Nd:GSAG laser for water vapor detection by LIDAR near 942 nm

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ABSTRACT

For weather forecast, especially for civil protection from high-impact weather events, measuring the three-dimensional distribution of water vapour by DIAL techniques is a fundamental concern. Especially for development and evaluation of atmospheric models, knowledge of water vapour distribution is important. Suitable wavelengths for a water vapour DIAL are e.g. around 943 nm. This region can be reached with well established technologies such as the optical parametric oscillator (OPO) and the Ti:Sapphire laser. But these systems suffer from low efficiency and complex set-up. In contrast the Nd:GSAG laser presented here can be directly pumped with 808 nm laser diodes. This supports the realisation of an efficient and compact laser system. Different oscillator and amplifier setups working at 943 nm were realised. An output energy of >17 mJ in a 100 ns pulse with 10 Hz repetition rate was demonstrated. In a MOPA system a double pass gain of 1.5 and an output energy of >18 mJ was achieved. The Nd:GSAG laser oscillator was successfully injection seeded with DFB laser diode from FBH-Berlin. Also the gain cross section in a Nd:GSAG laser crystal from 941-944 nm was measured. The FWHM of the homogeneous line is 2 nm with a peak stimulated emission cross section of $4.0\cdot10^{-20}$ cm^2 at 942.7 nm.

Keywords: mixed garnet laser, DIAL, water vapor detection, injection seeding

1. INTRODUCTION

The application of climate models relies on the availability of data about the distribution of the local and global water vapour concentration. Besides a two-dimensional water vapour distribution map the measurement of height profiles is necessary to create a three-dimensional distribution map of water vapour in the atmosphere. Therefore the knowledge on water vapor distribution in the upper troposphere and lower stratosphere is of high relevance. In various publications [1-3] it was shown that a DIAL system can measure water vapor profiles simultaneously with high resolution and accuracy. The parameters of the laser transmitter have a strong impact on the performance of the DIAL system. The requirements for the laser transmitter are summarized in table 1.

Table 1. Laser transmitter requirements for a water vapor DIAL [4].

Parameters	Value
Wavelengths	935/936 nm; 942/943 nm, 944 nm
Laser Linewidth	< 160 MHz
Laser frequency stability	< 60 MHz
Laser spectral purity	> 99.9%
Laser pulse energy	> 70 mJ

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For a space born DIAL system the wavelength regions of about 935 nm, 942 nm and 944 nm have been identified as the most suitable [4,5]. The more or less well established technologies such as the OPO and the Titanium Sapphire laser suffer from low over all conversion efficiencies to the desired wavelength range [6,7]. These frequency converter technologies use a Nd^{3+} laser as pump source and two further frequency converters. For an efficient laser transmitter a laser material that can be pumped directly with laser diodes is preferable. The laser lines of the Nd:YAG laser (938 nm and 946 nm) which result from $^4F_{3/2} - {}^4I_{9/2}$ transitions are in the desired wavelength region but do not match exactly the required water absorption wavelengths. By manipulation of the host lattice the upper and lower laser levels can be shifted to achieve the desired wavelengths. As suggested by G. Huber and K. Petermann from Hamburg University [5] laser materials like Nd:YGG and Nd:GSAG emitting at 935/936 nm and 942/943 nm as well as other garnets can be used for water vapor detection.

At our workgroup the Nd:GSAG laser crystal at 943 nm wavelength in oscillator and amplifier setups were investigated. The first part of the paper describes the measurement of the stimulated emission cross section using a Titanium:Sapphire (TISA) laser with diffraction limited beam quality as pump source. In the main part of the paper the experimental set-up and results with a q-switched Nd:GSAG laser oscillator and a Nd:GSAG MOPA system are shown. Also injection seeding of the Nd:GSAG laser was demonstrated.

2. MEASUREMENT OF STIMULATED EMISSION CROSS SECTION

The stimulated emission cross section was measured to understand and model laser and amplifier performance. The experiment was conducted at room temperature with the Nd:GSAG crystal (length 13 mm, diameter 5.5 mm) mounted in copper heat sink without active cooling. The Nd^{3+} concentration was 0.6%. A schematic of the experimental set-up for double pass gain measurements is shown in Figure 1. The Nd:GSAG laser crystal is pumped longitudinally with a gain switched TISA laser emitting at a wavelength of 808.5 nm with pulses of about 30 ns. The laser was collimated by a telescope to 1.3 mm beam diameter with energies of up to 20 mJ. The pulse energy incident on the Nd:GSAG crystal was controlled by a polarizer half-wave plate combination.

