WATER VAPOR DIFFERENTIAL ABSORPTION LIDAR MEASUREMENTS AT 935 NM USING A ND:YGG LASER

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ABSTRACT

A novel diode-pumped, single-frequency laser system emitting at 935 nm was developed to serve as the transmitter for water differential absorption lidar measurements. This laser uses Nd:YGG ($Y_3Ga_5O_{12}$) as the active medium. The system was directly diode-pumped at 806 nm and was built up in a master-oscillator power-amplifier configuration. It consists of a stable resonator in rod geometry and employs as the amplifier a stable-unstable hybrid resonator in an end-pumped slab design. Single frequency operation is achieved by injection seeding. The range of continuously tunable single-frequency radiation extends to ~0.4 nm centered around 935.31 nm. More than 30 mJ of pulse energy at 100 Hz repetition rate with a beam quality (M^2) of better than 1.4 and Q-switched pulse duration of 52 ns in single frequency mode were generated. Since water vapor DIAL demands for stringent requirements for the spectral properties those were carefully investigated. Values of the spectral purity of >99.995% were determined using long-pass absorption measurements in the atmosphere exceeding the requirements by a large margin. Finally, first time water vapor DIAL measurements were performed using a Nd:YGG laser. The reported results show much promise of these directly pumped lasers at 935 nm for future space-borne and airborne water vapor lidar systems.

1. INTRODUCTION

Water vapor (H_2O) is one of the most important atmospheric constituents as it controls weather and climate on all temporal and spatial scales. It is also important for a variety of chemical processes in the atmosphere and plays a central role in the global energy and water budget. The knowledge of vertically resolved profiles with high accuracy and precision of atmospheric humidity throughout the whole troposphere up to the lower stratosphere is therefore a prerequisite for numerical weather prediction (NWP) and climate research. Unfortunately, no global observation system is currently available that fulfils the needs defined by the World Climate Research Programme (WCRP) of

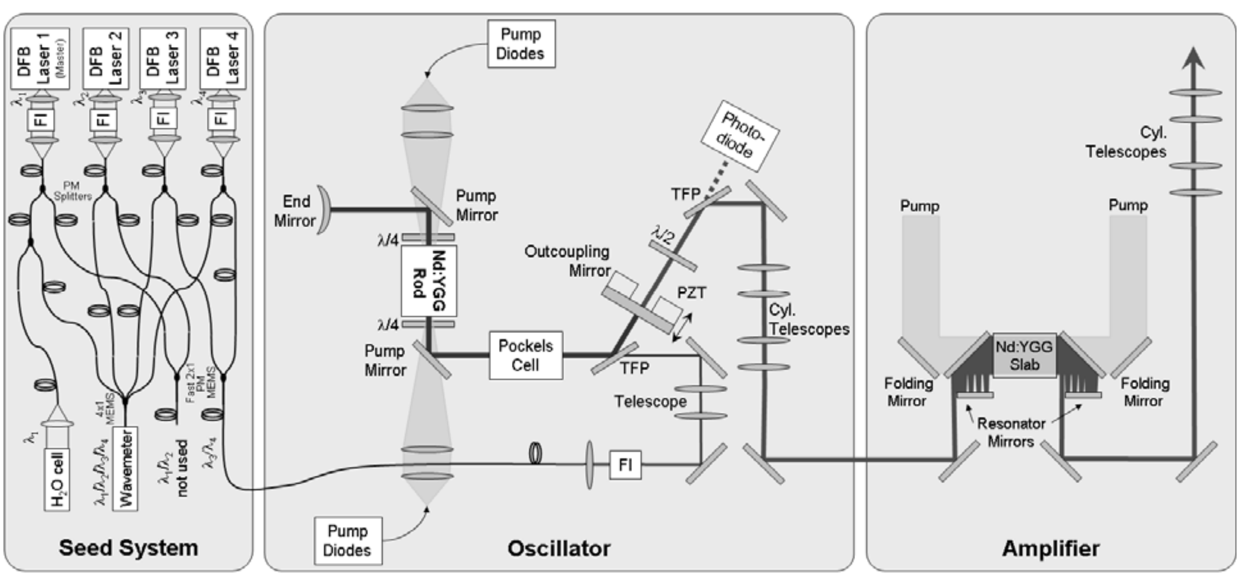

Figure 1: Schematic set-up of the injection-seeded Nd:YGG master-oscillator power-amplifier system.

the World Meteorological Organisation (WMO).

