International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik,
Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111805D · © 2018 ESA
and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536112

2-µm pulsed Holmium laser for a future CO_2/H_2O space lidar mission

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ABSTRACT

In the context of greenhouse gases monitoring such as carbon dioxide (CO_2), a powerful emitter in the near infrared (1.5–2 µm) is needed to get a useful precision on concentration measurement (< 1 %) with reasonably space and time resolution. Energy pulses larger than several millijoules at a pulse repetition frequency (PRF) of several hundred of Hertz are usually required. Such requirements call for a solid-state laser configuration at least for a part of it as demanded pulse energy is well beyond current pulsed fiber laser potential performances. These DIAL emitters also call for a specific multiple wavelength emission around the chosen atmospheric gas absorption line, single mode operation, high spectral purity and stability, high pulse energy stability, good beam quality, linear pulse polarization and good overall wall plug efficiency, especially for space Integrated Path Differential Absorption (IPDA) lidar measurements. In this paper we report on the development and the demonstration of a two-wavelength single-frequency Ho:YLF oscillator that was developed in the framework of a ESA contract. This laser is especially suitable for atmospheric carbon dioxide (CO_2) measurement using the R30 CO_2 absorption line at 2050.967 nm. The oscillator consists in a fiber-coupled and free-space solid-state hybrid system and can be used in high-energy middle-rate or moderate-energy high-rate configurations depending the detection scheme of the lidar. The pulse energy and frequency stabilities are specially documented in two-frequency single-mode operations in the context of CO_2 space borne IPDA measurements.

Keywords: Laser, Lidar, DIAL

1. INTRODUCTION

Over the last few years, a great interest has been put on detecting, identifying and quantifying major greenhouse gases such as H_2O, CO_2 and CH_4 ultimately from space. The usual technique considered for space-borne differential absorption lidar is the IPDA, i.e. an integrated column measurement using the ground reflectivity. However, recent advances in critical technological subsystems of the lidar, i.e. laser source and avalanche photodiode in the near infrared enables to consider more ambitious scenarios with a measurement of gaseous absorption in the boundary layer (first kilometer above ground). Emitter specifications for space borne measurements has been identified thanks to previous studies[1,2] : emitted wavelength to address the most important greenhouse gases, output energy, frequency stability, and beam quality. Several approaches were investigated to fulfill the requirements for space applications as a high accuracy on the ppm level for CO_2 or ppb level for CH_4. For space CO_2 and H_2O monitoring around 2.05 µm, some developments are based on injection-seeded laser oscillators [3,4] or on single mode optical parametric oscillator (OPO-OPA) source and amplifier stages [5]. Otherwise, for space CH_4 and CO_2 monitoring around 1.6 µm, others approaches are based on injection-seeded optical parametric oscillators (OPOs) [6-8]. The delay time between ON and OFF emissions is very short and it could be difficult to meet this requirement in a single pulse mode operation. Consequently, instruments operating in double pulse or triple pulse mode are under development. In the 2-µm spectral domain, they are usually based on co-doped Ho:Tm emitter delivering high energy pulses but at a repetition rate lower than 50 Hz [9]. An alternative approach is addressed in the present paper. It relies on Thulium fiber pumped injection seeded and Q-switched Ho:YLF oscillator [10]. The laser architecture has the basic potential of offering reduced overall complexity and superior wall-plug efficiency. In the present study, the emitter developed in Gibert et al. [10] has been improved to match CO_2 space lidar emitter requirements. First, a MOPA architecture has been developed to get high energy and limit intra-cavity fluence. Secondly, a double pulse operation has been tested and the performances are assessed in this paper. Although the method to obtain double pulse operation from a Q-switched laser is rather old [11], the application to Thulium fiber pumped Holmium oscillator is new and offers new insights in 2-µm emitter based lidar system.

In this paper we first present the spectroscopy in the 2-µm domain that enables both CO2 and H2O DIAL measurements. Then in a second part the Holmium Laser System (HoLaS) and the experimental set-up that has been used for the characterization of the performances are described. The third part is dedicated to the assess of some critical spectral performances of the emitter: pulse energy and central frequency stabilities. The overall set of performances is displayed in a final table and compared to initial searched performances for a CO_2 space lidar: duration, overall efficiency, polarization, beam quality and pointing stability, pulse spectral linewidth, spectral purity.

