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Hybrid Fiber-Bulk Laser for CO₂ and Wind Velocity Remote Sensing at 2.05 μm

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Abstract: This paper presents a laser source designed to measure CO₂ mixing ratio and wind speed at 2.05 μm using the Differential Absorption Lidar (DIAL) method with coherent detection. The all-fiber part of the laser offers robustness, high spatial and spectral quality and versatility. The main limitation in a single-frequency fiber laser source weighs on the signal peak power, which is limited by stimulated Brillouin scattering (SBS). The second part is a single-pass free-space amplifier able to achieve higher peak power, while maintaining low alignment sensitivity. We use a Ho:YLF crystal which is a good candidate to perform efficient power scaling at 2.05 μm. For 200 ns laser pulses, we achieved 1.2 mJ at 20 kHz and 9 mJ at 1 kHz repetition rate.

Keywords: Hybrid laser, DIAL, CO₂, wind

1. Introduction

Considering the increasing need to probe the carbon dioxide (CO₂) cycle from local to global scales, we develop a hybrid fiber-bulk emitter for long-range simultaneous measurement of CO₂ mixing ratio and wind speed by lidar. It is suited to the classical DIAL (Differential Absorption Lidar) technique and coherent detection. This hybrid architecture combines a fiber amplification followed by a single-pass bulk amplifier, offering a promising combination of robustness and performance.

After optimizing the all-fiber part of the laser source [1], we focus here on the bulk amplification. The goal of this free-space amplification stage is to avoid the Stimulated Brillouin Scattering (SBS) encountered in single-frequency fiber, which limits the laser pulse energy to tens or hundreds of μJ (for 200 ns pulse duration). Given the larger beam and much shorter interaction path, the power scaling is not limited by SBS in bulk amplification, which thus appears as a good candidate to close the gap between fiber laser capabilities and requirements of stringent applications such as long-range measurement (few km), from airborne or space-borne platforms.

2. Experimental setup

The global setup (including fiber amplification and bulk amplification) is shown on Figure 1.

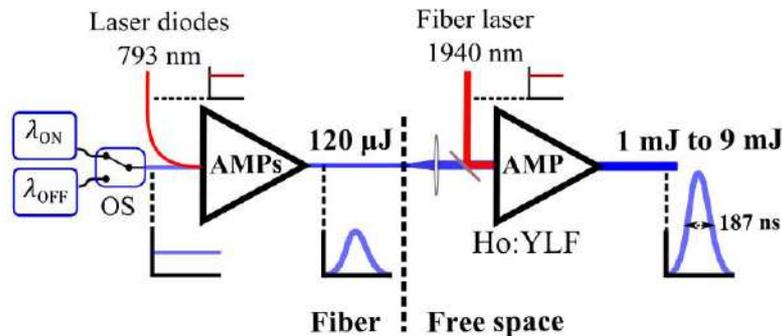


Figure 1. Schematic of the hybrid fiber-bulk amplification. Blue lines represent the signal at 2.05 μm and red ones represent optical pumps. Dashed lines attached to optical beams represent the operating regime (continuous wave or pulsed). The energy at the end depends on the pulse repetition frequency.

The full setup of the fiber amplifier (left side of the schematic) is described in [1]. At a Pulse Repetition Frequency (PRF) up to 20 kHz, it delivers a pulse energy of 120 μJ limited by SBS with a pulse duration of 200 ns, linearly polarized, nearly Fourier-transform and diffraction limited. An Optical Switch (OS) alternates $\lambda_{\text{ON}}/\lambda_{\text{OFF}}$ selection for DIAL operation.

The bulk amplification is made through a holmium-doped Yttrium Lithium Fluoride lattice (Ho:YLF). The YLF lattice is a relevant choice for our application because it exhibits a peak emission cross-section at 2.05 μm [2], long lifetime of upper-state level and lower upconversion parameter as compared to other lattices [3]. The pump is a continuous-wave commercial fiber laser at 1.94 μm (peak of the absorption cross-section [2]). The Ho:YLF crystal is already used in laser development for CO₂ remote sensing by lidar [4,5].

A significant benefit of this architecture is the absence of free-space laser resonator. It then requires lower effort in mechanical development thanks to a lower sensitivity to misalignment. Only a few number of free space optical elements is needed which is favorable for later integration in vibrating environments.

The setup of the bulk amplifier (right side on Figure 1) is described in Figure 2.

