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NEW ADVANCES IN 2-µM HIGH-POWER DUAL-FREQUENCY SINGLE-MODE Q-SWITCHED HO:YLF LASER FOR DIAL AND IPDA APPLICATION

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I. INTRODUCTION

In the absence of climate change policies, the fossil fuel emissions are projected to increase in the next decades. Depending on how the current carbon sinks change in the future, the atmospheric CO_2 concentration is predicted to be between 700–1000 ppmv by 2100, and global mean surface temperature between 1.1–6.4°C, with related changes in sea-level, extreme events and ecosystem drifts [1]. Keeping the atmospheric CO_2 concentration at a level that prevents dangerous interference with the climate system poses an unprecedent but necessary challenge to humanity. Beyond this point, global climate change would be very difficult and costly to deal with [2]. There are two main approaches that are currently analysed: (1) to reduce emissions; (2) to capture CO_2 and store it, i.e. sequestration. For these two ways, some monitoring at different scales ultimately from space would be needed. Lidar remote sensing is a powerful technique that enables measurements at various space and time resolution.

In this context, 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) larger than 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.

During the last five years, LMD lidar team worked on a new 2 µm injection –seeded single-frequency Q-switched Ho :YLF oscillator following the precursor work of Bollig et al. [3]. In this paper we report on the development and the demonstration of a two-wavelength single-frequency Ho :YLF oscillator. The oscillator consists in a fiber-coupled and free-space solid-state hybrid system and can be used in high-energy middle-rate (HE-MR) or moderate-energy high-rate (ME-HR) configurations depending the detection scheme of the lidar [4]. To obtain dual wavelengths single mode emission of the oscillator different Pound-Drever-Hall locking technique based methods have been implemented. The pulse energy and frequency stabilities are specially documented in free-running and two-frequency single-mode operations in the context of spaceborne IPDA measurements. This laser has been implemented in a coherent DIAL set-up and some first measurements of atmospheric CO2 mixing ratio are presented.

II. 2-µM Ho:YLF TRANSMITTER

A. Experimental set-up

The 2-µm Ho:YLF transmitter set-up is displayed in Fig. 1. The system is described in details in Gibert et al. [4]. The Ho:YLF laser is a 1-m long ring cavity pumped by a 100W linearly-polarized thulium-doped CW fiber laser from IPG Photonics. An intra-cavity polarization beam splitter ensures linearly polarized laser beam emission. Pulsed regime operation is obtained using an Acousto-Optic Modulator (AOM). At 2 kHz pulse repetition frequency (PRF) - ME-HR operation - and at a pump power of 80 W, the laser delivers 22 W. Typical pulse characteristics are: energy: 12 mJ; pulse duration: 40 ns; spectral linewidth: 10 MHz (nearly Fourier transform limited). Gibert et al. showed that a HE-MR operation of the laser is also possible for IPDA measurements from space (40 mJ at 100 Hz has been tested) [4] but a Master Oscillor Power Amplifier (MOPA) configuration should be preferred to avoid laser induced damaged of the intra-cavity mirrors/ couplers coatings. Such a MOPA has been demonstrated by Schellhorn and Eichorn [5] and is currently in development at LMD in the framework of new ESA contract. The oscillator is sequentially seeded by two fiber-coupled DFBs. The On-line DFB is locked to the R30 CO2 line center at 2050.967 nm by means of a PDH locking scheme. The Off-line DFB wavelength is set at 2051.26 nm. A Thulium Doped Fiber Amplifier (TDFA) boosts the seeding power to compensate for insertion losses from fiber-coupled components. The seeder beam is coupled into the cavity through the first diffraction order of the AOM during the pumping time. As the seeder is coupled in a low Q factor Fabry-Perot cavity, the PDH error signal is not optimum but still useful to obtain the resonance of the seeder. The main advantage of the method is to prevent from laser pulse feedback towards the seeding chain.

