AN EYE-SAFE, TUNABLE LIDAR TRANSMITTER AT 1.45 μm BASED ON A Cr^{4+}:YAG LASER

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ABSTRACT

This paper summarizes recent laboratory progress toward the development of a Cr^{4+}:YAG laser for lidar applications. When pumped by a Nd:YAG laser, Cr^{4+}:YAG converts the fundamental 1064nm to wavelength in the region of 1400-1500nm. Therefore, this laser material is very interesting for eye-safe water vapour DIAL measurements. Significant improvement of the pump beam properties were obtained with a vacuum spatial filter. Optical-to-optical conversion efficiency of 3% was demonstrated in our preliminary experiments. The laser pulse duration in gain- switched mode is less than 100ns. Further results are presented at the conference.

1. INTRODUCTION

The goal of this project is to design and build a solid-state laser for eye-safe aerosol backscatter lidar. Elastic backscatter lidars are very useful tools for investigating the structure of the atmosphere. However, their use is restricted by eye-safety issues of the transmitted light. Furthermore, frequency agility and spectral purity are highly desirable in order to perform water-vapor DIAL measurements.

2. LASER SYSTEM

In October of 2005, corresponding experiments have been carried out in the lidar laboratory at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, USA, in collaboration with the Institute of Physics and Meteorology (IPM) at the University of Hohenheim (UHOH). The initial design of the frequency converter was accomplished at IPM.

2.1 Pump laser

The pump laser is a flash-lamp-pumped Q-switched Nd:YAG laser (Continuum Surelite III), providing 800mJ pulse energy at 10Hz at 1064nm wave-length. The pulse duration at FWHM is 6-8ns. The beam is flat-topped multimode and slightly astigmatic. It is 70% horizontally polarized. This is the same pump laser used in the NCAR REAL transmitter [1].

2.2 Frequency converter

The frequency converter is based on a highly doped Cr^{4+}:YAG crystal (initial absorption coefficient $\alpha=4$ cm^{-1}). The crystal is a 40mm long Brewster-cut rod with 7mm diameter. It was provided by A. Shestakov, IRE-Polus, Moscow. The rod is clamped in a cooling system. The temperature of the crystal is stabilized to $\pm 0.2^oC$ of the set-temperature with water cooled Peltier elements. The crystal and rod clamp are mounted on a goniometer for fine adjustment of the Brewster angle.

For brevity we refer the reader to our previous 22nd ILRC paper [2] where we described the laser characteristics of the active medium.

3. EXPERIMENTAL ARRANGEMENT

3.1 Improvement of the pump beam characteristics

A diagram and a photograph of the experimental arrangement are shown in Figs. 1 and 2, respectively. A significant part of our setup is built in order to adapt the pump beam properties to our application.

The crystal must be pumped with a linearly polarized beam in order to achieve maximum conversion efficiency [3]. We use a thin film polarizer TFP_1 which transmits the horizontal polarization and reflects the vertical to a beam dump D. Furthermore, the horizontal polarization is adjusted by a half waveplate P_2 to be parallel to the incident plane of the Brewster-cut laser crystal for minimum energy loss at the surface.
The output power of the Nd:YAG laser can be changed by varying the flash-lamp voltage. However, this introduces different thermal lensing in the laser rod,

which leads to changes in the beam propagation. To investigate Cr^{4+}:YAG laser characteristics for different pump pulse energies and to keep the pump configuration constant, we are using a combination of a half waveplate P_1 and thin-film polarizer TFP_2. The incident energy on the laser crystal is adjusted by changing the transmission of the polarizer when the polarization of the beam is rotated with the half waveplate.

As many high-peak-power lasers, the pump laser has a distorted beam profile. Localized energy densities, known as “hot spots”, can exceed the damage threshold of the laser crystal and the optics even for low pulse energy. We overcome this limitation of pump pulse energy with a spatial filter. The spatial filter consists of a focusing lens, recollimating lens and a pinhole, placed at their common focal plane. The higher spatial frequencies are blocked by the surface surrounding the pinhole and only low spatial frequencies are passed. When used for high power lasers, the spatial filter must be in vacuum, because the high energy density in the focus causes optical air breakdown.

We have performed few tests of spatial filtering in order to find a compact and reliable design. The experiments showed that the burning and also deformation of the pinhole can be avoided, or sufficiently decreased, if the focus has diameter bigger than 2 mm. This automatically excludes the possibility of building a short spatial filter.