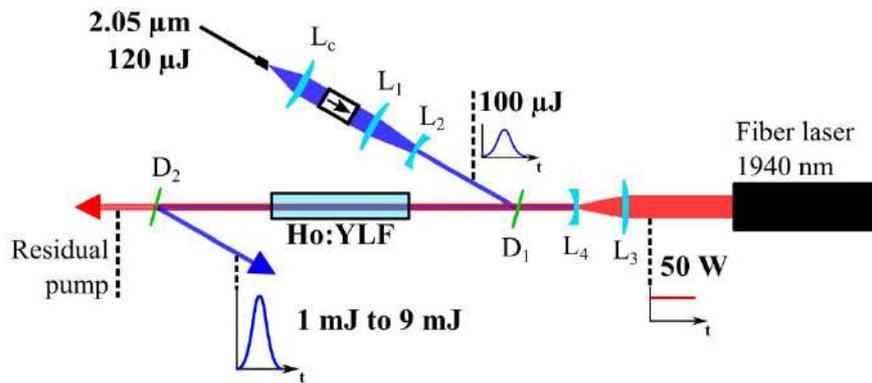


Figure 2. Schematic of the bulk amplifier. Optical elements marked “L” are lenses, “D” stands for combiner/separator element. Blue line is optical field at 2.05 μm and red one is the pump at 1940nm. The box with an arrow inside is an isolator.

The output of the fiber laser is collimated by lens L_c and isolated to protect it from back-reflected beam. The L_1/L_2 and L_3/L_4 lens pairs focus the signal and the pump into the crystal with the same sub-millimeter waist. The D_1 plate combines the signal and the pump. The crystal is 13 cm-long, 0.5% holmium-doped and anti-reflection coated. The D_2 plate separates the signal and the pump. The YLF lattice is birefringent, so it is important to align the signal polarization on the π -axis to maintain the linear polarization and take advantage of a higher emission cross-section than on the σ -axis [2].

Figure 3 represents the energy obtained with this architecture and its electro-optic efficiency.

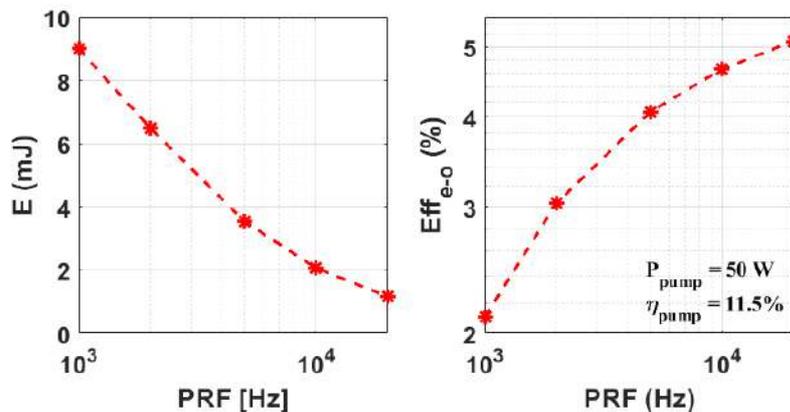


Figure 3. Energies (left) and electro-optic efficiencies (right) obtained at the output of the bulk amplifier. The electro-optic efficiency given in this plot is for the bulk amplifier only

As the pump is continuous, the signal energy depends on the PRF. The lower the PRF, the longer the pump period and the higher the population inversion, as long as it remains lower than the upper-level lifetime (~ 14 ms [2]). At the lowest PRF (1 kHz) the pulse energy is 9 mJ and represents a peak power of 48 kW, which is 60 times higher than the SBS limitation in our fiber amplifier. At the highest PRF (20 kHz), we reached 1.2 mJ which means a decade gain. The electro-optic efficiency of the bulk amplifier is higher than 2% for all assessed PRF. It is calculated using the specified efficiency of the pump laser (11.5%).

Taking also into account the pump power of the fiber part at 1 kHz (~ 40 W optical pump power) with an electro-optic efficiency of 50% (laser diode), we reach more than 1.9% electro-optic efficiency for the entire laser. This is comparable to the LASO laser (MERLIN space mission) electro-optic efficiency ($\sim 2.4\%$) [6].

The temporal pulse shape is shown on Figure 4.