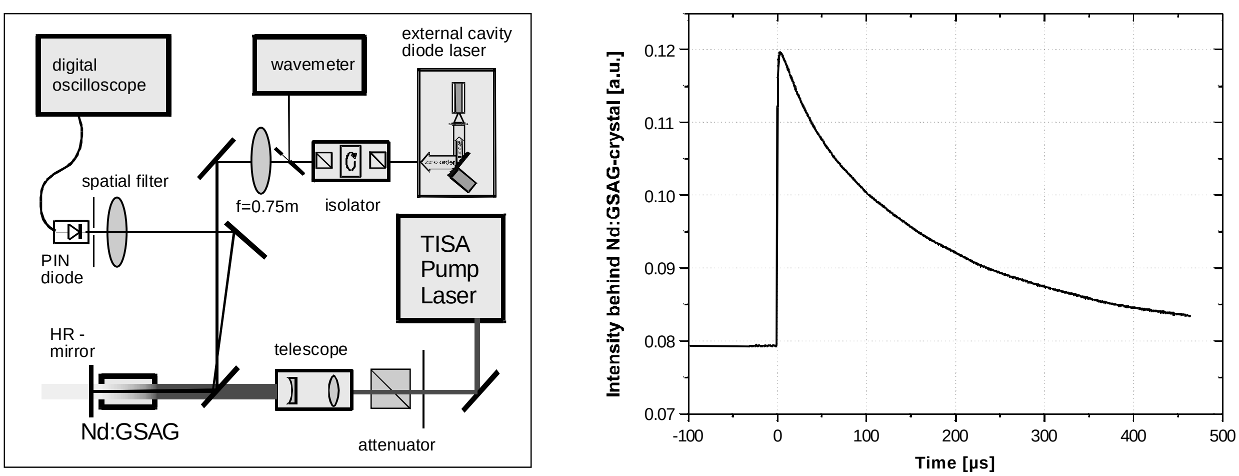

Fig. 1: The experimental set-up is shown left. On the right a typical temporal profile of a gain measurement is shown.

In order to determine the stimulated emission cross section in Nd:GSAG the amplification of a probe laser was measured. A diode laser with an external cavity in Littrow configuration supplying single longitudinal mode operation was used as probe laser. The wavelength of the output was measured using a wavemeter and could be tuned from 930 to 950 nm. With a lens of 0.75 m focal length the probe beam was focused to ~0.9 mm beam diameter to the end face of the Nd:GSAG crystal. Due to the long focal length the change of the beam diameter within the crystal length was negligible. The probe beam was made almost collinear (angle < 1°) to the pump beam by a dichroitic mirror with a high reflectivity at 943 nm and low reflectivity at 808 nm, the pump wavelength. Because of the low gain of the amplifier also a double pass configuration was used to improve the accuracy of the measurement. The intensity of the amplified probe beam was measured with a fast photo diode and recorded with a digital oscilloscope. To reduce the influence of the stray light from the pump pulse the detector was placed behind a spatial filter. Probe laser powers up to 10 mW were used. Additionally the polarization of the probe laser as well as the pump laser was changed. But no polarization dependent effects to the absorption of the pump light and the amplification of the probe beam were observed.

A typical oscilloscope track of a gain measurement is shown on the right side of Figure 1. The graph shows the time dependence of the probe beam intensity on the photo detector for an incident pump pulse area density of 1.4 J/cm2. At t=0 the pump pulse excites the Nd3+ ions from the $^4I_{9/2}$ ground state to the $^4F_{5/2}$ pump band which has a fast decay to the upper laser level $^4F_{3/2}$. On the time scale of Figure 1 the temporal width of the pump pulse can be ignored coinciding with a rapid raise in signal intensity at t=0. With the end of the pump pulse the intensity decays to the unamplified probe beam intensity. The single pass small signal power gain is given by equation (1), where I_{in} and I_{out} are the input and output probe laser intensities, g_0 is the small signal gain coefficient averaged over the length L of the amplifier. With the knowledge of g_0 and the inversion density ΔN the stimulated emission cross-sections can be calculated. In equation (2) $h\bullet\nu$ is the pump photon energy and E_p is the absorbed pump energy area density.

$$G_0 = \frac{I_{out}}{I_{in}} = \exp\left(g_0 \cdot L\right) \quad (1) \qquad\qquad \sigma = \frac{g_0}{\Delta N} = \left(\frac{h \cdot \nu_p}{E_p}\right) \cdot g_0 \cdot L \quad (2)$$

A peak emission cross-section of $\sigma_e = 4\bullet10^{-20}\,cm^2$ at 942.7 nm was determined assuming a homogeneous line with a FWHM of 1.5 nm is shown in Figure 2.

