DEMONSTRATION OF AN OPTICAL PARAMETRIC OSCILLATOR SYSTEM AT 1.57µm FOR INTEGRATED PATH DIFFERENTIAL ABSORPTION LIDAR MEASUREMENTS OF CARBON DIOXIDE

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ABSTRACT

In order to measure the concentration of atmospheric carbon dioxide an Integrated Path Differential Absorption (IPDA) lidar is developed based on an optical parametric oscillator (OPO) using potassium titanyl phosphate (KTP) in noncritically phasematched configuration. The tuning range of this device was found to match favorably to CO2 absorption lines showing adequate absorption cross-section with low temperature and pressure sensitivity. The spectral properties of the OPO were investigated in detail. A prerequisite for meaningful CO2 measurements is a high precision of the lidar system. Therefore, first error analyses have been performed on an experimental basis in addition to CO2 column measurements showing the potential of the system.

1. INTROCUCTION

Carbon dioxide (CO2) is recognized as one of the most important of the Earth’s greenhouse gases, whose concentration has been directly modified by human activities i.e. burning of fossil fuels and changes in land management [1]. Since pre-industrial times the atmospheric concentration of CO2 has increased from 280 ppmv to about 380 ppmv [2].

Despite its importance and the establishment of the Kyoto Protocol there are still large uncertainties in the understanding of the Global Carbon Cycle. The exact quantification of the CO2 uptake on the Earth´s surface and in particular its spatial and temporal variability is still very poorly known. In addition, the anthropogenic influence is masked by natural variability. Therefore, observations are urgently needed to close the annual carbon budget at the global level and to unambiguously determine the (temporal and spatial) distribution of carbon sinks and sources.

In general, the satellite-borne lidar technique is able to measure carbon dioxide at the global level [3,4]. However, it turns out that the observational requirements to measure CO2 with adequate accuracy and spatial resolution are very stringent. In a recent study performed under the auspices of ESA these requirements were carefully reviewed [5]. While conventional satellite-borne differential absorption lidar would require a decent size (in power-aperture product) the use of a Integrated Path Differential Absorption (IPDA) lidar system to measure the CO2 column using the backscatter from Earth’s surface returns comes much closer to the status of contemporary lidar technology. However, this method has its specific error sources.

The purpose of the current study therefore is to set-up a laboratory model to demonstrate the technical feasibility, to investigate the achievable measurement accuracy and precision, to pinpoint critical aspects and to perform error analyses on an experimental basis.

2. SPECIFIC ERROR SOURCES

Integrated Path Differential Absorption uses backscatter signals from target reflections such as the ground or a cloud surface, only. Similar to the conventional DIAL, the online target return is more attenuated than the offline, so that the trace gas molecule column content can be measured as integral value along the laser beam. However, this method is not calibration-free. It requires knowledge on the relative on- and offline laser pulse energies as well as the relative receiver transmission at both wavelengths. In addition the molecular absorption cross section has to be known with appropriate accuracy as well as temperature and pressure. A high spectral purity of the transmitter needs to be maintained as in conventional DIAL. IPDA also requires that the distance to the target be measured with sufficient accuracy. Horizontal averaging over structured terrain may not cancel any bias. In addition, care must be taken that target albedo differences between the on- and offline pulses keep below an appropriate value. These error sources need to be analyzed systematically.

3. EXPERIMENTAL SET-UP

The lay-out of a CO2 lidar requires careful selection of the specific absorption line [4]. Appropriate lines are found for example in the spectral regions at 1.6µm or 2.0µm. Careful selection of the specific absorption line is

