

Higher-energy thulium-doped fiber amplifier for space lidar applications at 2051 nm

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ABSTRACT

The European HALLOA project aims to develop a space-borne Light Detection and Ranging (LIDAR) system based on the Differential Absorption LIDAR (DIAL), for greenhouse gas monitoring at 2051 nm, corresponding to the CO₂ and H₂O absorption lines. The overall laser architecture combines fiber and bulk amplification stages within a Master Oscillator Power Amplifier (MOPA) configuration seeded by a dual narrow linewidth diode source. It relies mostly on European components. The fiber amplification stage, developed by KEOPSYS INDUSTRIES, is designed to emit double pulses separated by 300 μ s, each delivering 50 μ J at a repetition rate of 500 Hz and a pulse duration of 200 ns. The main limitation is the nonlinear stimulated Brillouin scattering (SBS) effect, which occurs at high optical intensities in the fiber core and depends on the length and the effective area of the guided mode. The pulsed signal is amplified through two successive thulium-doped fiber stages cladding-pumped at 793 nm. The amplifier was operated beyond its nominal conditions to investigate its limits. Limited by SBS, a maximum pulse energy of 116 μ J was achieved, corresponding to a peak power of 579.8 W for a pulse duration of 204 ns. This performance is achieved without applying mechanical strain to the doped fiber, a technique commonly used to increase the SBS threshold but not suitable for space applications.

Keywords: MOPA, SBS, TDFA, DIAL, narrow linewidth

1. INTRODUCTION

In recent years, thulium-doped fiber amplifiers (TDFAs) have attracted significant attention owing to their high optical performance, compact architecture, excellent beam quality, and high quantum efficiency [1,2](#). The availability of high-energy operation has led to the development of applications in various fields, including medical applications, gas monitoring, advanced spectroscopy, and defense. Thulium ion (Tm³⁺) offers a broad transition $^3F_4 \rightarrow ^3H_6$ extending from 1.7 to 2.1 μ m [3,4](#), as shown in the figure [1a](#).

Thulium-doped fibers exhibit three main pump bands, one centered at 793 nm, another around 1220 nm, and one broad absorption band extending from 1550 to 1750 nm. For these pump bands there are several efficient laser sources. In this work, we use multi-mode laser diodes at 793 nm. At this wavelength the peak core absorption is high and wide, typically a full width at half maximum (FWHM) of 17 nm. These characteristics are compatible with high-powerbroadband multimode laser diodes in clad pumping configuration. Furthermore, one of the objectives of the HALLOA project is the development of a European distributed Bragg reflector (DBR) pump diode by Lumibird Photonics Italia (LPI), a company part of the Lumibird group.

Combining thulium-doped fiber emission around 2051 nm with satellite based LIDAR techniques enables accurate measurement of atmospheric greenhouse gas concentrations on global scale. The wavelength choice is driven by the high absorption peak of the greenhouse gases CO₂ and H₂O [4,6](#), as well as by atmospheric transparency and eye safety [5,7](#). The technology employed is the DIAL LIDAR which measures greenhouse gas concentrations based on their spectral absorption. Two pulses at different but close wavelength are sent into the atmosphere. One of these pulses named ON is absorbed by the target gas, whereas the other, named OFF, is not.

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of 500 Hz and stable linearly polarized beam (polarization extinction ratio (PER) more than 15 dB). At the energy of 50 μJ , a beam quality factor M^2 of 1.1 is measured. The laser exhibits excellent operational stability, maintaining its maximum output energy over sixteen hours of continuous operation.

2. EXPERIMENTAL SETUP

The optical setup is divided into several amplification stages, as shown in figure 2. In the first part, the 2051 nm signal is amplified to 33 dBm in continuous wave regime and then passes through an acousto-optic modulator (AOM) to generate the pulsed signal. The AOM is driven to generate a Gaussian pulse shape of 200 ns FWHM at 500 Hz repetition rate.

