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Diode-laser-seeded optical parametric oscillator for airborne water vapor DIAL application in the upper troposphere and lower stratosphere

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Abstract. Powerful narrow-band pulsed radiation was generated by a diode-laser-seeded optical parametric oscillator (OPO) in the 940 nm wavelength region. With a pump energy of 180 mJ/pulse from a Q-switched Nd:YAG laser an OPO output energy as high as 40 mJ/pulse could be extracted at the signal wavelength. By injection seeding with a 4.5 mW external cavity diode laser system, the spectral width of the pulsed OPO was line-narrowed, ending up at a bandwidth of 190 MHz. The spectral purity was measured by long-path absorption, yielding a value of 99.8%. Seed powers of less than 0.1 mW are sufficient in order to obtain a value as high as 99%. The line-narrowed OPO fulfils the spectral and energy requirements for airborne water vapor DIAL measurements in the upper troposphere and lower stratosphere. The residual measurement error caused by the finite bandwidth of the OPO is of the order of 1%, only.

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Accurate water vapor profiles in regions of low water vapor content at upper-tropospheric heights are of fundamental importance for validation and interpretation of water vapor images obtained from satellites. In midlatitude the upper tropospheric water vapor distributions often display complex spiral-like structures on synoptic and subsynoptic scales caused by stratospheric intrusions that cannot be measured accurately enough by satellite remote sensing or in situ sensors [1]. By contrast, airborne differential absorption lidar (DIAL) applied in the near-infrared spectral region promises to provide measurements of water vapor cross sections spanning the region of interest near the tropopause level. The methodology of DIAL and its applicability for tropospheric research have been the subject of many studies in the past [2–12]. It was shown that absorption lines lying in the 4ν overtone vibrational bands of H_2O near 720 and 830 nm are optimum for water vapor DIAL measurements in the lower and middle troposphere. However, in order to achieve a high measurement sensitivity at tropopause height, particularly in case of very dry air from the lower stratosphere, DIAL operation in the 940-nm wavelength spectral region is recommended. In this spectral region the strong 3ν overtone vibrational band of H_2O is accessible, where the strongest lines exceed the above-mentioned lines by more than one order of magnitude.

Powerful radiation at 940 nm can be generated by means of optical parametric oscillators (OPOs) pumped by the harmonics of a Q-switched Nd:YAG laser [13, 14]. In the past, different OPO designs have been investigated in order to demonstrate their ability as potential radiation sources for remote sensing of atmospheric constituents [15–18]. The high pulse energy and high average power are advantageous, but the spectral performance of the OPO is of particular importance for water vapor sounding in the upper troposphere, where the spectral width of the H_2O lines is on the order of 1–2 GHz. The OPO bandwidth should be considerably smaller than the molecular line widths at the investigated altitude in order to avoid systematic errors caused by the finite bandwidth [4, 6]. In addition, a high spectral purity of as much as 99% has to be guaranteed by the radiation source [6] because spectral impurity is another major source of experimental error in DIAL measurements [4, 6, 9]. Any measurement with strong absorption is extremely sensitive to radiation outside the nominal bandwidth of the light source, since this radiation would not be absorbed by the respective absorption features. If, for example, 10% of the transmitted energy is broadband and 90% of the narrowband radiation are absorbed, the resultant error would be 100%.

An appropriate means of reducing the bandwidth and controlling the spectral properties of OPOs is injection seeding [19]. The narrowest OPO bandwidths can be achieved by using tunable narrow-band cw lasers as seed sources. This has been demonstrated with color center lasers [20], dye lasers [21] or Ti:sapphire lasers [22–24]. These lasers are not, however, a practicable means for airborne DIAL application. It is generally acknowledged that a diode-laser-seeded OPO is a better technical solution to increase the overall system efficiency. Narrow-band diode-laser-seeded OPOs have already been demonstrated with BBO [25–29], KTP [30], or

$LiNbO_3$ [18, 31, 32] as the OPO crystal and diode lasers in the 800-nm [25–30] or 1500-nm [31, 32] spectral regions.