2. SPECTROSCOPY IN THE 2-µM DOMAIN

In order to get a boundary layer or high-pressure sensitivity in the airborne or space borne DIAL/IPDA measurement, one may take advantage of the narrowing of absorption line as the pressure decreases with altitude. This requires the use of a strong absorption line and a laser line positioning on the wing of the absorption line. In addition, other conditions must be fulfilled: the total optical depth due to absorption has to be close to unity to optimize IPDA statistical error [12], the absorption line has to be rather insensitive to temperature variation and interference with other trace gas absorption has to be avoided. Such absorption line has been found in the 2 µm spectral band, i.e. the R30e line of the 20013←00001 band of $^{12}CO_2$, centered at 4875.748732 cm^{-1} [1]. As displayed in Figure 1, a H_2O absorption line is also located close to the CO_2 line and enables both gaseous absorption measurements with the same emitter.

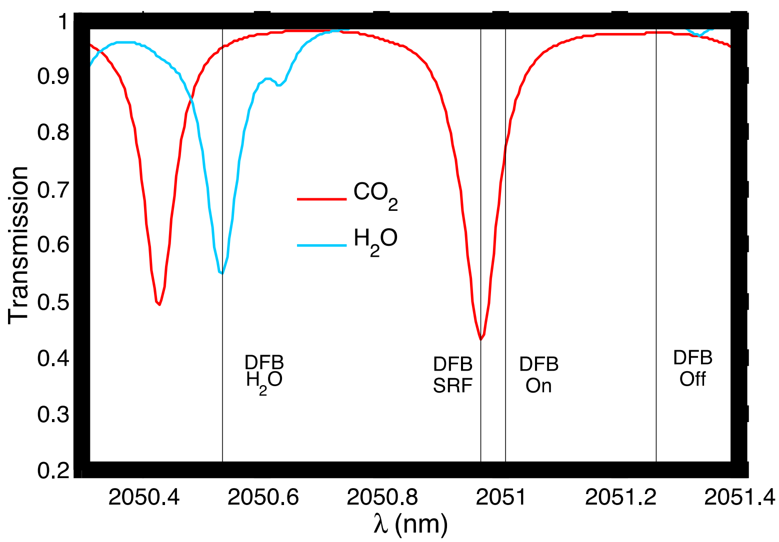

Figure 1. Atmospheric transmission spectrum for CO_2 (400 ppm) and H_2O (15 $g.kg^{-1}$) in the 2.05 µm domain for 1 km vertical path starting from ground level. The Ho:YLF oscillator seeders are indicated for the frequency reference system (SRF), the CO_2 DIAL measurement (On and Off) and the H_2O DIAL measurement. DFB: Distributed Feedback laser diode.

3. EXPERIMENTAL SET-UP OF THE HO:YLF EMITTER

The detailed design of the Holmium Laser System is displayed in Figure 2. The HoLaS may be divided in four different critical subsystems: the pump lasers, the HoLaS master oscillator (MO), the seeding module, the HoLaS power amplifier (PA). Two different Thulium fiber pump lasers are used, one for the MO and the second one for the PA. The MO consists in a single cavity that is used for both ON and OFF wavelength emissions in a double pulse operation. Then, a PA is used to amplify both ON and OFF pulse energy. The seeding module contains a frequency reference system for ON and OFF wavelengths locking. For the characterization of the system different tools were implemented: an integrating sphere with a photodiode and a powermeter for pulse energy and duration monitoring, a Pyrocam for laser beam characterization, two fiber-coupled inputs for beat note analysis and for spectral purity monitoring.