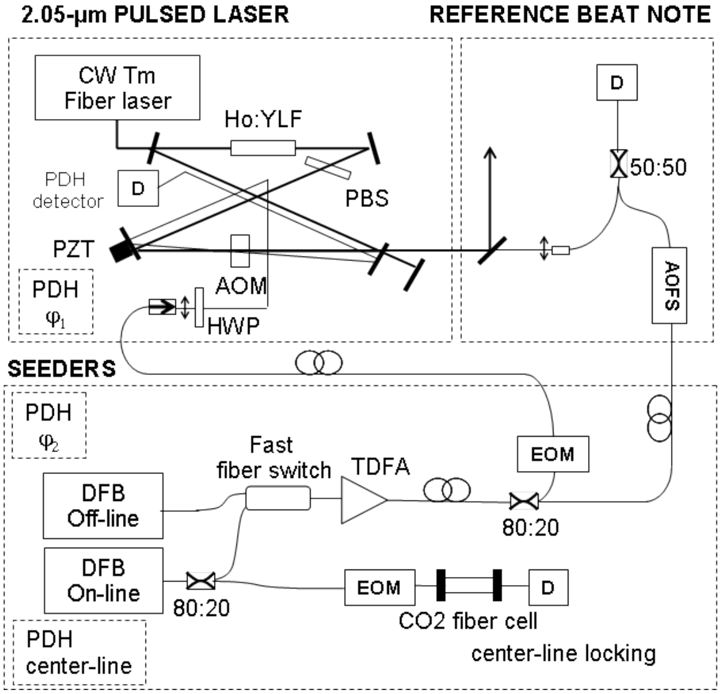

Fig. 1. Experimental set-up of the 2.05 µm DIAL transmitter. The seeders are two Distributed FeedBack (DFB) diode lasers. A reference beatnote is measured to test the seeding performance. AOM: Acouto-Optic Modulator. HWP: Half Wave Plate. PBS: Polarization Beam Splitter. D: detector. EOM: Electro-Optic Modulator. AOFS: Acousto-Optic Frequency Shifter. TDFA: Thulium-Doped Fiber Amplifier.

B. Locking methods for dual wavelength single mode operation

When two seeders with different frequencies are sequentially coupled inside the slave cavity, the servo loop has to adjust the cavity length to be at the resonance. To avoid large PZT displacement, one may think that the seeders frequencies have then simply to be separated by an integer number of cavity free spectral ranges. The frequency differences between the seeders may be locked using an offset-locking scheme. This has indeed been implemented successfully in a DIAL transmitter [4]. However, this solution is practically limited by the ability to measure the frequency difference between the seeders with current photodetector (i.e. few tens of GHz). In addition, longtime operation shows that the PZT displacement increases with time (and seeding efficiency decreases) as the cavity free spectral range usually changes with environmental conditions (temperature, vibrations…). To overcome these limitations, we propose a more robust multiple-wavelength seeding technique that we call “multiple-phase PDH technique”. The multiple phase PDH use a typical optical external phase modulation using an electro-optical modulator (EOM) and a resonance detector. The electronics uses an appropriate voltage-controlled oscillator (VCO) suited to the resonator. However, different phase shifters are used to deliver the useful error signal (by demodulation) to different proportional integral amplifiers (PI). The first serving loop (PI 1) aims at maintaining the cavity length at resonance with the On-line seeder wavelength (which is usually locked to a frequency reference system). The second serving loop (PI 2) is used to tune the Off-line DFB to be resonant into the cavity. It is worth noting that Off-line DFB wavelength can only be locked as an integer number of cavity free spectral range (FSR) with respect to On-line DFB wavelength. The same way applies for the other potential seeders. For a DIAL application, and given a typical hundred of MHz cavity free spectral range, this limitation is usually acceptable as the Off-line wavelength is located in an absorption-free window.