In order to produce an appropriate waist diameter, we use a weak focusing lens L_4 with 2m focal length and an additional 2:1 beam reducer L_2-L_3 (L_2: plan convex lens with f=150mm, L_3: plan concave lens with f=-75mm), to enlarge the focus by almost a factor of two. The separation between the foci in the x- and y-plane is reduced by a cylindrical lens L_1 (fx=10m). The beam remains astigmatic so that the pinhole can be placed in the medial focus where the spot is approximately round. The medial focus is 2.65m after the focusing lens and has diameter 2.68mm and 2.60mm in x- and y- plane, respectively. Best results for the filtered beam were achieved with a 1.9mm pinhole diameter. About 20% of the incident energy in the vacuum spatial filter (VSF) is blocked by the surface surrounding the pinhole. The recollimating lens L_5 with focal length 1m is placed 1.1m after the pinhole. The vacuum box containing the pinhole is sealed with Brewster windows BW_1, BW_2 and evacuated down to 133.3Pa. Beam profiles before and after the pinhole were taken and the maximum energy density was calculated. The Brewster windows and the folding mirrors HR_2 and HR_3 were placed at positions where the energy density was below their damage threshold. The overall length of the vacuum box is 2.6m. The VSF is long and requires maintance of constant pressure. But it does improve the beam profile to a nearly Gaussian energy distribution, which permits investigating of Cr^{4+}:YAG laser properties at high pump energies. Furthermore, the use of this filter is only required as long as the pump laser has a poor beam profile. In the future, it can be expected that new flash lamp pumped or diode laser pumped high-power Nd:YAG laser become available with much better beam profiles (without any spatial filtering) [4]. Therefore this experiment can be used as baseline of the expected performance of Cr^{4+}:YAG pumped with this generation of pump lasers.

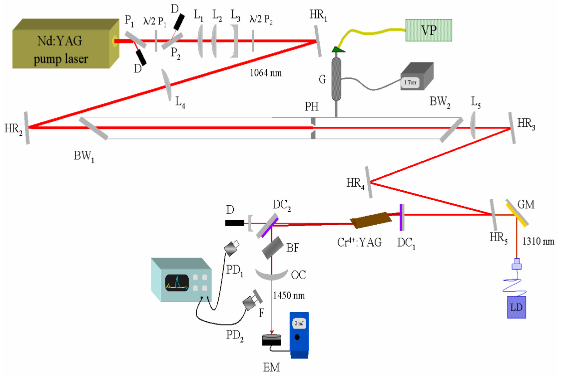

Fig. 1. Schematic diagram of the experimental setup of Cr^{4+}:YAG laser. TFP_1, TFP_2: thin film polarizers, P_1, P_2: half waveplates, L_1: cylindrical lens, L_2-L_3: beam reducer:, HR_1-HR_5: high reflectivity mirrors for 1064nm, L_4: focusing lens, L_5: recollimating lens, BW_1,BW_2: Brewster windows, PH: pinhole, G: gauge, VP: vacuum pump, LD: laser diode, GM: gold coated mirror, DC_1, DC_2: dichroic mirrors with high transmission for 1064nm and high reflectivity for 1400-1500nm, BF: birefringent filter, OC: output coupler, EM: energy meter, PD_1, PD_2: photo detectors, F: interference filter for 1450nm.

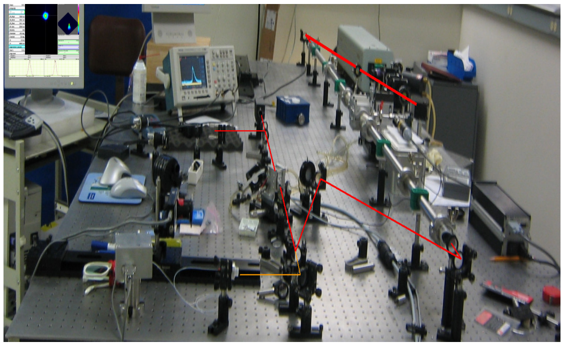

Fig. 2. Photograph of the experimental set up of Cr^{4+}:YAG laser in the NCAR Earth Observing Laboratory (EOL) lidar laboratory.

3.2 Resonator design

An important parameter for the design of the resonator is the focal length of the induced thermal lensing in the laser crystal for certain pump energies. The thermal lens is measured with a pump-probe technique using an additional focusing lens (f=0.7m) placed immediately after the crystal. The CW probe beam is produced by a fiber coupled DFB laser diode at 1310nm. This wavelength is chosen so that it is out of the broad and very strong absorption spectra of Cr^{4+}:YAG crystal– between 300nm and 1200nm. The measured values for thermal lensing for 130mJ pump energy are: 4.5m in the tangential plane and 15m in the sagittal plane.