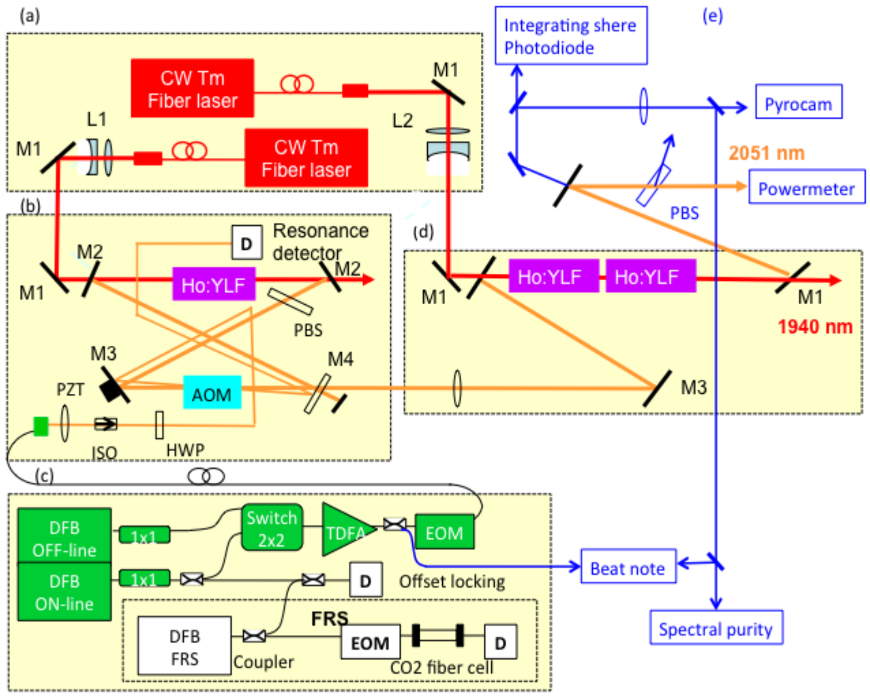

Figure 2. HoLaS experimental set-up and characterization: (a) Thulium fiber laser pumps, (b) Master Oscillator (MO), (c) Seeding chain including the frequency reference system (FRS) (d) Power Amplifier (PA) and (e) characterization set-up: integrating sphere and powermeter for pulse energy and duration monitoring, pyrocam for laser beam characterization, beat note for frequency monitoring and spectral purity. DFB: Distributed-Feedback laser diode; AOM: Acousto optical modulator; EOM: electrical optical modulator; PZT: piezotransducer; PBS: polarizer; TDFA: Thulium doped fiber amplifier; HWP half wave plate;

The MO uses a 5-cm long 0.5 % doped Ho:YLF crystal inside a 1 m long ring cavity with a 50% transmission output coupler. The Ho:YLF birefringent crystal is pumped along the π axis. The waist inside the MO crystal is around 500 µm to limit the intra-cavity fluence at 5 J/cm^2. The polarization of the emitted beam is forced by inserting a Brewster polarizer plate inside the cavity. The 1-m length of the cavity mainly imposed a pulse duration lower than 50 ns for pulse energy larger than 10 mJ. Actually the double pulse laser delivers a first 12 mJ/ 74 ns pulse at OFF wavelength and a second 42 mJ/ 33 ns pulse at ON wavelength. The pulse spectral width is Fourier-transform limited. The pulse repetition frequency (PRF) is controlled by the Q-switching rate of the acousto-optic modulator (AOM) and is fixed to 303.5 Hz in the current design. The double pulse operation is obtained with a modulation of the RF level of the AOM command (and consequently the loss inside the cavity). The time delay between ON and OFF emissions is fixed to 250 µs.

The Q-switched MO is sequentially injection seeded (through the first order of diffraction of the AOM to obtain the specified OFF and ON wavelengths. A fiber-coupled frequency reference system (FRS) has been developed to assess the spectral stability of the Ho:YLF oscillator. The precision and accuracy of the FRS are 150 kHz at 10 s (Allan deviation) and 1 MHz respectively. The FRS DFB is locked to the center of the R30 CO_2 absorption line using a Pound-Drever-Hall (PDH) technique. The ON DFB is shifted in frequency at around 3 GHz out of the CO_2 absorption line center and locked to the FRS DFB using a beat note and a phase loop locking (PLL, offset locking). A PZT is used to lock the MO cavity length to the ON wavelength. The OFF wavelength is locked to the cavity length using the current of the DFB at an integer number of free spectral range. PZT and OFF DFB current locking uses the same PDH technique. The current HoLaS configuration is relevant for more than two wavelengths emission (two ON and one OFF) given than the double pulse operation of the MO can be easily modified in a triple pulse operation using the RF level modulation of the AOM.

The PA uses two Ho:YLF crystals (4 and 5 cm long crystals) to increase the gain of the PA and the overall optical efficiency of the system. The waist inside the PA crystals is around 800 µm to limit the fluence. With this configuration excellent beam quality is obtained. Polarization is linear with a ratio of 100:0.5. A dedicated bench with a CO_2 absorption cell used as a spectral notch filter enables to estimate the spectral purity up to 99.999 %. The HoLaS mechanical architecture consists in a 60 x 90 cm breadboard that is used for both the MO, the PA and for characterization. The all fiber coupled seeding chain including the frequency reference system, the fiber pump lasers, the electronic for control, command and synchronization as well as the locking devices are all integrated in the same rack. The system may be better integrated in the future in a smaller architecture given that the largest component is only the MO cavity (20 x 20 cm square). A dry air circulation is currently used for MO and PA pump beam paths but the laser could be integrated in a pressurized box with dry air as well. The Ho:YLF crystals and the AOM are currently water-cooled but a conductively cooled solution (with Peltier components) may also be implemented in a future system.