In order to end up with a small and rugged radiation source suitable for future airborne water vapor DIAL measurements in upper tropospheric regions of low water vapor content the performance of a diode-laser-seeded OPO operating in the 940-nm spectral region has been investigated in this study. Because of its importance for water vapor DIAL measurements, special emphasis is placed on the investigation of the spectral bandwidth and spectral purity of the pulsed OPO as a function of seed power from a diode laser. In addition, the accuracy of a water vapor DIAL measurement influenced by the residual measured finite bandwidth of the OPO is briefly discussed.

1 Experimental set-up

The investigations were performed with the experimental set-up shown in Fig. 1. The second harmonic of an injection-seeded Q-switched Nd:YAG laser served as the pump radiation for the OPO. As already demonstrated, the pump source used (Continuum NY61) fulfils the size and energy requirements for operation onboard the DLR's meteorological research aircraft [33, 34]. The pump laser is flashlamp-pumped at a repetition rate of 10 Hz and provides 6.5-ns-long pulses with a maximum energy of 200 mJ at a wavelength of 532 nm.

Narrow-band OPO radiation is achieved by injection seeding with a tunable external cavity diode laser (ECL) system (EOSI Inc. Model 2010). The ECL uses a Littman design that is tunable from 930 to 960 nm with continuous tuning ranges up to 60 GHz. The bandwidth was measured to be less than 10 MHz. Tunability, spectral behavior, and seeding performance of the OPO can be controlled by means of a spectrum analyzer in conjunction with both a wavemeter and a multipass absorption cell for precise water vapor measurements.

For efficient injection seeding of the OPO ring configuration, use of a Faraday isolator is recommended in order to protect the diode laser from any optical feedback. Without the isolator we have observed occasional mode hops of the ECL, but this is not critical, as it could be suppressed even by using a 10% filter in the seed beam. In addition the ring resonator has to be locked to the seed frequency by servoloop control of the cavity length with the internal PZT mounted mirror. To generate the error signal we applied the polarization locking scheme first introduced by Hänsch and Couillaud [35]. To avoid frequency drifts of the ECL during the measurements of the bandwidth we additionally stabilized the seed wavelength on the edge of a water vapor line.

2 Results

In the scope of this work, two different OPO crystals, one a type-I β-barium borate (BBO) and the other a type-II potassium titanyl phosphate (KTP), have been investigated. The crystals were 12 mm long. The second harmonic of the Nd:YAG laser was used to provide the pump radiation for both OPOs. Besides the ring geometry, which is generally preferable for injection seeding to protect the seed laser from strong optical feedback, a linear OPO cavity was tested as well. In the linear case, a total efficiency of up to 30% was achieved by using the BBO OPO. This results in a signal energy exceeding 20 mJ at 930 nm at a pump energy of 130 mJ. The highest output energy could be achieved with KTP as the nonlinear material. A total efficiency of as high as 53% was measured, resulting in a maximum signal energy of 39 mJ (Fig. 2). The relatively large discrepancies of the total efficiency can be explained partly by the fact that in contrast to the BBO crystal the KTP was antireflection coated, which is preferable because of its higher refractive index and thus higher Fresnel losses of the uncoated surface. In the ring configuration, a pump energy of 180 mJ was necessary to obtain a signal energy of 40 mJ due to a longer cavity length. The following measurements are performed with the OPO