Fig. 2 shows a comparison of frequency stability for On and Off wavelengths pulse emissions using the reference beat note detection in Fig. 1. The reference beat note frequency is expected to be detected around 77

MHz due to the 27 MHz shift of the AOM and an additional 50 MHz frequency shift from the AOFS. Both pulse frequency distributions have a Gaussian-like shape with a slightly larger standard deviation for the On-line than for the Off-line. The Allan deviation shows that this higher standard deviation is mainly seen at high frequency. This may be explained by a higher bandwidth of Off-line serving loop which involves the DFB current only comparing to the On-line one which implies a motion of the PZT.

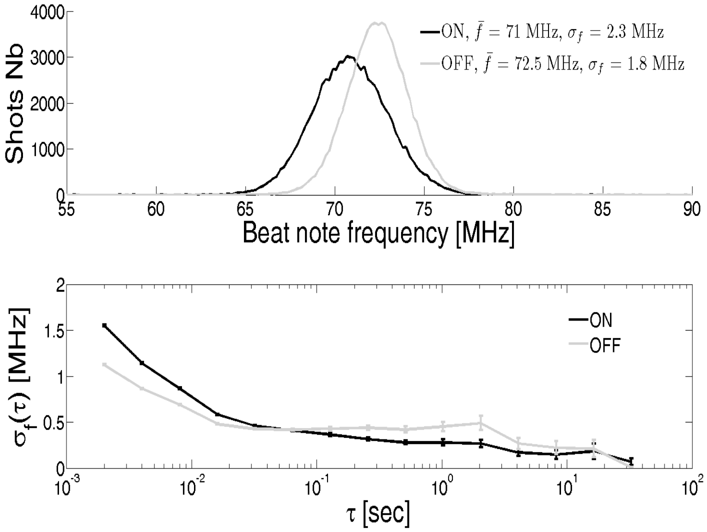

Fig. 2: Top: On and Off pulse frequency beat note frequency histograms
Bottom: On and Off pulse frequency Allan deviations

For space IPDA application, absolute frequency locking and standard deviation should be lower than 200 kHz over 10 s. Even if absolute frequency locking depends for an important part of the frequency reference system (FRS) that is used (currently a low-pressure CO2 absorption cell at LMD), Allan deviation shows that the requirements are already achieved with the multi-phase PDH technique (Fig. 2).

III. DIAL APPLICATION: RANGE-RESOLVED MEASUREMENTS OF ATMOSPHERIC CO2 MIXING RATIO IN THE ATMOSPHERE

The Ho:YLF transmitter has been associated with a fiber-coupled coherent detection to test coherent DIAL measurements of atmospheric CO2 at LMD facility, 20-km south-west Paris. The instrument was installed at the second floor of the lab and shoot horizontally above Ecole Polytechnique campus. More than 20 h of continuous measurements of the lidar were made during day and night on July, 22, 2013.

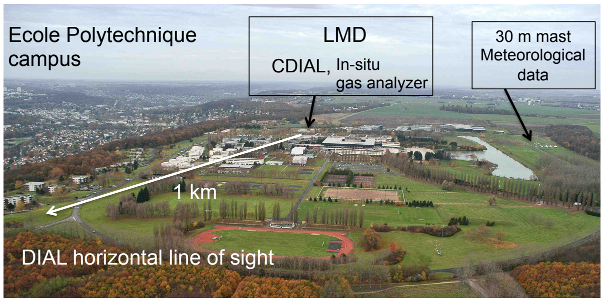

Fig. 3: Field experiment at Ecole Polytechnique campus. CDIAL: coherent differential absorption lidar

Typical lidar horizontal profiles are displayed in Fig. 4: Carrier to Noise Ratio (CNR) that is a proxy for lidar backscatter signal at 2-µm, radial wind speed, optical depth due to CO2 absorption along the line of sight of the laser and CO2 absorption (first derivative of the optical depth). Space and time resolution are 100 m and 15 min, respectively. Fig. 4 sows that the error on CO2 absorption retrieval increases dramatically when the CNR is lower than -10 dB. In addition, at lower CNR, potential bias due to signal processing has to be considered and corrected [6].