The differential absorption lidar (DIAL) technique applied from satellites shows high potential to meet those requirements. In recent years several missions have been proposed to measure water vapor profiles from space. However, the feasibility of a space mission heavily depends on the availability of mature and reliable laser sources at ~935 nm with high electrical-to-optical efficiency. Although DIAL systems have been successfully deployed on aircraft, their laser transmitters do not quite meet the efficiency requirements yet. In most cases either Ti:Sapphire lasers or optical parametric oscillators (OPOs) have been used. Those sources are pumped by the second harmonic of the ubiquitous Nd:YAG laser at 1064 nm. In this frequency conversion process about half of the pump energy is wasted. In principle it should be possible to come up with more efficient and less complex all-solid-state lasers that directly generate wavelength in the respective wavelength range.

It has been suggested that Nd-doped $Y_3Ga_xAl_{(5-x)}O_{12}$ lasers can be specifically tuned by changing the material composition and thus the lattice parameters to generate wavelengths at 935 nm [1]. However, these materials were not yet investigated to a stage that allows their use in practical lidar systems.

The purpose of this work, therefore, is the development of a highly efficient, diode-pumped and single-frequency laser, that uses Nd:YGG ($Y_3Ga_5O_{12}$) as the active material to directly generate laser radiation at 935 nm appropriate for H_2O-DIAL measurements. Its performance was studied in detail and its potential was investigated by first-time lidar measurements of water vapor.

2. LASER SYSTEM

As the laser transmitter a Nd:YGG master-oscillator-power amplifier (MOPA) laser was used. The Nd:YGG oscillator is set up as a linear cavity in twisted mode configuration with an electro-optic Q-switch (see Figure 1). The crystal rod was pumped from two sides by fiber coupled passively cooled diode bars. The oscillator generated 4.3 mJ in Q-switched operation at a pulse duration of 52.5 ns (FWHM) and a repetition rate of 100 Hz. The M^2-value was experimentally determined to be 1.06. The oscillator beam was mode matched to the astigmatic amplifier mode using two cylindrical telescopes.

In order to boost the pulse energy into the multi-ten-millijoule range an amplifier stage with a stable-unstable hybrid resonator according to the INNOSLAB concept [2] was employed (see Figure 1). The Nd:YGG slab crystal was end pumped from both sides by a total of 44 laser diode bars through a free-space transfer optic. At a maximum diode pump energy of 828 mJ within 200 µs and 13 passes of the oscillator beam through the slab crystal, the amplifier generated 33.2 mJ of energy. The astigmatism induced by the amplifier design was mostly compensated using a cylindrical telescope. The energy is well in the range for what is required for ground-based or airborne DIAL systems. For spaceborne applications an energy of ~ 80mJ was suggested [3]. Further enhancement of the amplifier output energy, however, would be possible by adding a subsequent amplifier stage of identical design.

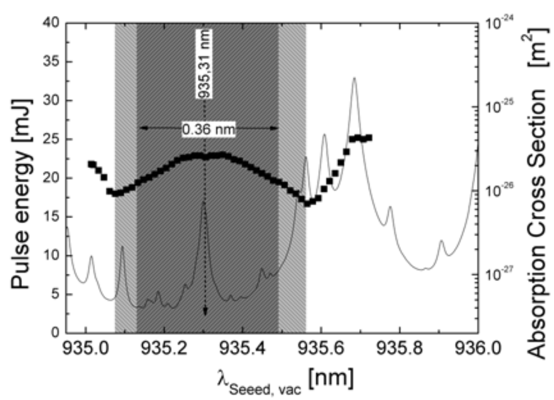

Figure 2: Pulse energy of the Nd:YGG MOPA as function of the seed wavelength. In the darkly hatched wavelength range the laser is efficiently seeded. In the lightly hatched range seeding becomes less efficient and modes in the gain center start to oscillate. When the seed wavelength is too far off, the laser becomes totally unseeded and the energy equals the energy of the free running system. Overlaid is the absorption cross section of water vapor.

The output spectrum of the free-running MOPA shows two distinct emission lines at 935.31 nm and 938.43 nm, respectively. The bandwidth of the main emission line at 935 nm is estimated to be 0.2 nm. Since this is orders of magnitude to high, the technique of injection seeding was employed to operate the MOPA laser in single-longitudinal-mode (SLM) operation.

The injection seeding system (see Figure 1) consists of four independent distributed-feedback (DFB) diode lasers of which in the context of this paper only three have been used. In order to achieve high absolute frequency stability the first DFB laser (the “master”) is frequency stabilized onto the strongest H2O-absorption line in this band (935.68 nm) using a multipass absorption filled with water vapor and using a standard lock-in technique. The other DFB diode lasers are stabilized to a wavemeter which is continuously re-calibrated against the master. During the experiments described below, DFB lasers #3 and #4 were used for injection seeding. Using a fast fiber-coupled micro-electromechanical switch (MEMS) the seed lasers are consecutively switched to the Nd:YGG oscillator cavity. Up to ~ 5mW of seed power were available in front of the Nd:YGG laser resonator. The cavity length of the oscillator was matched to the seed wavelengths using a ramp-and-fire technique. For this purpose, the transmitted seed light through the cavity was measured behind the outcoupling mirror using a photodiode. To protect the photodiode from optical damage as the laser pulses propagated along the same optical path as the seed laser signal the intensity was controlled by means of a half wave plate and a thin-film polarizer.