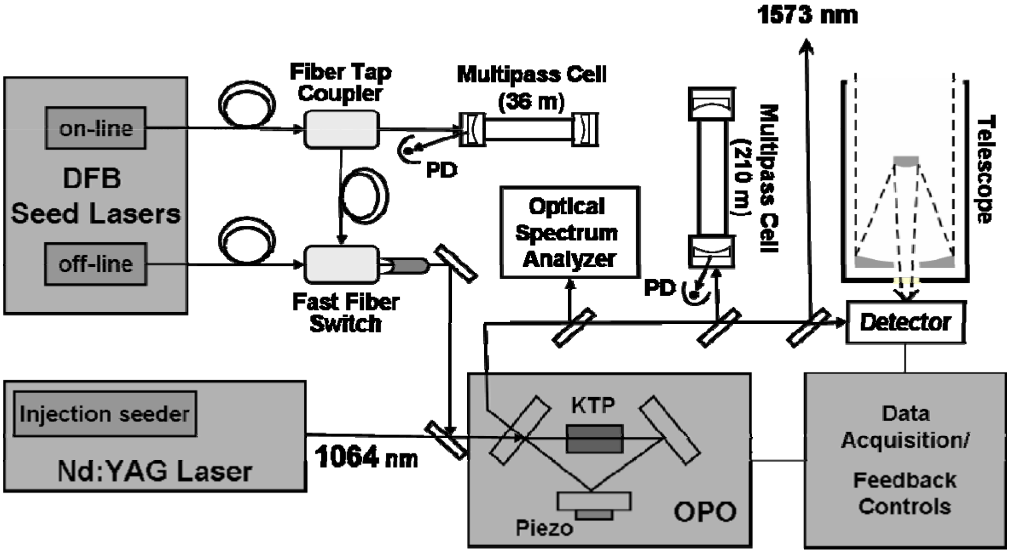

Fig. 1: Schematic set-up of the transceiver system

also needed to ensure that no cross-interferences with water vapor absorption lines occur which are abundant in these spectral regions.
In principle, wavelengths around 2µm result in a better sensitivity to measure carbon dioxide near the surface. On the other hand, current detector technology shows much better performance at 1.6µm. For this reason the latter wavelength range was chosen and absorption lines with low temperature and pressure sensitivity selected.

As the lidar transmitter a single longitudinal mode optical parametric oscillator has been developed. It uses KTP in a noncritically phase-matched (NCPM) configuration as the nonlinear crystal (Fig. 1). Noncritical phasematching shows no walk-off between the interacting beams and therefore bears the potential to achieve a good spatial beam quality at high efficiencies. When pumped with the fundamental radiation of a Nd:YAG laser the wavelengths that can be generated (by pump wavelength or temperature tuning) favorably match with carbon dioxide absorption lines (Fig. 2). The Nd:YAG laser is a commercially available flashlamp-pumped system operated at 10 Hz. Stable single-longitudinal-mode operation is achieved by injection seeding.

Single longitudinal mode operation of the OPO is achieved using injection seeding at the OPO’s signal wavelength. Two standard telecom fiber-coupled diode lasers operating at slightly different wavelengths are alternatively switched using a fast fiber switch to be injected into the OPO cavity that is actively matched to the seed. This enables the OPO to alter its wavelengths from on-line to off-line between two pulses. The online diode laser is frequency stabilized to the CO2 absorption line by means of a multipass absorption cell to a stability of ± 12 MHz (pk-pk). The stabilization of the offline laser is performed relative using its internal étalon.

The design goal was not to achieve highest efficiencies, though, energies of several millijoules per pulse at 1.57 µm can be easily achieved.

Of predominant interest are, however, the spectral

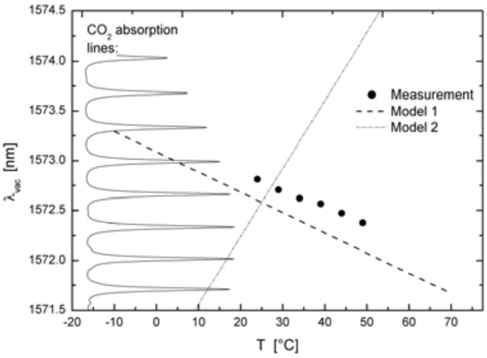

Fig. 2: Measured and calculated temperature tuning curves of the signal wavelength of the NCPM OPO. The obtained wavelengths match favorably to the CO2 absorption lines. Model 2 (using Sellmeier and thermo-optic coefficients from [6]) fails to precisely predict the wavelengths while model 1 (according to [7]) gives much more realistic results. The tuning range can further be extended by tuning the pump wavelength.