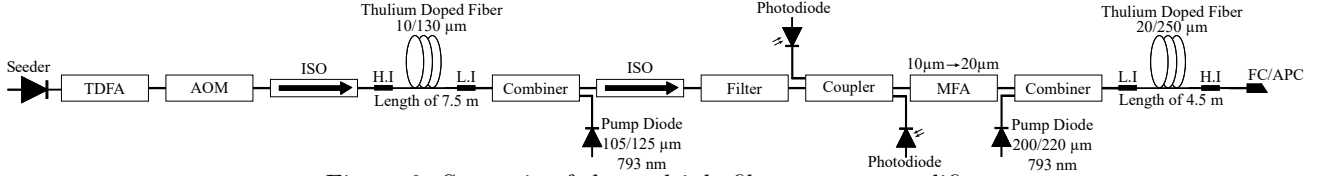


Figure 2: Synoptic of the multiple fibers stages amplifier

The first stage consists of a 7.5 m long 10/130 μm thulium-doped fiber, counter-pumped through the cladding using KEOPSY INDUSTRIES 105/125 μm hermetic pump diodes at 793 nm. Dual-stage optical isolators (ISO) are placed on either side of the fiber to protect the system from potential signal back-reflections. To limit the onset of SBS caused by excessive fiber length of small core fibers, the length of passive fiber between the components of the two amplification stages is minimized. Our goal is to maintain maximum fiber length of 80 cm between each component (this length cannot be significantly reduced due to the limitations imposed by our fiber-optic fusion splicing and recoating equipment).

The low PRF of 500 Hz imposes a significant constraint on the amplification efficiency. The upper laser level $^3F_4$, from which stimulated emission occurs, has a lifetime of approximately 400 μs , corresponding to a characteristic decay frequency of about 2.5 kHz, nearly five times higher than the 500 Hz pulse repetition rate. Consequently, a significant fraction of the excited thulium ions relaxes spontaneously between successive pulses, limiting the population inversion available for signal amplification and increasing the amplified spontaneous emission (ASE) generated in the doped fiber. To suppress this ASE and prevent self-lasing in the second stage, a filter is placed after the second isolator. Most high-gain fiber amplifiers, such as low-noise optical amplifiers, use fiber Bragg gratings (FBGs) combined with optical circulator to suppress ASE [4, 5]. This approach introduces additional insertion losses, requires precise temperature control to maintain the FBG at the target wavelength, and adds extra splices to the optical chain. Instead, a dichroic filter was selected, offering a lower extinction ratio than a typical FBG (≈ 27 dB, see figure 3b) but sufficient for our system. In addition, this filter offers a passband of 7 nm centered at 2051 nm which is well suited to the spectral requirements of the DIAL system employed for the HALLOA project. A 90/10 % 2×2 optical coupler is used to monitor both stages with photodiodes, allowing the average power at the output of the first stage and the potential back-scattered power from the second stage to be measured. The 90/10 % coupling ratio was selected because of the low average optical power.

A Mode Field Adapter (MFA) developed by KEOPSY INDUSTRIES is used to optimally inject the beam from the 10/130 μm fiber into the LP_{01} mode of the 20/250 μm large mode area (LMA) fiber of the second stage without exciting higher-order modes (HOMs). This allows to keep a low M^2 factor. The second stage consists of a 4.5 m long 20/250 μm thulium-doped fiber, cladding co-pumped using KEOPSY INDUSTRIES 200/220 μm hermetic pump diodes at 793 nm, with optical chips developed by LPI. By enlarging the fiber core area, the SBS threshold is raised, allowing the signal power to be further increased. To filter the input beam and prevent the amplification of HOMs, the doped LMA fiber is coiled to a diameter of 7 cm. An 80 cm long optical pigtail is used at the output to guide the beam the bulk amplifier.

Each component of the architecture will be qualified for space applications by Laser Zentrum Hannover (LZH), one of the partners in the HALLOA project. The environmental qualification tests will include shock, vibration, thermal cycling and radiation testing (proton irradiation for the pump diodes and gamma irradiation for the fiber amplifier) to ensure the reliability and robustness of the system.