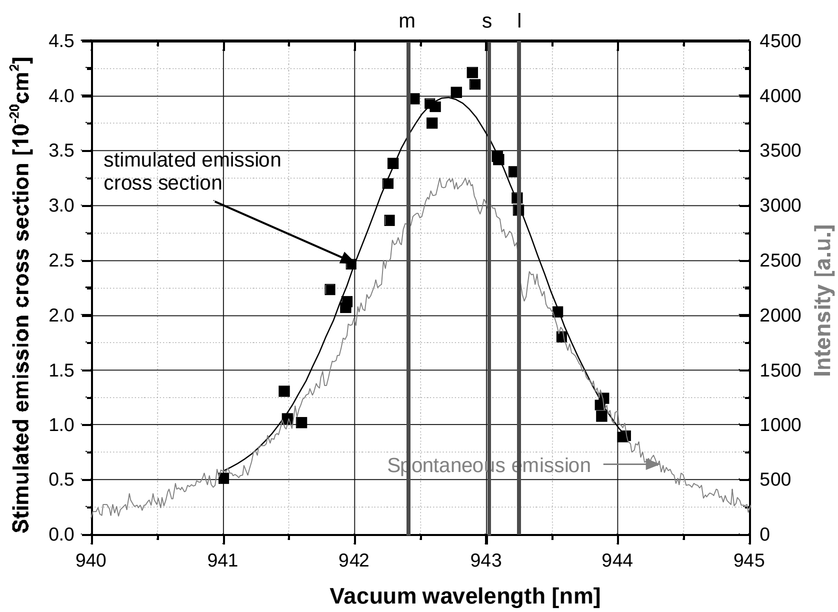

Fig. 2: Measured stimulated emission cross section of Nd:GSAG laser crystal in dependence of wavelength is shown. Also the spontaneous emission spectrum is shown. The vertical lines indicates water vapor absorption wavelength.

All three designated water vapor absorption wavelengths shown as vertical lines possess $\sigma\bullet\eta > 3.0\bullet10^{-20}$ cm^2. Here, η is the quantum efficiency for excitation of the upper laser level. It has been shown for Nd:YAG crystals that η~0.6. If all absorbed pump photons contribute to the inversion, the quantum efficiency is 1. The measured stimulated emission cross section $\sigma_e=\sigma\bullet\eta$ is therefore an effective cross section and σ the real stimulated emission cross section of the laser ion.

3. ND:GSAG LASER OSCILLATOR

The requirements on a space born DIAL transmitter are high (table 1). Besides the spectral requirements also a high overall efficiency and a compact design are needed. To achieve a high overall efficiency and a diffraction limited beam quality longitudinal pumping with laser diodes is recommended. In order to reduce energy consumption and heat generation the pump diodes should be operated in pulsed mode.

The laser diodes of the pump module provides up to 1 kW pump power with a maximum duty cycle of 7%. In the following experiments a pump pulse duration of 300 µs and a repetition rate of 10 Hz was used. The laser diodes are coupled into a fiber with 1.0 mm core diameter. The end face of the fiber is imaged to the Nd:GSAG crystal by a telescope. The pump beam profile in the Nd:GSAG crystal is a soft aperture and higher oscillator modes with a bigger beam diameter will have a lower gain. Thus fundamental mode operation can be easily obtained by adapting the pump beam diameter to the oscillator fundamental mode diameter. This can be done by changing the magnification of the telescope. The central emission wavelength of the pump module was ~804 nm with a FWHM of 2 nm. The wavelength of the pump diodes could be tuned by temperature, but not far enough to reach the strongest absorption peak of the Nd:GSAG laser crystal at 808.5 nm. Nevertheless the absorption at the lower absorption peak was sufficient for efficient laser operation. The emission spectrum of the pump diodes and the transmission spectrum through a 10 mm long Nd:GSAG laser crystal with 0.6% Nd concentration is shown in Fig. 3. The transmission of the pump light depends also on the crystal length. A transmission of the pump light of 13% through the 13 mm Nd:GSAG rod used in the oscillator and of 21% through the 10 mm rod used in the amplifier were achieved which corresponds to ~85% and ~77% absorption assuming low reflection and scattering losses.