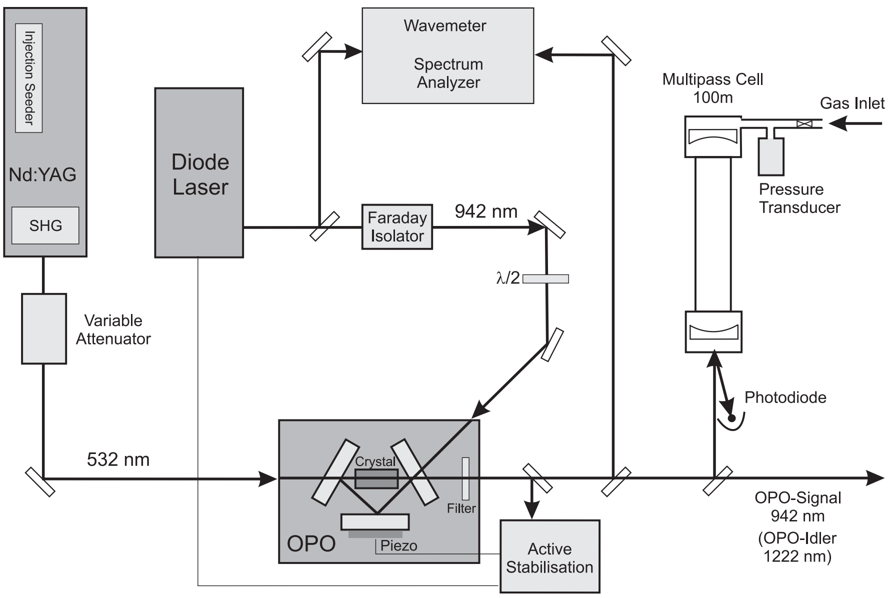

Fig. 1. Experimental set-up of the OPO system

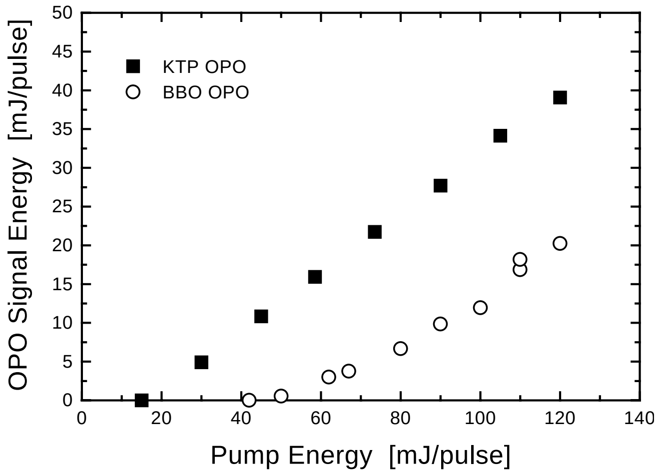

Fig. 2. Signal of the linear OPO as a function of pump energy for KTP and BBO crystals. With the KTP crystal, a total efficiency of 53% was obtained

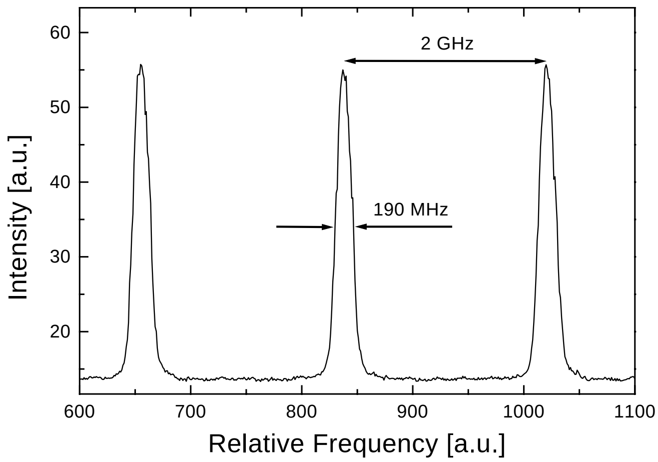

Fig. 4. Bandwidth of the OPO signal measured with the confocal FPI. During this measurement the OPO cavity length was actively stabilized as described in the text. At the OPO pulse energy of 23 mJ and seed power of 4.3 mW a bandwidth of 190 MHz was achieved

ring configuration as displayed in the experimental set-up and KTP was selected as the nonlinear OPO material.