3. EXPERIMENTAL RESULTS AND ANALYSIS

In this section, the experimental results obtained from the two amplification stages are presented and analyzed, with particular emphasis on the output power (peak and average), pulse energy, optical spectrum, pulse shape, and beam quality. The optical pulse energy is increased until the SBS threshold is reached. The onset of SBS is monitored using the optical coupler through two parameters: the temporal stability of the output pulse and the evolution of the back-scattered power. The SBS threshold is identified when the output pulse becomes temporally unstable or distorted and the back-scattered power exhibits an exponential increase.

For the first amplification stage, the 10/130 μm thulium-doped fiber is cladding counter-pumped using 105/125 μm hermetic pump diodes at 793 nm, providing up to 12.4 W of available pump power. At a PRF of 500 Hz, the SBS threshold is reached at a peak power of 61.9 W with a pulse duration of 204 ns, corresponding to a pulse energy of 12.4 μJ and an optical gain of 29.5 dB. The measurement was performed after the second isolator, which introduces 1.4 dB of insertion loss and is followed by 160 cm of passive fiber. Under these conditions, the first stage is limited by SBS rather than by the available pump power. Figure 3a shows the evolution of the output peak power and the average back-scattered power as a function of pump power. When assembling the first stage, an optical coupler was placed between the first isolator and the doped fiber to measure the back-scattered power. The back-scattered power remains low and stable up to approximately 4 W of pump power, above which it increases exponentially, a signature characteristic of the onset of SBS.

Taking into account the losses introduced by the optical components and the passive fiber length between the two amplification stages, the first stage is operated at a peak power of 30 W after the second isolator. This corresponds to an operating point approximately 50 % below the measured SBS threshold in terms of peak power, providing sufficient input power to the second stage while maintaining a safe operating margin with respect to SBS.

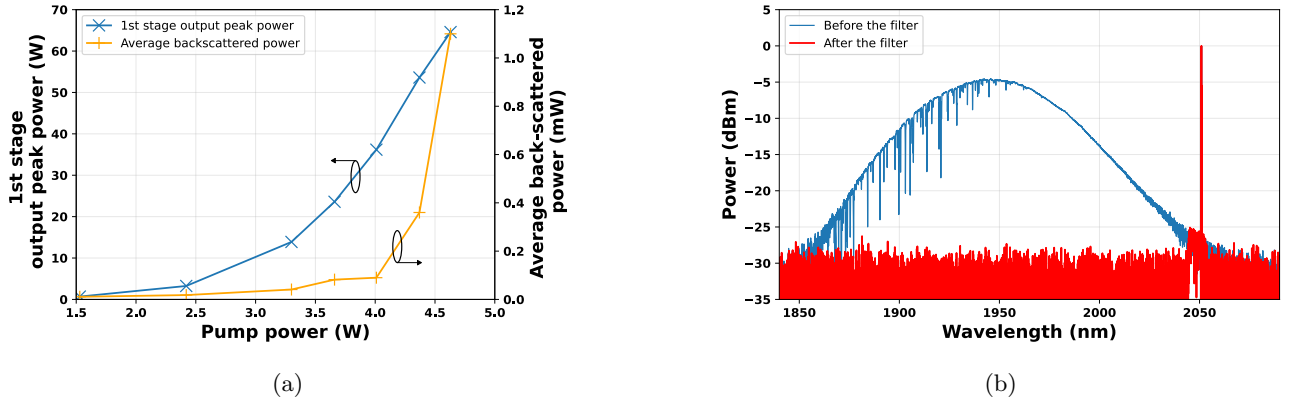


Figure 3: Diagram (a): Evolution of the output peak power and average back-scattered power as a function of pump power at a PRF of 500 Hz frequency rate and a FWHM of 200 ns, measured at the output of the second isolator. Diagram (b): Comparison of the spectrum before and after the filter for 500 Hz and pump power of 4 W.

At this operating point, the optical signal-to-noise ratio (OSNR) is approximately 5 dB at the isolator output. Figure 3b shows the optical spectrum measured before (blue) and after (red) the dichroic filter. The filter provides approximately 27 dB of attenuation outside its 7 nm transmission band, significantly improving the OSNR from approximately 5 dB to approximately 25 dB, thereby removing most of the ASE before the second amplification stage.

