped fibers				Active	
#3	Pump diode 793 nm					Passive
#4	TDFA	Passive	Passive	Passive		

Thulium-doped Fiber Amplifier (TDFA). In the HALLOA project, the test activities are divided into four environmental test campaigns covering critical passive fiber components, Thulium-doped fibers, the 793 nm pump diode, and the complete TDFA. The different tests and numbers # of the campaigns are given in Table 1.

The staged approach allows to investigate degradation mechanisms first at component level before environmental testing of the complete amplifier. Therefore, the focus in this work lies on the first two environmental test campaigns, in which the functionality of both the critical fiber components and the active Thulium fibers is verified under realistic environmental conditions encountered during space missions to demonstrate TRL5. In this context, vibration and shocks, as well as significant temperature fluctuations, are only expected during the launch phase; therefore, only passive testing is required on the critical fiber components. Passive testing means, the components under test are characterized before and after exposure using a defined set of optical performance parameters. The Thulium doped fibers, in turn, must be tested in operation because self-recovery behavior may be detected following irradiation. In the following, a detailed description of the two test campaigns is presented, including the optical performance tests before and after the environmental tests.

2. ENVIRONMENTAL TEST CAMPAIGN #1 - CRITICAL FIBER COMPONENTS

The investigated critical fiber components originate from the final double-stage TDFA system developed in the project, shown schematically in Fig. 1. Six different critical fiber components were selected based on their function within the amplifier and their potential sensitivity to mechanical, thermal, and radiation-induced degradation: the pump-signal combiners *PSC1* and *PSC2*, the isolator *ISO*, the band pass filter *F*, the optical 10/90 coupler *C*, and the mode field adapter *MFA*. An overview of the specifications of the different components as well as of the individual verification tests specific to each component is given in Section 2.2, Table 2.

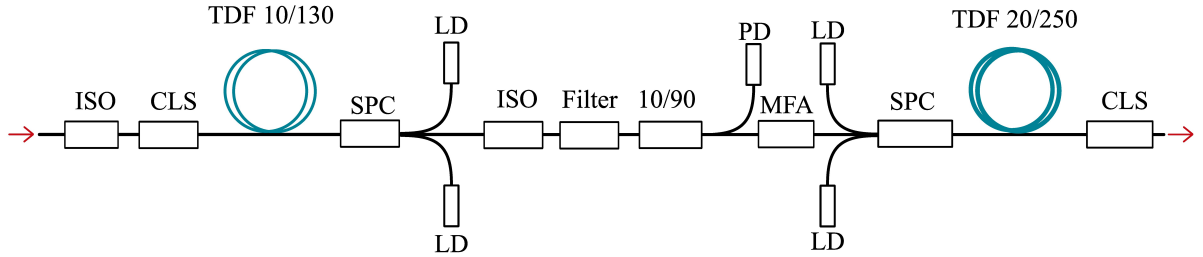


Figure 1. Design concept of the final TDFA in a double-stage configuration. Abbreviations: ISO: Isolator, CLS: Cladding light stripper, TDF: Thulium doped fiber, SPC: Signal pump combiner, LD: Laser diode, PD: Photo diode, MFA: Mode field adapter.

The critical fiber components were fully environmentally tested, which includes vibration, shock, thermal cycling, and gamma irradiation. To distinguish the degradation due to the individual environmental loads, optical characterization was performed after each test. Fig. 2 summarizes the test procedure.

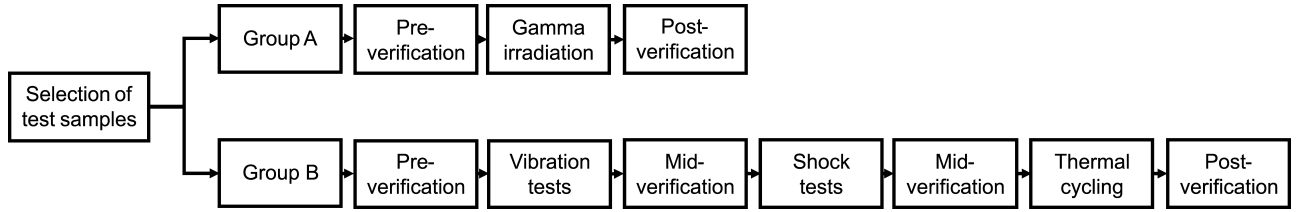


Figure 2. Process chart for the environmental test campaign #1. Each step includes a thorough visual inspection.