4. CRITICAL PERFORMANCES OF THE HO:YLF EMITTER FOR DIAL SPACE APPPLICATION

4.1 Pulse energy stability

The MO pump power is limited to 37 W (70%) to deliver a MO output power of 7 W. At a 47 W PA pump power the MOPA delivers an output mean power of 15.8 W (from the powermeter). In order to make the conversion between pulse shape (monitored by the integrating sphere and the photodiode) and pulse energy, we made a calibration of the photodiode in single pulse operation using the powermeter. From a linear fit we were able to convert pulse shape area in pulse energy in double pulse operation. The distributions of OFF and ON pulses energies are then presented in Figure 3a. Mean OFF pulse energy is 11.7 +/- 0.1 mJ and mean ON pulse energy is 42.1 +/- 0.1 mJ. The total mean power in double pulse operation is therefore 16.3 W which is close to the measurement of the powermeter (15.8 W). Indeed, in the configuration of double pulse operation with a first low energy pulse and a second high-energy pulse, the powermeter gives a good estimate of the total power. This is not the case for the opposite [13]. The overall optical efficiency of the MOPA is then 19.5 %. Given that the electrical to optical efficiency of the IPG Photonics Thulium fiber laser is 11.5 %, the overall electrical to optical efficiency of the MOPA is 2.2 %. From the pulse shape monitoring of pulses OFF and ON, we also infer their Allan relative deviation (Fig. 3b). There are under the 2 % limit for a characteristic time larger than 0.3 s up to 1 min, and lower than 1% at 10 s. The difference between pulse OFF and ON energies entails an expected difference in pulses duration. The mean pulse duration (FWHM) of the pulse of the highest energy ON is 33 +/- 1 ns whereas OFF pulse shows a longer mean duration of 74 +/- 9 ns.

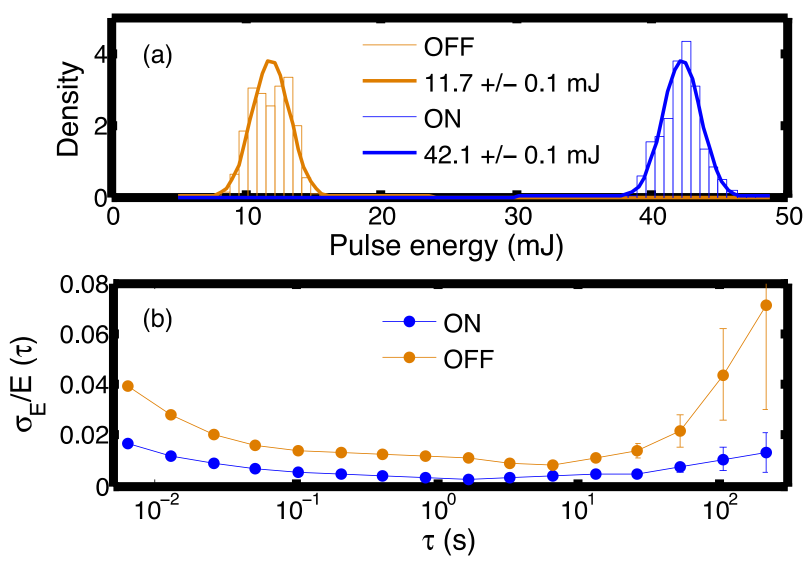

Figure 3. Pulse energy monitoring for the MOPA double pulse injection seeded experimental set-up: (a) Pulse energy distributions with 100000 shot-pair (b) Allan relative deviation for the two pulses. The legend figures are from the mean and the standard deviation of the distribution Gaussian fits.

4.2 Central frequency stability

Using the spectrum of the beat note made with the emitted MOPA pulse and the seeder, we are able to infer the pulse central frequency stability with respect to the seeder frequency. Figure 4a displays the central frequency distributions for pulse OFF and ON and figure 4b the Allan deviation. The distributions are similar and centered around the 40 MHz. This is expected as the seeding through the first order of diffraction of the AOM creates a frequency shift given by the acoustic wave frequency of the AOM, i.e. 40.7 MHz. Some differences with respect to 40.7 MHz may be explained by an offset in the error signals (PZT length locking and OFF DFB current locking).