When the diode laser wavelength was stabilized on the edge of a water vapor line its frequency did not vary more than 0.5 MHz. The OPO cavity length could be stabilized to the wavelength of the diode laser over periods of more than an hour without loosing lock, as demonstrated in Fig. 3. The spectral width of the injection-seeded KTP OPO was measured by using a high-finesse (200) confocal Fabry–Pérot interferometer (FPI) with a free spectral range of 2 GHz. The PZT of the FPI was slowly scanned and the signal was recorded with a box-car averager. A bandwidth of 190 MHz can be deduced from the result shown in Fig. 4. The pulse length was 5.2 ns. We do not expect to achieve a much narrower bandwidth of the OPO due to the bandwidth of the seeded Nd:YAG (pulse length 6.5 ns), which was measured to be 110 ± 10 MHz. In addition, phase variations over the beam profile of the pump laser may contribute to further spectral broadening of the OPO [36].

Another important parameter that characterizes the ability of a radiation source to carry out water vapor measurements is the spectral purity. Spectral purity relevant to DIAL measurements is defined as the ratio of the energy contained within a narrow bandwidth (on the order of a few line widths of the absorption line) to the total output energy. The spectral purity of the diode-laser-seeded OPO was investigated by long-pass

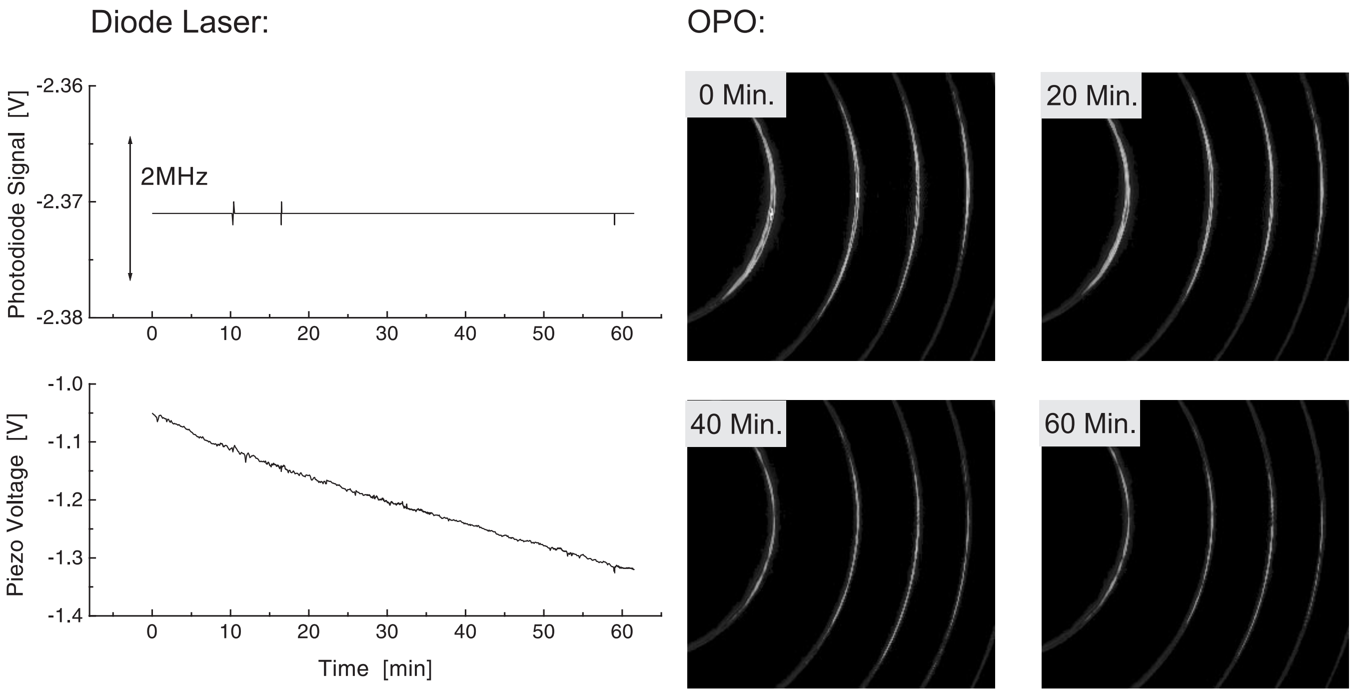

Fig. 3. Frequency stabilization performance of the diode laser and the diode-laser-seeded OPO. The *upper left diagram* shows the photodiode signal of the transmitted diode laser power stabilized on the edge of the water vapor absorption line as a function of time. The *lower left diagram* shows the piezo voltage applied to the diode laser cavity in order to compensate for a drift of ~ 3 GHz/h. Stable seeding of the OPO over the time period of one hour is demonstrated by a sequence of four Fabry–Pérot fringe patterns (FSR = 20 GHz) recorded by a CCD camera at time intervals of 20 min