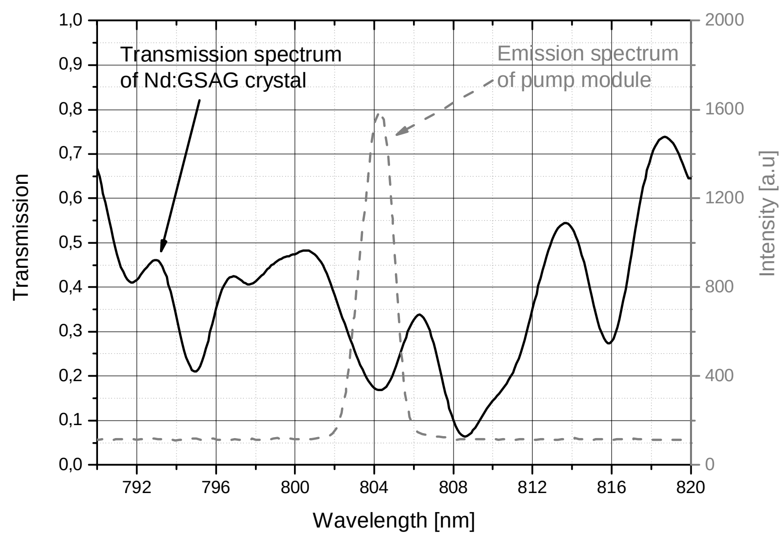

Fig. 3: Transmission spectrum of a 10 mm long Nd:GSAG laser crystal with 0.6% Nd concentration in the 808 nm wavelength region (solid line) and emission spectrum of the diode pump laser (dashed line).

An Nd:GSAG laser rod (13 mm long, 4 mm diameter) was mounted in a water cooled cooper heat sink and stabilized to a temperature of 20°C was used in the oscillator. The surfaces were coated with an anti-reflection coating and the Nd^{3+} concentration of the crystal was 0.6%. A sketch of the laser set-up is shown in Fig. 4. It is a linear resonator with two plane mirrors. The pump light was coupled into the resonator through the end mirror which was high transmittive (HT) at 808 nm and high reflective (HR) at 943 nm. The reflectivity of the output coupler (OC) at the laser wavelength was 82%. Both mirrors were high transmittive (HT) at 1061 nm to suppress the $^4F_{3/2} - {}^4I_{11/2}$ transition which has an about 8 times higher emission cross-section. An active q-switch with an electro-optical modulator (EOM) was used to generate short laser pulses. The EOM was controlled by a PC that was triggered by the pump module.

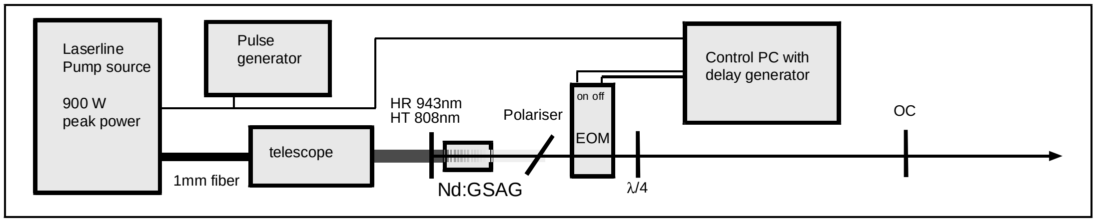

Fig. 4: Sketch of the longitudinally pumped q-switched Nd:GSAG oscillator set-up.

In the first set-up a pump beam diameter of 1 mm and a resonator length of L = 27 cm were used. In this configuration the output pulse energy was limited to 6 mJ due to damages on optical surfaces inside the resonator (Fig. 5). Especially the thin sheet polarizer and the AR-coating of the laser rod were subject to damages. To overcome this limit the diameter of the resonator mode had to be enlarged. A plane - plane resonator is stabilized by the thermal lens of the laser rod. In our case the laser crystal which acts like a lens is located near the end mirror. This configuration is similar to a plan - concave cavity. An increase in cavity length will increase mode diameter until the resonator becomes unstable if the cavity length exceeds the focal length of the thermal lens. The cavity length was enlarged from L = 27 cm to L = 85 cm. The mode diameter of the L = 27 cm oscillator was measured to be ~0.9 mm and of the L = 85 cm oscillator to be ~1.5 mm. With this bigger resonator mode pulse energies up to 17 mJ with 100 ns pulse duration were achieved until damages occur. The slope efficiency was 11.6% and the optical efficiency 6.5%.