Vibration, shock, and thermal cycling were performed sequentially on the same components with performance verification before and after the tests (Group B). Irradiation was carried out on separate parts (Group A). Two samples of each component type were tested in each environmental test. The limited sample size does not allow for a statistical assessment of component reliability. However, using two nominally identical samples enables the identification and differentiation of systematic environmental effects from individual manufacturing defects. The individual environmental tests are described in the next section.

2.1 Description of the environmental tests and parameters

The test parameters were selected to represent the mechanical, thermal, and radiation loads relevant to a space borne laser system during launch and operation in LEO and mainly taken from comparable LiDAR missions.⁴ Attention was also paid to ensuring that they comply with the relevant ECSS standards.

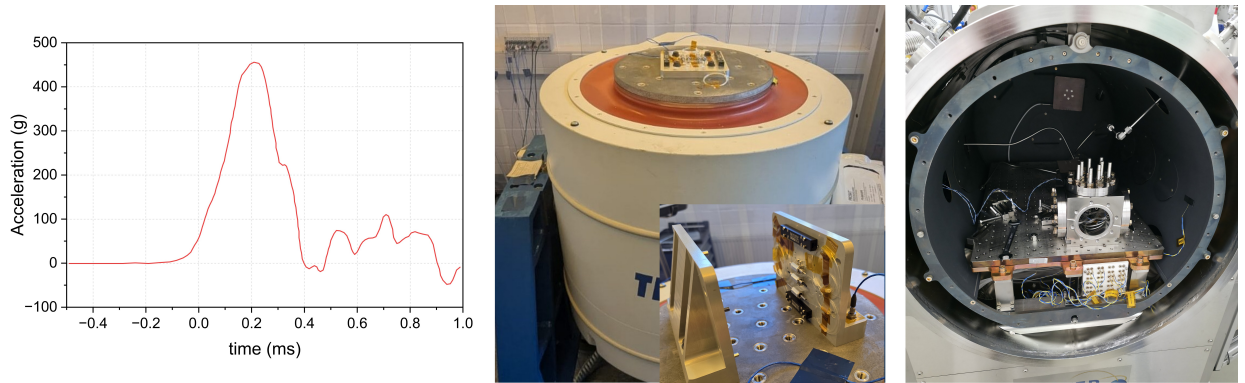


Figure 3. Representative shock profile measured at TechnoLab Berlin (left) and setups for vibration (center) and thermal cycling (right), which were carried out at LZH.

Vibration test Vibration tests were conducted in accordance with the requirements of *ECSS-E-ST-10-03C Rev.1*.⁵ The critical fiber components were tested in a non-operational configuration along all three orthogonal axes (X, Y, and Z). Unlike the normal procedure for such tests, no low-level sine sweeps were performed to identify and monitor the fundamental resonance frequencies before and after each vibration test. This was due to the insufficient surface area and the geometry of the components, which prevented the attachment of acceleration sensors. Sinusoidal vibration tests were carried out in the frequency range of 5 to 140 Hz using qualification levels of 1 to 20 g (5 to 20 Hz), 10 g (20 to 75 Hz) and 2.5 g (75 to 140 Hz) with a sweep rate of 2 octaves per minute. Subsequently, random vibration testing was performed from 20 to 2000 Hz for 2 min per axis using a qualification spectrum with an overall level of 20 g RMS and increased in steps of -12 dB, -9 dB, -6 dB, -3 dB, and 0 dB. The vibration tests were conducted on an in-house vibration table, which is shown in Fig. 3 in the center picture, including the mounted critical fiber components for x-axis testing. The inset shows the mounted components for testing in y-axis.