absorption measurements in analogy to a former study [17] where a pulsed dye laser was used as the OPO seed source at ∼ 830 nm. We used a multipass cell with a path length of 100 m for the investigations. For the on-line measurement the narrow-band OPO was tuned to the strong water vapor absorption line at 942.825 nm. The water vapor pressure inside the cell was about 4 mbar, while the total pressure amounted to 24 mbar. The spectral width of the strongly saturated line was about 1.7 GHz. At the line center the multipass cell was optically dense under these conditions for a path length of 100 m and therefore acts as a narrowband notch filter. From the on- and off-line measurements shown in Fig. 5, a spectral purity as high as 99.8% was calculated. We note that the OPO pulse energy was 23 mJ and the power of the seed laser was only 4.3 mW in this case.

Figure 6 depicts the measured spectral purity as a function of seed power. As is shown, a seed power of only a few tens of μW is sufficient to obtain a spectral purity as high as 99%. We note that the spectral purity of the ECL was measured to be 96%, only. However, the seeded OPO shows significantly higher spectral purity because of its amplification bandwidth, which is much narrower (∼ 0.8 nm) than the broadband spectral background of the ECL (several tens of nm).

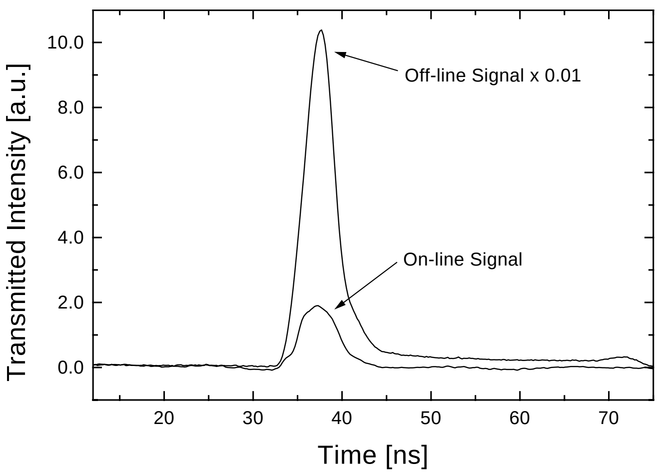

Fig. 5. OPO on- and off-line signals transmitted through the multipass absorption cell filled with water vapor. 100 shots were averaged on each pulse. From the pulse amplitude (or area) ratio, the spectral purity of 99.8% was calculated

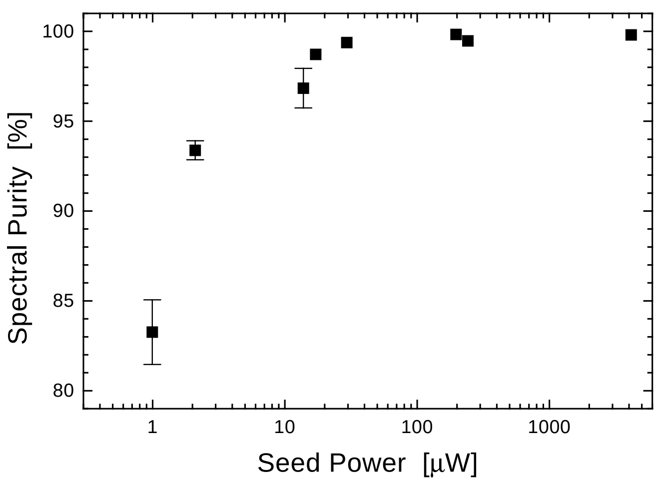

Fig. 6. Spectral purity of the seeded OPO as a function of seed power. As is clearly shown, the required 99% spectral purity can already be achieved with a few tens of microwatts