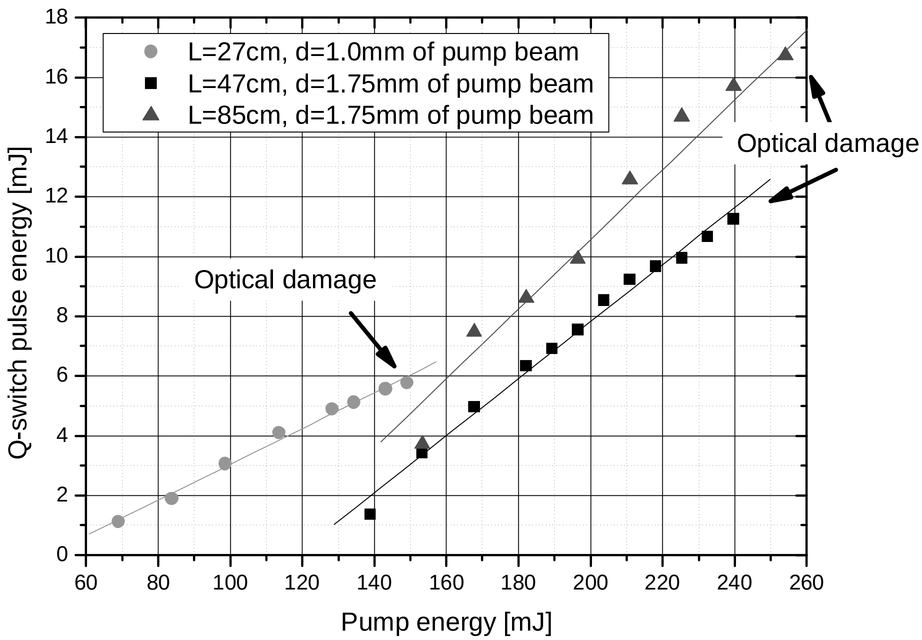

Fig. 5: Q-switched pulse energy for longitudinally pumped Nd:GSAG oscillators with different resonator lengths in dependency on the pump energy. The pump beam diameter was also changed.

The output pulse energies of three different oscillators in dependence of the pump energy are shown in Fig. 5. For the longer oscillators the diameter of the pump beam was changed. The pump beam acts like a soft aperture which results in a decrease in efficiency for bigger modes. Best efficiency is achieved if pump mode diameter and cavity mode diameter matches. A further increase in resonator mode diameter can be achieved by a further increase of resonator length or by the compensation of the thermal lens with a convex mirror.

4. ND:GSAG LASER AMPLIFIER

A simple theory of laser amplifiers is described in [8]. The rate equations are solved for square pulses. Amplified spontaneous emission is not included. With these assumption the output fluence E_{out}, which is the output energy over beam area, can be calculated. G_0 is the small signal gain and E_{IN} is the Input fluence and E_S is the saturation fluence.

$$E_{out} = E_S \cdot \ln\left[1 + \left(\exp\left(\frac{E_{In}}{E_S}\right) - 1\right) \cdot G_0\right] \quad (3) \qquad E_S = \frac{h \cdot f}{\gamma \cdot \sigma} \quad (4)$$

The factor γ describes the reduction in the inversion due to population of the lower laser level. In a four level system $\gamma = 1$ because the lower laser level is always empty. In our case it is thermally populated but with a small amount. Thus for the simulations $\gamma = 1$ was used.

To predict the output energy and to compare theory and measurement the small signal gain was measured in dependence of the pump energy. A similar set-up as shown in Fig. 1 was used. Fig. 6 shows the small signal gain in dependency on the pump energy for three pump beam diameters. The small signal gain at maximum pump beam energy is $G_0 = 1.5$ for 1.5 mm pump beam diameter whereas it is $G_0 = 1.32$ for the 2.0 mm pump beam diameter. For bigger pump beam diameters the energy density of the pump beam is lower and a lower small signal gain is obtained.