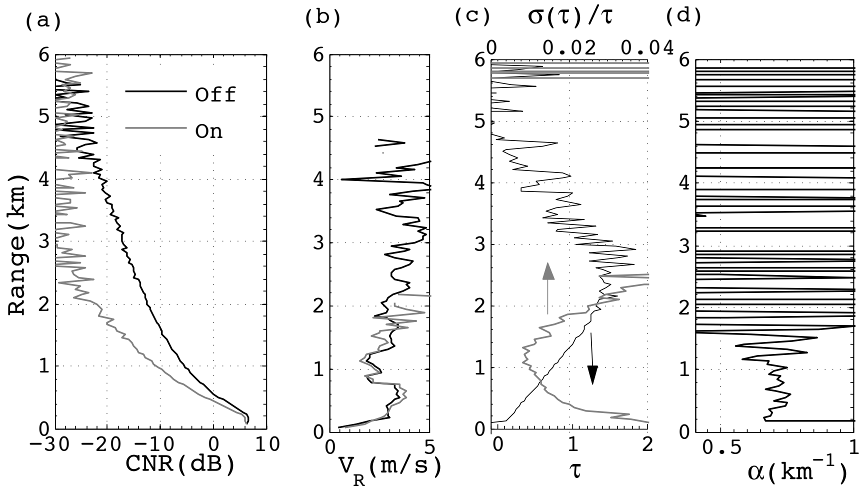

Fig. 4: (a) CNR: Carrier to Noise Ratio in dB for Online (CO2 absorbed) and Off-line wavelengths (b) Radial wind speed at both wavelengths (c) Optical depth due to CO2 absorption and statistical error (d) CO2 absorption

Given some additional information on the differential absorption cross-section [7] and the dry air density (calculated with in-situ meteorological and spectroscopic data) one can retrieve the CO2 mixing ratio variations in the atmosphere. Fig. 5 shows lidar preliminary measurements of the CO2 profile with unprecedented space and time resolution (100 m and 15 min) in the surface layer. Statistical error is around 1% over 1 km and is in agreement with the theoretical error calculated with respect to the CNR at both wavelengths.

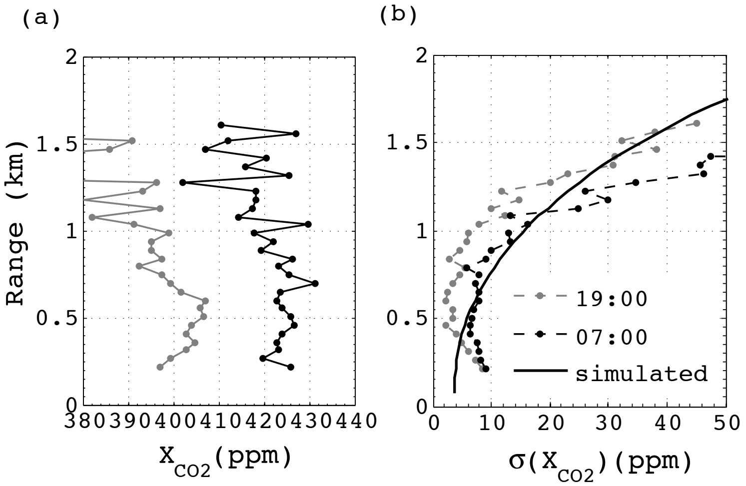

Fig. 5: (a) CO2 mixing ratio horizontal profiles at 07:00 am and 19:00 pm. (b) Statistical error on the measurements and comparison with simulated error with respect to the CNR.

IV. CONCLUSION

A dual wavelength single mode 2-µm Ho-YLF oscillator has been developed at LMD. A new multiphase PDH technique has been successfully tested to provide dual injection seeding and single mode operation with frequency stability that meets the requirements for accurate lidar CO2 remote sensing in the atmosphere ultimately from space. The oscillator has been associated with a coherent detection to test atmospheric CO2 measurements using a DIAL technique.

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