Shock test A mechanical shock test was performed to verify the structural integrity of the fiber components under representative launch-induced shock loading. The test consisted of one 450 g 0.2 ms half sine shock, applied sequentially in all three orthogonal axes (X, Y, and Z). These test parameters are further consistent with the shock qualification levels defined in *ECSS-E-10-03A, Space engineering - Testing*⁶ taking into account the tolerance levels of -3 dB/ +6 dB.⁵ The shock tests were performed on a shock test machine at TechnoLab Berlin. An exemplary shock profile is shown in the left diagram in Fig. 3.

Thermal cycling test Thermal cycling tests were conducted to assess the influence of mission-specific non-operational temperature variations as well as operational temperature variations for the instrument inner core where the laser is implemented (+20°C to +30°C). The thermal cycling tests were performed with an in-house thermal vacuum chamber. The components were placed in a sealed enclosure that was flushed with dry air. A sensor located inside this enclosure allowed for continuous monitoring of temperature, pressure, and humidity. The chamber and the enclosure are shown on the right picture in Fig. 3. The following test parameters were applied for the thermal cycling of the fiber components tests:

- Temperature range: -40°C to +50°C
- Temperature hold time: 2.5 h
- Temperature accuracy: 5 %
- Number of temperature cycles: 8

Gamma irradiation For testing of passive fiber components, gamma radiation is typically used to simulate the effects of the radiation environment and characterize any resulting degradation.⁷ According to Ott et al.,⁸ LEO missions usually accumulate a total gamma dose of 5-10 krad. The orbit height, mission duration, and launch date are the primary determinants of the radiation values. In the HALLOA project, the components were tested to a gamma radiation dose level of 10 krad with a dose rate of 400 rad/h. This rate was held fixed for this test campaign.

2.2 Verification tests and results

The performance of the individual fiber component before and after each environmental test is evaluated using a custom-made measurement setup for the verification of the optical specifications. The method and procedure of the verification tests are always the same for each part and tailored to its optical function. The following verification tests were performed:

- S: Insertion loss
- SW: Stop wavelength at -0.5 dB
- P: Pump insertion loss (2 ports green and blue)
- PB: Pass bandwidth at -0.5 dB
- PER: Polarization extinction ratio
- R: Coupling ratio
- I: Isolation

The specifications for each verification test are listed in Tab. 2, column three, and taken from the data sheets of the manufacturers. To exclude measurement errors caused by the splice, splice losses are determined for each measurement and factored in. To pass the tests, the additional losses after all environmental tests have been completed must not exceed 5% of the specification. If the initial characterization is already below the specifications, e.g. the PER of all signal pump combiners, that measurement is used as a reference. In total, a component was considered environmentally stable if no functional failure occurred and the environmentally induced change remained within the predefined acceptance criterion. The results of all verification tests except the measurement after gamma irradiation testing are listed in Table 2. Based on the pass-/fail criteria described above, all components passed the test. No functional failures were observed after vibration, shock, or thermal cycling. The measured changes in insertion loss remained small compared with the absolute specified value, indicating that the applied mechanical and thermal loads did not result in significant permanent degradation. The variations observed for example in the PER were greater than those in insertion loss; however, no systematic degradation was observed with the progression of the campaign. The gamma tests had not yet been completed at the time this article was written and will be presented at the conference.

Table 2. Results of the environmental test campaign #2 including specifications.