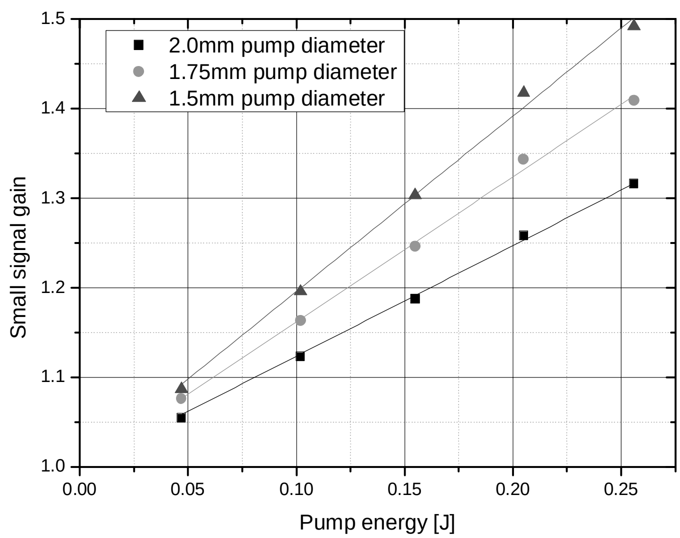

Fig. 6: Small signal gain for different pump beam diameters in dependence of pump energy.

Master oscillator power amplifier (MOPA) setups with single and double pass were investigated. An example set-up for a double pass MOPA is shown in Fig. 7. For the single pass configuration the HR-mirror behind the amplifier crystal was removed.

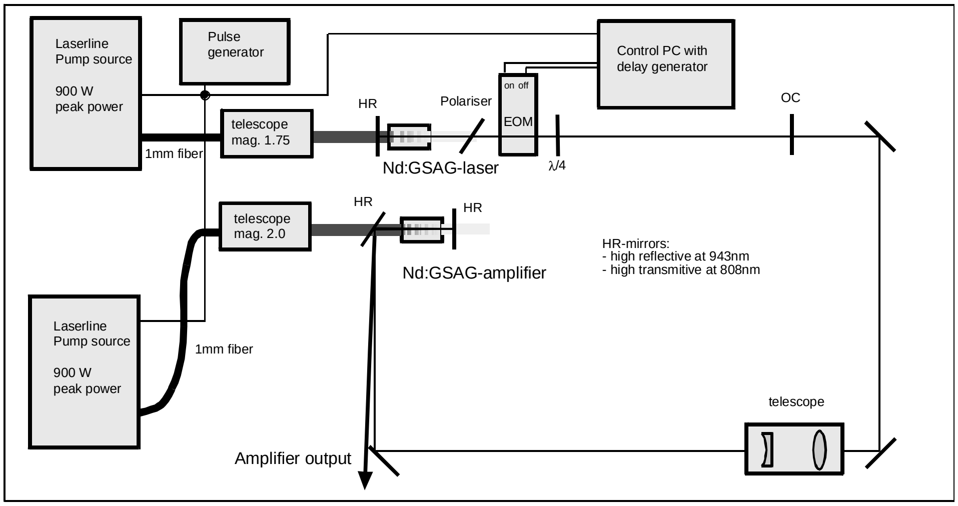

Fig. 7: Double pass Nd:GSAG MOPA set-up

Only small saturation effects were observed in the single pass configuration. The maximum gain drops from 1.32 for small signal to 1.29 for 11 mJ input pulse energy. The measured amplifier output energy fits well with the theoretical curve as shown in Fig. 8. But the experimental results for the double pass configuration differ from theoretical predicted values. This can be explained by a not complete overlap of pumped volume in the Nd:GSAG crystal with the signal beam due to a small angle between signal and pump beam in the double pass configuration. An amplifier output energy of 18.3 mJ was achieved with an input energy of 12.1 mJ in the double pass configuration. This corresponds to a total gain of 1.5. With an input beam diameter of 1.5 mm the input fluence is ~0.7 J/cm^2. The saturation fluence (~5.3 J/cm^2) is nearly a magnitude larger which explains the small saturation of the amplifier.