3. SPECTRAL CHARACTERIZATION OF THE MOPA SYSTEM

In single frequency mode 30.5 mJ could be generated from the MOPA system at gain maximum (935.31nm) which corresponds to an overall optical efficiency of 3.4 %. By tuning the seed wavelength across the gain profile it was found that the range of single-frequency operation extended over ~0.36 nm from 935.12 nm to 935.48 nm (see Figure 2). The M^2-value of the outgoing beam was measured to be less than 1.4. The spectral width and frequency stability were determined by means of a heterodyne technique. The bandwidth was less than 28 MHz (pk-pk) and the frequency stability relative to the seed laser frequency was better than 17 MHz (pk-pk). These numbers are by far exceeding the requirements for water vapor DIAL.

Spectra of the seeded laser as function of the seed power were measured using an optical spectrum analyzer. Such spectra are depicted in Figure 3 for a seed wavelength of 935.48 nm for different seed powers between 0.0 mW and 4.2 mW. It is clearly seen that for this wavelength, further in the wing of the gain curve, modes in the vicinity of the gain center at 935.31 nm increase in intensity with decreasing seed power. For wavelengths closer to the gain center only at seed powers as low as ~10 µW central modes become distinguishable from the background.

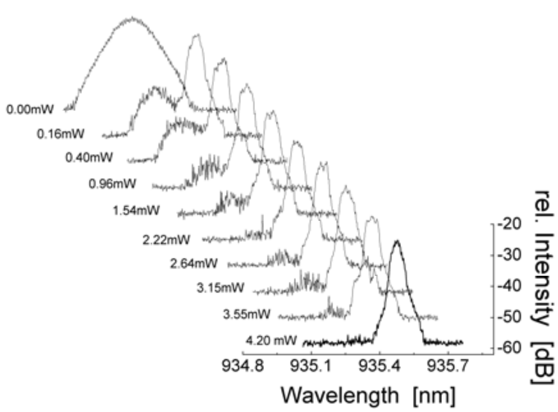

Figure 3: Spectra of the Nd:YGG MOPA seeded with different seed powers at 935.48nm

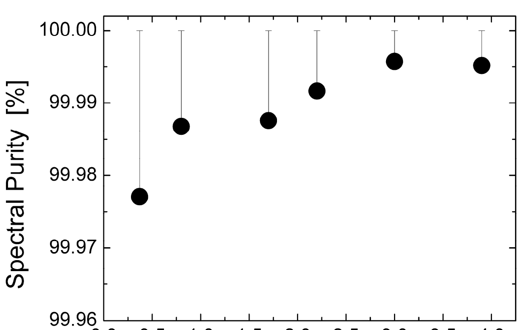

Figure 4: Spectral purity of the Nd:YGG master oscillator power amplifier as function of the seed power in the range between 0.37 and 3.9 mW. A spectral purity of as high as 99.996% was achieved.

Measurements using the OSA, however, are not adequate to measure values of the spectral purity in the range of SP=99.99% or higher. A convenient way to measure the spectral purity is the use of long-pass absorption cells. For the determination of the spectral purity of the Nd:YGG laser using absorption lines within the accessible wavelength range the cell has to be very long. It is therefore more convenient to measure the backscattered signal through an optically dense atmosphere. For the spectral purity measurements the set-up described in Section 2.4 was employed. We used the line at 935.2992 nm (10691.765960 cm-1) as the on-line wavelength using seed laser #3 and, as the reference, a wavelength of 935.2241 nm using seed laser # 4. Both lasers were consecutively switched to the Nd:YGG oscillator. The laser beam was directed out of the lab window at a slant angle of 7.5 degrees with respect to the horizon. This means that at a range of 12 km the sounding altitude equals 1570 m. Therefore, the planetary boundary layer is more or less within the measurement range. The receiving system consists of a 35-cm Cassegrainian telescope, an interference filter to suppress the solar background, and an avalanche photo diode.