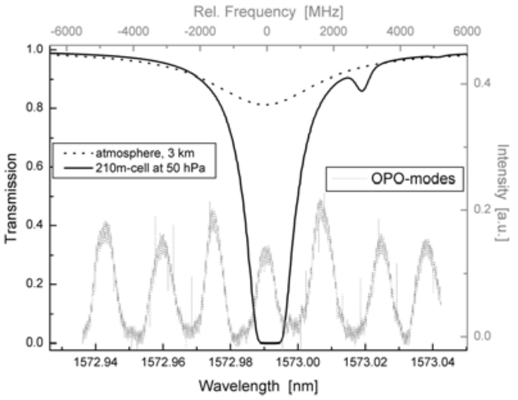

Fig. 3: Calculated transmission of an atmospheric measurement path of 3 km (370 ppm CO2 concentration) and of the 210-m cell in relation to the OPO resonator modes. The modes have been measured using the seed laser.

properties of the OPO. For this purpose, the outgoing radiation is analyzed using an optical spectrum analyzer (resolution: 0.011 nm)

In order to measure the spectral purity of the injection seeded OPO at the online wavelength a multipass cell filled with CO2 at a pressure of 50 hPa and an optical path length of as long as 210 m was used (see Fig. 3). Using this set-up the detection limit of the spectral purity was about 99.9% which was measured with both the DFB laser and the OPO radiation.

As the telescope an 8” Schmidt-Cassegrain system was employed. The detector is an InGaAs PIN diode. In order to measure the relative on- and offline laser pulse energies part of the outgoing beam was split off and imaged onto the detector as the reference. The signals are digitized with a resolution of 12 bit at a sampling rate of 400 MS/s and stored on a PC.

4. RESULTS

Fig. 4 shows data of the atmospheric transmission measured to a topographic target at a distance of 1.5 km from the lab. The experimental determined transmission due to CO2 absorption matches well with the calculated value (see Fig. 3).

Of particular importance to obtain a high precision of the lidar system is the stability of the reference power measurement. For this purpose we performed short-distance measurements showing no absorption by CO2 and optimized the reference measurement for.

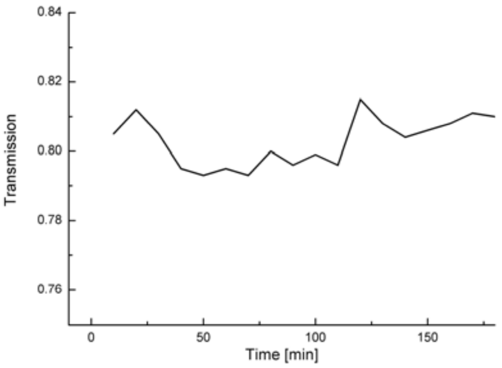

Fig. 4: Measurement (10-minute average) of the atmospheric transmission due to CO2 absorption. The distance from the lidar to the topographic target was 1.5km (one way). The transmission thus matches well to the calculated value of ~80% (see Fig. 3).

Fig. 5 shows such result recorded over ~1.5 hours. The standard deviation of a 3000 on- and offline pulse pair average is 0.16% (the peak-to-peak deviation is 0.3%). This reduces to 0.08% for a 6000 pulse pair average. There is no noticeable trend. However, there is still a bias of ~ 1.5%, which is assumed to arise from differences in the imaging of on- and offline reference onto the detector. This issue will be further investigated.

In summary, it is demonstrated that a noncritically phasematched KTP OPO is suitable for measurements of atmospheric carbon dioxide. It shows a high quality of its spectral properties and its wavelengths match favorably

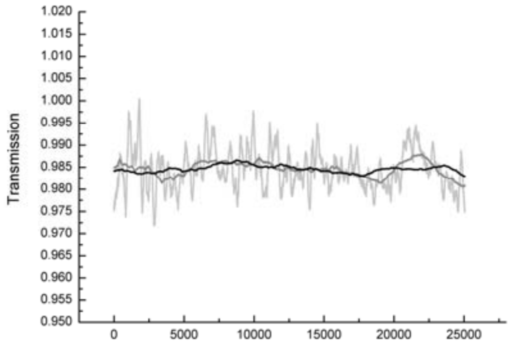

Fig. 5: Short-distance zero measurement which demonstrates the stability of the reference measurement. The three curves show averages of 200, 3000, and 6000 on- and offline pulse pairs, respectively, recorded over ~ 1.5 h.

to appropriate CO2 absorption lines showing adequate absorption cross section and low temperature and pressure sensitivity. First column measurements of atmospheric carbon dioxide and a preliminary assessment of the error introduced by the reference power measurement have been performed.

5. REFERENCES

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