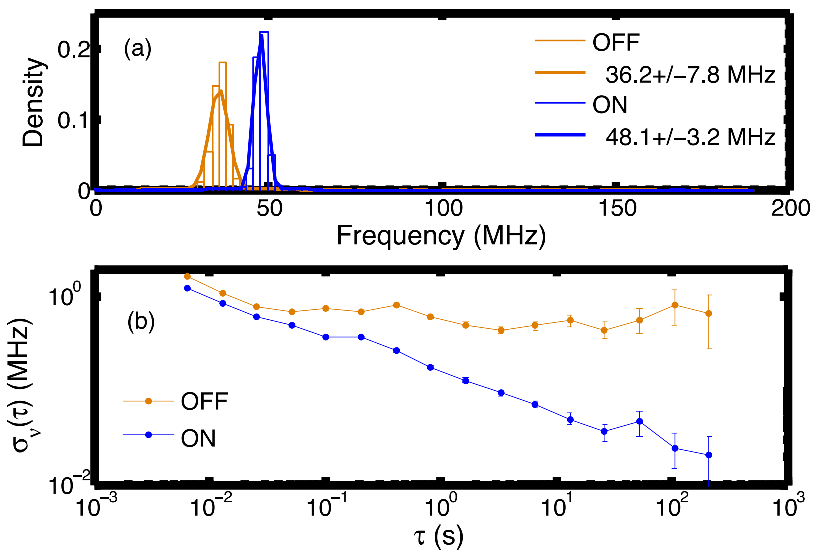

Figure 4. Pulse centre frequency monitoring for the MOPA double pulse OFF-ON injection seeded experimental set-up: (a) Pulse centre frequency distributions (b) Allan deviation for the two pulses. The legend figures are from the mean and the standard deviation of the distribution Gaussian fits.

The ON stability is 70 kHz for a characteristic time of 10 s. Given that the seeder frequency locked to the FRS has a stability of 150 kHz at 10 s, the overall pulse central frequency stability is lower than 170 kHz at 10 s. The OFF stability is rather around 600 kHz. The main raison of larger OFF center frequency standard deviation is that it was not possible to use the serving loop controller in the integral mode but only in proportional allowing a larger frequency jitter of the OFF pulse central frequency. However, this has not a significant impact on DIAL/IPDA measurements given that the requirement for OFF wavelength locking is usually around 10 MHz.

5. CONCLUSION

A two-wavelength single frequency q-switched Holmium laser has been achieved and fully characterized. The laser relies on a MOPA architecture and is operated in double pulse operation to generate a first low energy (12 mJ) and a second high energy (42 mJ) pulse at respectively 2051.01 nm (ON-line) and 2051.25 nm (OFF-line) at a pulse repetition frequency of 303.5 Hz. Beyond pulse energy and frequency stabilities, the performances of the laser have been checked with respect to CO_2 space lidar emitter requirements as defined in A-SCOPE ESA study (Table 1). The HoLaS presents outstanding performances regarding beam quality and spectral purity. The overall electrical to optical efficiency is 2.2% and may be upgraded to space emitter standards, as there is some room for it both in the Thulium fiber laser pump efficiency and in power amplifier optimization.

Table 1. IPDA/DIAL space-based requirements derived from A-SCOPE ESA study and results obtained in this study with our HoLaS MOPA system.

Parameter		**IPDA/DIAL requirements**	Results in this study
Laser wavelength ON/ OFF		2051.01/ 2051.25	2051.01 / 2051.25 nm
Output energy per pulse ON/OFF		> 40 mJ / > 10 mJ	42 mJ / 12 mJ
Pulse repetition frequency (PRF)		> 50 Hz	303.5 Hz
Delay between ON and OFF laser pulses		250 µs	250 µs
Pulse relative energy stability ON/OFF	rms		< 2 % / < 4 %
	@ 10 s	< 2 %	< 0.5 % / < 1 %
Pulse polarization		linear > 100 :1	linear, 200: 1
Spatial mode / Longitudinal mode		gaussian / single	gaussian / single
Spatial beam quality		M2 < 2	$M^2 < 1.05$
Beam pointing stability (rms)		< 120 µrad	< 20 µrad
Pulse duration (FWHM) ON/OFF		< 50 ns	33 ns /74 ns
Fluence		< 5 J/cm2	< 5 J/cm2
Wallplug efficiency		> 2 %	2.2 % (Tm fiber laser pump : 11.5%)
Pulse spectral linewidth (FWHM) ON / OFF		< 60 MHz	14 MHz / 6 MHz
Pulse linewidth variation ON /OFF	rms		0.6 MHz / 0.4 MHz
	@ 10 s	< 6 MHz	< 60 kHz
Spectral purity ON/OFF (within 1 GHz)		99.98%	99.986 % / 99.96 %
Pulse centre frequency stability ON/OFF	rms		1 MHz/ 1.5 MHz
	@ 10 s	< 200 kHz	< 70 kHz / < 600 kHz (beat note)
			< 170 kHz / < 600 kHz (beat note and FRS)

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