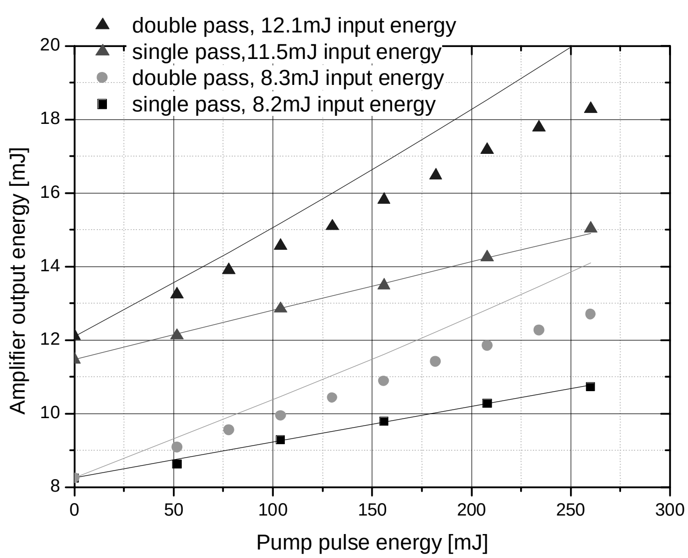

Fig. 8: Nd:GSAG amplifier output energy for two input energies in single and double pass configuration. The solid lines are the results from theory.

5. INJECTION SEEDING OF ND:GSAG LASER

The spectral requirements on a laser transmitter for a water vapor DIAL are very strict. The laser has to operate with a narrow linewidth directly on a water vapor absorption line. This can be achieved by injection seeding. In this technique a low power laser that fulfills the spectral requirements is coupled into the high power laser oscillator. These seed photons influence the build-up of the laser pulse. The oscillator mode with the same frequency as the seed laser has an advantage because the build-up for this mode starts at a higher initial photon number. All other modes will start from noise. As a result the pulse-build-up time will become shorter if the laser is injection seeded.

The experimental set-up of the q-switched laser had to be changed to realize injection seeding. An operation of the q-switched laser in twisted mode to avoid spatial hole burning was necessary to achieve injection seeding. It was not possible to put additional components between the laser crystal and the HR-mirror in the old set-up. A 45° bending mirror was used to expand the resonator on the pumping side of the laser crystal. This gives the possibility to sandwich the Nd:GSAG crystal between a quarter-wave-plate and the EOM. The set-up is shown in Fig. 9. A distributed feedback laser (DFB) from FBH Berlin with up to 200 mW output power was used as seed laser. The DFB laser was protected by optical isolators and coupled into the laser resonator via the thin-sheet polarizer. The end mirror was mounted on a piezo-electric driven translation stage to adapt the resonator length.

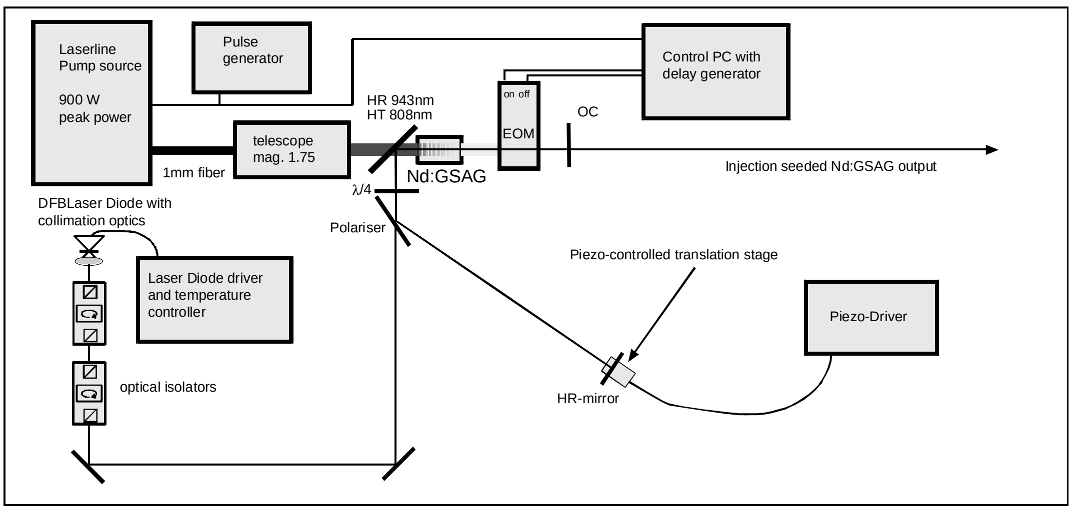

Fig. 9: Sketch of the experimental set-up for the injection seeded, q-switched Nd:GSAG laser.