CFC	Verification test	Specs	Pre-verification test results				After vibration		After shock		After thermal		After gamma	
			A		B		B		B		B		A	
PSC1	SN	NA	PSC1#1	PSC1#2	PSC1#3	PSC1#4	PSC1#3	PSC1#4	PSC1#3	PSC1#4	PSC1#3	PSC1#4	PSC1#1	PSC1#2
	S (dB)	<0.3	0.18	0.14	0.104	0.14	0.17	0.21	0.19	0.16	0.18	0.17		
	P Blue (%)	>90	96.4	97	95.95	95.14	97.4	96	93.8	94.8	96.9	96.6		
	P Green (%)	>90	96.1	96.3	95.11	94.3	93.4	94.2	93.9	93.6	94.5	94.5		
	PER (dB)	>18	15.3	13.9	16.13	15.5	15.3	13.3	14.9	16.4	15.08	13.5		
ISO	SN	NA	ISO1	ISO2	ISO3	ISO4	ISO3	ISO4	ISO3	ISO4	ISO3	ISO4	ISO1	ISO2
	I (dB)	>20	30.8	31.9	31.3	29.4	30.3	31.5	30.3	32	30.3	31.9		
	S (dB)	<1.2	0.45	0.59	0.46	0.52	0.48	0.61	0.49	0.63	0.46	0.57		
	PER (dB)	>20	30.2	31.7	27.8	24.8	31.8	34.6	34.6	34.5	32.66	30.89		
F	SN	NA	F1	F2	F3	F4	F3	F4	F3	F4	F3	F4	F1	F2
	S (dB)	<1.4	1.25	1.26	0.80	0.76	0.72	0.76	0.83	0.67	0.8	0.84		
	SW (nm)	>2053.5	2050.1	2052.1	2052.8	2052.1	2050	2052.1	2050.1	2052.2	2050.2	2052.3		
	PB (nm)	>5	7.5	7.6	7.6	7.5	7.6	7.7	7.6	7.8	7.5	7.7		
C	SN	NA	C1	C2	C3	C4	C3	C4	C3	C4	C3	C4	C1	C2
	S (dB)	<0.6	0.05	0.12	0.09	0.09	0.11	0.15	0.3	0.17	0.12	0.04		
	R (%)	10	13.2	11.6	12.3	11.5	13.4	11.6	14	11.7	14	11.9		
	PER (dB)	>20	22.7	23.1	24.6	22.6	21.7	24.1	22	24.4	21.99	27.24		
MFA	SN	NA	MFA1	MFA2	MFA3	MFA4	MFA3	MFA4	MFA3	MFA4	MFA3	MFA4	MFA1	MFA2
	S (dB)	<1.3	1.23	0.9	0.56	0.87	1.2	0.93	1.1	1.25	1.1	1.05		
	PER (dB)	>20	18.5	18.3	17.94	19.05	19.2	18.5	18.9	19.1	18.4	17.8		
PSC2	SN	NA	PSC2#1	PSC2#2	PSC2#3	PSC2#4	PSC2#3	PSC2#4	PSC2#3	PSC2#4	PSC2#3	PSC2#4	PSC2#1	PSC2#2
	S (dB)	<0.35	0.26	0.3	0.21	0.16	0.27	0.29	0.25	0.31	0.21	0.28		
	P Blue (%)	>95	94.9	95.9	97.4	96.1	93.9	95.2	94.6	95.1	94.9	94.9		
	P Green (%)	>95	95.3	94.3	97.1	95.3	95.1	94.9	95.4	94.5	95.4	95.8		
	PER (dB)	>18	14.8	11.9	14.3	12.9	14.7	11.6	14.6	12.2	13.3	12.15		

3. ENVIRONMENTAL TEST CAMPAIGN #2 - ACTIVE FIBER TESTING

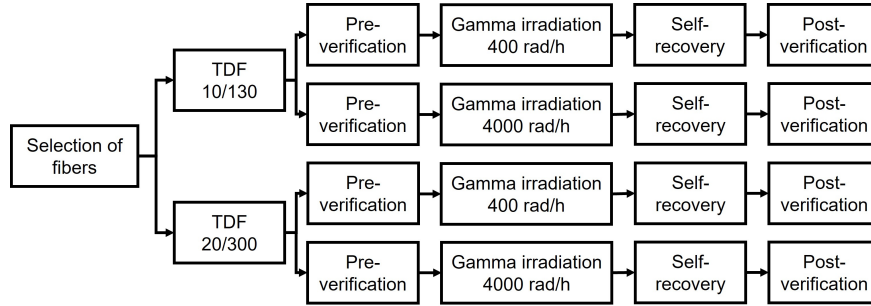


Figure 4. Process chart for the environmental test campaign #2.