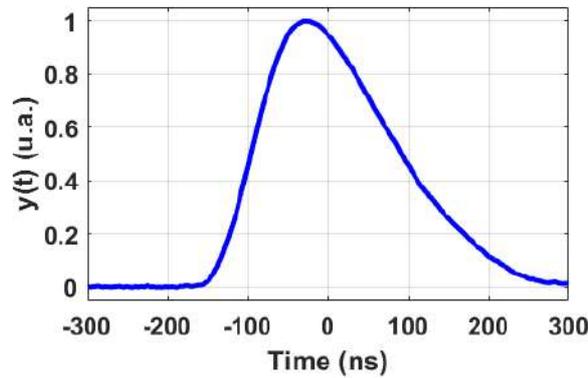


Figure 4. Temporal pulse shape for 1 kHz PRF and 9 mJ pulse energy

At full width half maximum, the pulse duration is 187 ns. The signal is subject to pulse distortion due to the decreasing gain in the amplifier during amplification [7]. It does not represent an important drawback for our lidar application even for coherent detection. Nevertheless, it could be fixed using a pre-distortion method [8].

3. Laser performance for lidar applications

DIAL lidar using coherent detection requires stringent spectral and spatial qualities [9], especially a narrow linewidth (i.e. Fourier-transform limited) as the Carrier to Noise Ratio (CNR) is directly proportional to the linewidth, and a nearly diffraction limited beam. The measured Power Spectral Density (PSD) of the signal and beam quality factor (M^2) are shown on Figure 5.

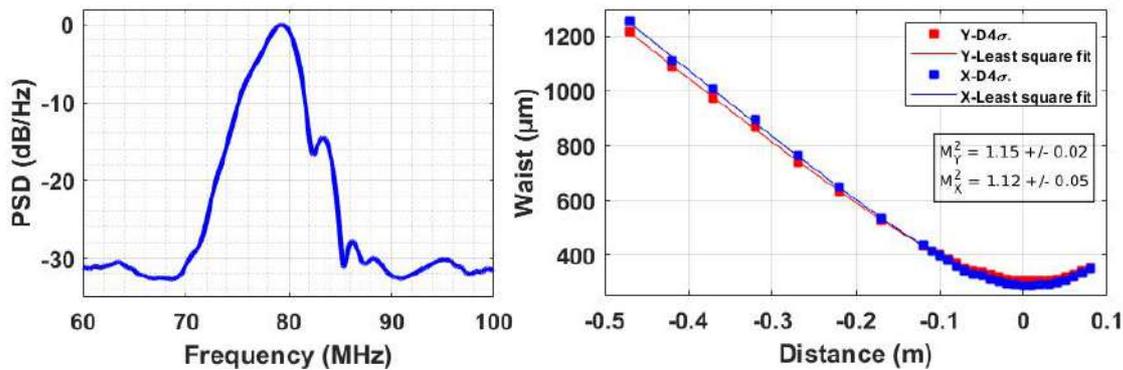


Figure 5. PSD of the hybrid laser (left, log-scale) and M^2 estimation of the signal beam (right). These measurements have been made at 1 kHz PRF and 9 mJ pulse energy

The linewidth is measured using self-heterodyne technique [10] with a long delay-line and acousto-optic modulator with a frequency of 80 MHz (hence the PSD peak located at 80 MHz). At a PRF of 1 kHz

(i.e. 9 mJ pulse energy) the pulse duration is 187 ns and the measured linewidth is 3.1 MHz which is nearly Fourier-transform limited. The “bounce” at 84 MHz for the bulk amplifier is the result of self-phase modulation.

The M^2 is measured by fitting the beam waist ($D4\sigma$ definition) along its propagation. The M^2 factor is lower than 1.2 on both axes which is close to optimal for coherent lidar application.

4. Conclusion

This paper has described a hybrid fiber-bulk laser at 2.05 μm suited to CO_2 DIAL measurement using coherent detection. Details of the fiber part are available in [1] (architecture and performance). The bulk amplifier is made of a Ho:YLF crystal pumped at 1.94 μm by a commercial fiber laser. The hybrid laser provides pulse energy up to 9 mJ at 1 kHz repetition rate for 187 ns pulse duration (which represents 60 times the SBS limitation encountered in the fiber amplifier). The signal is quasi-Fourier-transform limited and diffraction limited. Thanks to a very few number of free-space optical elements and single-pass amplification, this architecture is still much more robust than a cavity configuration while reaching high energy. Lidar measurement of CO_2 and wind will be conducted in future works with this source.

5. References

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