3 Discussion

In order to analyze the residual water vapor error in a DIAL experiment, which can arise from the finite bandwidth of the radiation source, the measured OPO bandwidth is compared to the H_2O line width of a selected water vapor line at 942 nm. Under atmospheric conditions the H_2O lines in the near-infrared spectral region are collisional and Doppler broadened. Thus their spectral variability as a function of altitude can be described by a Voigt profile [37]. Because of decreasing atmospheric pressure with height, the H_2O line width also decreases with altitude as illustrated in Fig. 7. Below 5 km the line width is greater than 3 GHz (FWHM) and collisional broadening (Lorentz limit) dominates. At a height of 5–18 km, both Doppler and collisional broadening contribute to the line width. Above 20 km, at atmospheric pressures below 10 mbar, collisional broadening can be neglected and the line width of about 1 GHz (FWHM) is determined by Doppler broadening alone, which does not change much with height.

The influence of bandwidth and spectral purity on DIAL measurement accuracy has been the subject of several studies in the past [4, 6, 33, 38]. From results given in [4] a small 1% error is obtainable only if the line width ratio (in our case OPO bandwidth to H_2O line width) is less than 0.3. Otherwise large errors can be introduced. For the investigated system the line width ratios are smaller than 0.25 for all altitude levels shown in Fig. 7. From the measurement of the spectral purity of greater than 99% we conclude, according to the analysis of [38], that the residual error is smaller than 2% for appropriate optical densities of ∼ 1. Therefore, the investigated diode-laser-seeded OPO fulfils the requirements of a precise water vapor DIAL measurement in the upper troposphere and lower stratosphere.

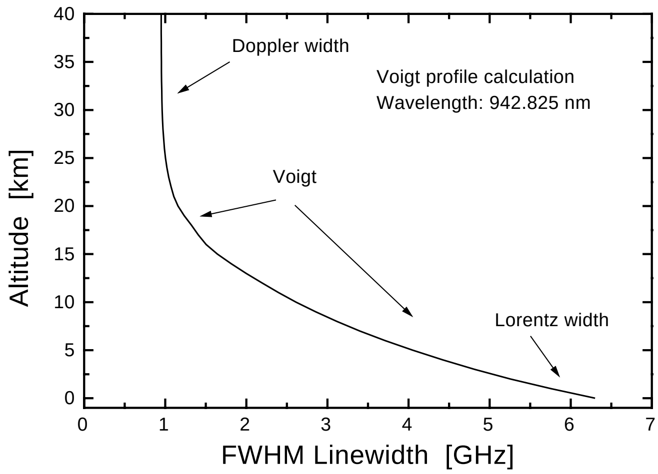

Fig. 7. Calculated collisional and Doppler broadened H_2O line width as a function of altitude. The results show that even at higher altitudes in the stratosphere, where the H_2O line width is ∼ 1 GHz, the bandwidth of the diode-seeded OPO (190 MHz) can be treated as nearly monochromatic in a water vapor DIAL measurement

4 Summary

The performance of a diode-laser-seeded optical parametric oscillator in the 940-nm spectral region has been investigated in detail. These results demonstrate that this system is well suited for water vapor DIAL application in the near-infrared spectral region and fulfils the requirements for airborne measurements in the upper troposphere and lower stratosphere.

Using KTP as the nonlinear material, a signal energy of up to 40 mJ was obtained and a maximum conversion efficiency of 53% was achieved. The bandwidth was measured to be 190 MHz. The measurement of the spectral purity of a diode-laser-seeded OPO was performed for the first time and yielded a value of as high as 99.8%. Even with a seed power of only 20 μW, a 99% spectral purity was achieved.

The residual error of a water vapor DIAL measurement in the upper troposphere and lower stratosphere caused by the finite bandwidth of this radiation source is on the order of 1%, only. Further improvements in terms of average power, overall efficiency, and spectral characteristics are expected when a diode-pumped Nd:YAG laser replaces the currently used flashlamp-pumped system.

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