Test campaign #2 comprises the testing of the Tm-doped fibers. The Tm-doped optical fiber must pass specific testing to be qualified. In literature, it was shown that rare earth doped fibers are sensitive to radiation effects in space-based environments and adverse radiation environments.^{9–11} Irradiation can induce color center formation in the glass-based fibers, which can cause the final failure of fiber lasers. In this case, the fiber laser properties mostly depend on the radiation tolerance of the active fiber. It has also been reported in the literature that both an active recovery due to the propagation of a high light intensity in the fiber core and a passive process are possible. Unfortunately, it is not feasible to conduct a test using the irradiation rate which occurs in during the space mission because this would require testing periods that are similar to the many-year lifespan of an actual earth observation mission. Consequently, higher irradiation rates that accumulate the mission lifetime dose in a few hours must be used for accelerated testing. It can be assumed that prospective degradation processes occur there at a proportionately quicker rate during the test, whereas potential recovery processes occur at the initial

rate. Therefore, obtaining the worst-case outcome in terms of possible fiber performance deterioration will be the aim of the fiber irradiation test. For this, the fiber will be used in an amplifier configuration during the test, and the performance of the amplifier as well as the pump light's absorption properties will be tracked.

Since the dose rate of gamma radiation also influences the magnitude of the arising effects (high dose rates lead to increased occurrence of radiation induced effects),¹¹ the Tm-fibers will be tested with two dose rates to estimate the influence of the dose rate. Testing more than two dose rates would be no longer economically viable due to the high time commitment. The preliminary parameter set for the irradiation tests of the Tm-doped fibers are the following:

- Gamma radiation dose level: 10 krad
- Gamma irradiation dose rate 1: 400 rad/h
- Gamma irradiation dose rate 2: 4000 rad/h

There are two different Tm-doped fibers used for the TRL5 relevant testing due to the double stage TDFA (see Fig. 1), a Tm fiber with a core diameter of 10 μm and a cladding of 130 μm , as well as a fiber with 20 μm core and 300 μm cladding diameter. Both types of fibers are tested with both gamma irradiation dose rates. The environmental test campaign #2 will be conducted for one piece of each fiber for each dose rate. The process chart in Fig. 4 gives an overview of the tests. A self-recovery measurement is performed after every irradiation test in active mode.

To perform active fiber testing a special amplifier test setup is developed to allow testing under class-1 laser conditions. This incorporates a closed box containing the amplifier pump and seed source, all necessary fiber components like signal pump combiner, protected fibers leading to and from the irradiation chamber, and an exposed section of the Tm-doped fiber, which will be placed in the irradiation chamber. The analysis setup for the amplifier output is placed in a second closed box. The amplifier operates in a double pulse mode with a separation of the pulses by 300 μs and a total repetition rate of 500 Hz. The generated pulse energy behind the first amplifier is 5 μJ and behind the second amplifier 50 μJ . Since the test campaign was not completed at the time of the paper preparation, no results are shown here, but will be presented on the conference.

4. SUMMARY

In this work, we presented the two test campaigns of the HALLOA project, in which critical fiber components and Tm-doped fibers were environmentally tested to demonstrate TRL5 of the TDFA. The first test campaign comprised testing of the critical fiber components against vibration, shock, thermal cycling, and gamma irradiation. Regarding the mechanical tests, all components passed the campaign, determined via different verification tests performed before and after each test. Furthermore, test campaign #2 was described, in which active fiber testing of the Tm-doped fibers under class-1 laser conditions will be performed. The results of the gamma irradiation tests are presented on the conference.

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