For the second amplification stage, the 20/250 μm thulium-doped fiber is cladding co-pumped using 200/220 μm hermetic pump diodes at 793 nm, providing up to 25.3 W of available pump power. Using the same configuration as the first stage, a maximum peak power of 579.8 W is achieved, corresponding to a pulse energy of 116 μJ and an optical gain of 14.33 dB at a pump power of 15.2 W. Figure 4a shows the evolution of the output peak power and the back-scattered power as a function of pump power. As in the first stage, the back-scattered power

remains stable up to a pump power of 14.7 W, above which it increases exponentially, marking the onset of SBS and setting the ultimate power limit of the amplifier. Figure 4b shows the optical spectrum at the amplifier output, with an OSNR of approximately 23 dB. As in the first stage, additional ASE is generated within the second doped fiber, although at a proportion that remains negligible with respect to the amplified signal. The spectral lines observed below the signal wavelength result from the low PRF of 500 Hz, which limits the number of points integrated by the optical spectrum analyzer (OSA).

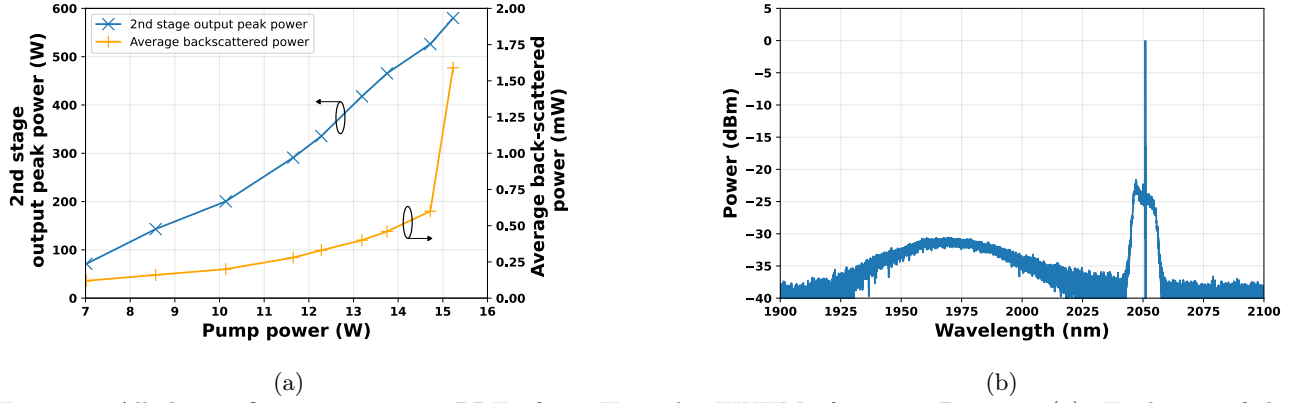


Figure 4: All the configurations are at PRF of 500 Hz and a FWHM of 200 ns. Diagram (a): Evolution of the output peak power and the average back-scattered power as a function of pump power. Diagram (b): Optical output spectrum.

The temporal pulse shape at the amplifier output is shown in figure 5a. The pulse exhibits a Gaussian profile with a FWHM of 200 ns, in line with the target pulse duration, and a slight increase voltage compare to the low level is attributed to the generation of ASE between pulses. A M^2 of 1.1 is measured at the amplifier output, confirming efficient LP_{01} mode injection through the MFA from the 10 μm to the 20 μm core fiber and validating the essential beam quality required for DIAL system. A PER greater than 15 dB is also measured. Furthermore, a 16-hour stability test was performed under the target operating conditions of the HALLOA project (figure 5b), at 50 μJ pulse energy and a PRF of 500 Hz, corresponding to an average output power of 25.7 mW. The measured RMS fluctuation was 2.7 %, demonstrating the long-term stability and robustness of the setup for space applications.