In first experiments the wavelength control by injection seeding and the narrowing of the wavelength spectrum could be demonstrated. Fig. 10 shows the spectrum of the Nd:GSAG when the seed laser is blocked (dashed line) and the spectrum in the injection seeded mode (solid line). The laser emission at the unseeded wavelength nearly vanishes resulting in an intensity peak at the wavelength of the seed laser.

It was not possible yet to force the Nd:GSAG laser further away from the natural emission wavelength. The roundtrip gain in the laser resonator is low. This has a consequence for the maximal wavelength difference of the seed laser and the emission peak. The lower gain besides the emission peak may reduce the output energy and prevents injection seeding. To maintain output energy and achieve a similar gain as at emission peak a higher pump energy is needed. In this case it may be necessary to use a filter to suppress the peak emission wavelength. Another solution can be fine tuning of the peak emission wavelength by temperature or by the laser crystal composition.

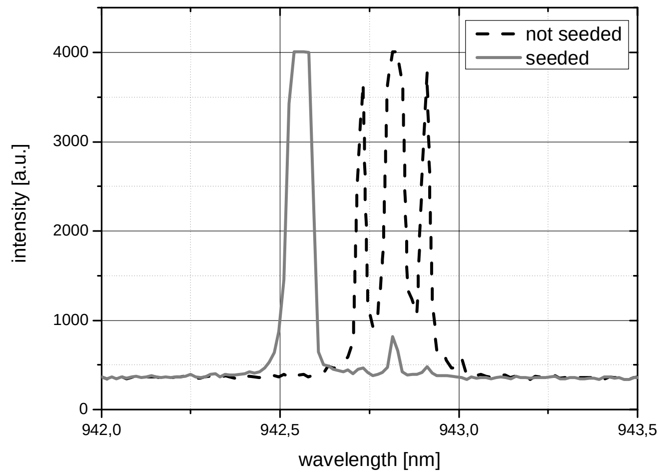

Fig. 10: Demonstration of injection seeding of the q-switched Nd:GSAG laser using a high power DFB diode from FBH-Berlin as seed laser. The dashed line shows the natural emission spectrum and the solid line the emission spectrum of the injection seeded laser.

6. CONCLUSION

In this paper the direct generation and amplification of laser radiation around 943 nm with an Nd:GSAG laser is presented. This wavelength region is important for a water vapor DIAL.

With a q-switched Nd:GSAG laser oscillator an output energy of >17 mJ in 100 ns pulses with 10 Hz repetition rate, a slope efficiency of 11.6% and a maximum optical efficiency of 6.5% could be demonstrated. The output energy of the laser was limited by optical damages due to the high energy density inside the laser resonator. By a further increase of the resonator mode diameter a higher output energy can be obtained. Another way to achieve more pulse energy is a MOPA set-up. In a diode pumped amplifier a small signal gain of 1.32 with 2 mm pump beam diameter was measured. Due to the high saturation fluence of 5.3 J/cm^2 only small saturation of the gain was observed. With a 11.5 mJ input signal a gain of 1.29 was achieved with an output pulse energy of 15 mJ. In a double pass configuration a total gain of 1.5 and an amplifier output energy of >18 mJ was achieved. To optimize the extraction efficiency of the amplifier a higher input pulse energy should be applied to saturate the amplifier. Also a more passes are recommended to increase the total gain.

Also the wavelength dependence of the stimulated emission cross-section of Nd:GSAG in the 943 nm region was successfully measured. The lineshape of σ was estimated to be Lorentzian (homogeneous line) with a FWHM of 2 nm. For all three water vapor absorption wavelengths needed for DIAL in this wavelength region $\sigma > 2.5 \cdot 10^{-20}$ cm^2 and therewith quite near the gain peak. The peak cross-section is with $4.0 \cdot 10^{-20}$ cm^2 at 942.7 nm similar to the cross-section in Nd:YAG and the same performance can be expected.

The Nd:GSAG laser has a high potential as a water vapor DIAL laser transmitter. A compact set-up and a high efficiency are possible. The presented results also show that high pulse energies can be achieved with a Nd:GSAG laser. The next steps are the up scaling of the pulse energy and the improvement of the frequency stabilization to a water vapor absorption wavelength.

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