The backscatter signals were recorded, and the spectral purity calculated from the ratio of on-line and off-line signals averaged over 10 minutes. The spectral purity of the Nd:YGG MOPA as function of seed power is depicted in Figure 4. At seed powers in the 3-4 mW range a degree of the spectral purity of as high as 99.996% was achieved. This is far above the requirements for water vapor DIAL. However, the numbers given are only a lower boundary for the spectral purity. For higher seed laser powers the on-line signal could not yet be distinguished from the detection

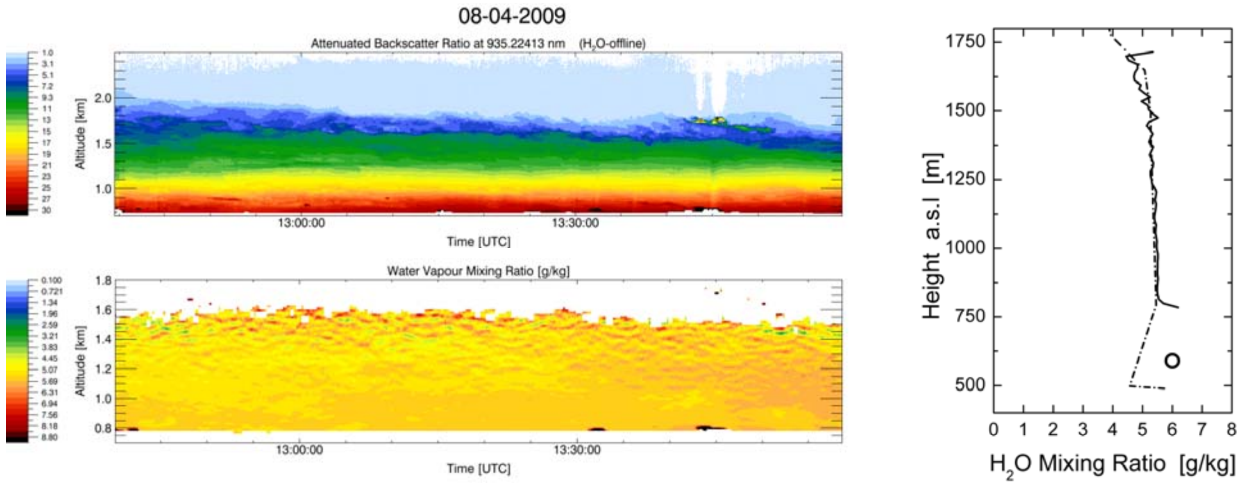

Figure 5: Lidar measurement using the Nd:YGG MOPA system recorded on 8 April 2009 between 12:40 and 14:00 UTC. Upper panel: Attenuated backscatter ratio in the altitude range from 0.8 km to 2.5 km a.s.l.. Lower panel: Water vapor mixing ratio (in g/kg) in the altitude range from 0.8 km to 1.8 km a.s.l.. Due to the slanted measurement geometry the altitude resolution is as low as 30m. The left panel shows the comparison of the DIAL water vapor profile (solid line) to the profile of the Oberschleissheim radiosonde launched at 12UT (dashed line). The corresponding water vapor mixing ratio measured in-situ on the lidar site is given by the dot.

limit and thus the spectral purity is probably even higher. For lower seed powers we noticed the very sporadic occurrence of badly seeded pulses. These pulses happen when electronic noise peaks occasionally became larger than the signal of the transmitted seed and triggered the Q-switch at a wrong point in time.

4. WATER VAPOR DIAL MEASUREMENTS

For the water vapor measurements the lines at 935.4491 nm and 935.2241 nm were used for the on-line and off-line wavelengths, respectively. As an example, Figure 5 shows a lidar measurement using the Nd:YGG MOPA system recorded during daytime on 8 April 2009 between 12:40 and 14:00 UTC. The upper panel displays the attenuated backscatter ratio at the off-line wavelength in the altitude range from 0.8 km to 2.5 km a.s.l.. Due to the measurement geometry (the beam was slanted at an angle of 7.5deg from the horizon) this corresponds to a maximum range of ~15km. Faint clouds at the top of the planetary boundary layer appear at ~13:35. The water vapor mixing ratio is depicted in the lower panel. Due to the slanted measurement geometry the altitude resolution is as low as 30m. The water vapor measurements could be compared with the operational radiosounding at Oberschleissheim, Germany (48°14'43"N, 11°33'21"E, 489m a.s.l.) located at a distance of 27 km from the measurement site. At the same time a continuous record from a standard weather station was available for the in-situ data on the ground. The left panel in Figure 5 shows the comparison of the radiosonde profile launched at 12UT in Oberschleissheim to the average DIAL water vapor profile. The corresponding water vapor mixing ratio measured in-situ on the lidar site is also given. It facilitates comparisons that the well-mixed boundary layer shows a very homogeneous water vapor profile. Despite a difference of ~1h and 27 km in time and distance, respectively, the agreement between lidar and radiosonde profile is excellent particularly above altitudes where ground effects become negligible. This clearly demonstrate the capability of the Nd:YGG laser for water vapor DIAL measurements.

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