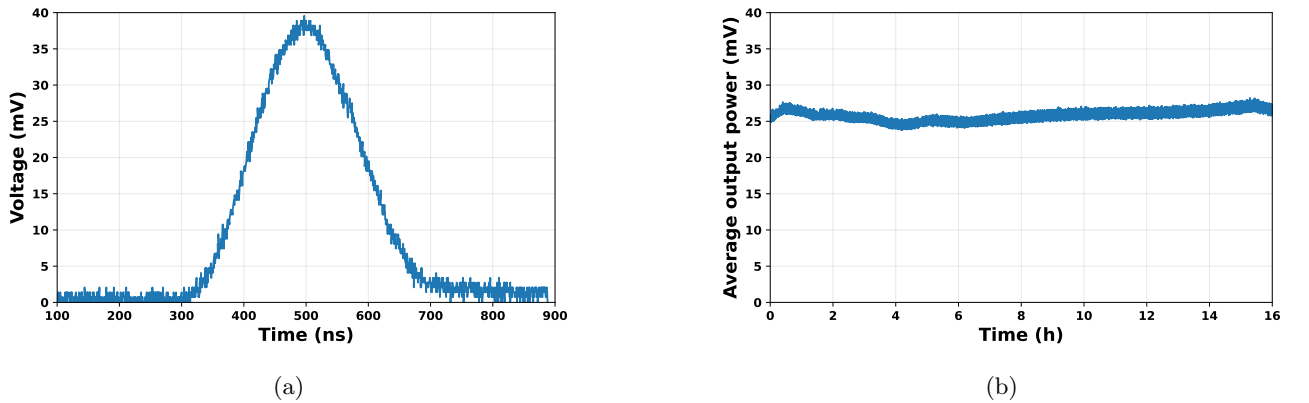


Figure 5: All the configurations are at PRF of 500 Hz and a FWHM of 200 ns. Diagram (a): Gaussian pulse shape at the output. Diagram (b): Amplifier stability at 50 μJ output.

These results demonstrate a two-stage thulium-doped fiber amplifier delivering up to 116 μJ per pulse at 500 Hz PRF, more than twice the 50 μJ target energy specified for the HALLOA project, while maintaining a great beam quality, a PER above 15 dB, and long-term stability (2.7 % RMS over 16 hours) compatible with

space operation requirements. In both amplification stages, the achievable performance is ultimately constrained by SBS rather than by pump power availability, confirming that nonlinear effects represent the primary limitation for this architecture at 2051 nm.

The dichroic filtering approach adopted between the two stages proved effective in mitigating ASE build-up resulting from the low PRF and the long upper-state lifetime of thulium. Improving the OSNR from approximately 5 dB to 25 dB while avoiding the additional losses, thermal sensitivity, and splicing complexity associated with a conventional circulator/FBG filtering system. This result supports dichroic filtering as a viable, space-compatible alternative for ASE suppression in low-PRF thulium-doped fiber amplifiers.

These performances were obtained without applying mechanical strain to the doped fiber, a technique commonly used to raise the SBS threshold but unsuitable for space applications due to long-term reliability and mechanical stability constraints 5.

4. CONCLUSION

This study presented the development and characterization of a two-stage thulium-doped fiber amplifier, designed to meet the requirements of the HALLOA project. The proposed architecture, based mainly on European components, demonstrated performance exceeding the specifications: a pulse energy of 116 μJ was achieved, more than twice the 50 μJ target, while maintaining excellent beam quality ($M^2 = 1.1$), a polarization extinction ratio above 15 dB, and good long-term stability (2.7 % RMS fluctuation over 16 hours of continuous operation).

The results confirm that stimulated Brillouin scattering constitutes the main limiting factor of both amplification stages, the available pump power not being the restrictive factor. This limitation was managed without resorting to mechanical strain on the doped fiber, a technique commonly used to raise the SBS threshold but unsuitable for space applications.

This module, qualified at TRL 6, thus constitutes a key and sovereign technological building block for the complete laser chain of the HALLOA project. Immediate perspectives include the environmental qualification of the module by LZH (shock, vibration, thermal cycling, and irradiation testing), as well as its integration with the Ho:YLF bulk crystal amplifier developed by ONERA and LMD, in order to reach the millijoule-level energies required for DIAL measurement of atmospheric CO₂ and H₂O concentrations from space.

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