A dynamically stable linear plane-concave resonator was calculated with the matrix technique proposed in [5]. The pump beam is coupled into the resonator through a dichroic mirror DC_1, placed 0.10 m from the first principal plane of the crystal (fig. 1). The output coupler is a concave mirror with 1m radius of curvature and 5% transmission for the 1400-1500nm wavelength region. It is located 0.57 m from the second principal plane. An additional dichroic mirror DC_2 was used to remove the residual pump energy from the resonator.

This resonator ensures total overlap of the broad stability zones in the tangential and sagittal planes and very low misalignment sensitivity. The beam spot in the crystal is calculated to be 0.96mm. We have chosen such a small beam spot in the crystal in order to reach laser threshold at low pump energy in this laser experiment.

4. RESULTS

With a VSF we achieved a 90% Gaussian-shaped pump beam. The pump beam in the crystal is approximately collimated and has diameters of 2.74mm in x-plane and 2.47mm in the y-plane, respectively. A large pump spot allows interaction of the pump energy with larger volume of the low gain Cr^{4+}:YAG crystal. The maximum pump energy did not exceed 130mJ in order to avoid optical damage of the crystal but pumping with higher pulse energy may still be possible. Furthermore, higher pump pulse energies can be achieved by pumping the laser crystal from both sides in a future set up. The crystal temperature was stabilized to $15^{o}C$.

4.1 Absorption behaviour of Cr^{4+}:YAG crystal

At the beginning of this project we were using Cr^{4+}:YAG rods with lower initial absorption coefficient ($\alpha=2cm^{-1}$), 20mm long and 5mm in diameter. The pump experiments showed saturation of the absorption at 40mJ and the transmission for 130mJ pump energy was 45%. The transmission of the pump energy is reduced by factor of 2.3 with the new, longer, highly chromium doped YAG rod. The measured saturation of the absorption is shown in fig. 3. Adapting the beam profile of the pump laser, the doping, and the length of the crystal turned out to be critical for optimizing laser performance. This is special feature of this laser crystal.

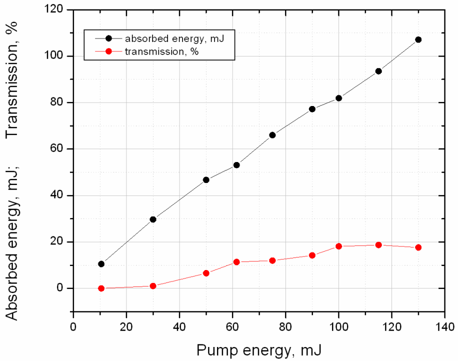

Fig. 3. Transmission and absorbed energy as a function of the pump energy.

4.2 Laser output characteristics

The experimental data for laser output energy are presented in fig. 4.

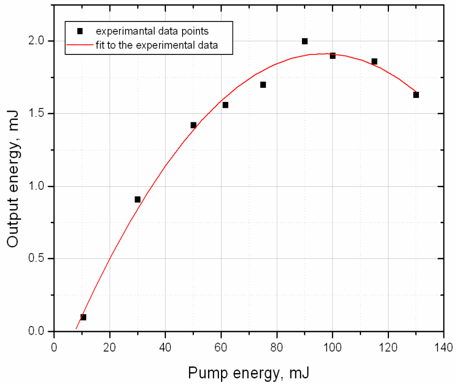

Fig. 4. Laser output pulse energy as a function of the pump energy.

Low laser threshold was achieved at 10.5mJ pump energy. Maximum conversion efficiency of 3% was measured for 30-50mJ pump energy. Suda et al. calculated the stored energy as a function of the pump energy and showed that, despite the linear increase of the absorbed energy with the pump energy, the stored energy in the gain medium saturates and becomes constant. The rollover in the output energy was observed in other Cr^{4+}:YAG laser experiments [3], [6], [7], [8] and was attributed to the rise of the pump and laser excited-state absorption (ESA) for higher pump pulse energies.

The build-up time and the laser pulse duration were measured with a high-speed InGaAs photo detector (fig. 5).

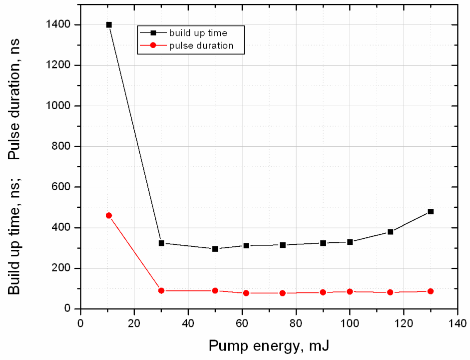

Fig. 5. Build-up time and pulse duration as a function of the pump energy.

The build-up time is almost constant for pump energies ranging from 30mJ to 100mJ. Slight decrease was observed for higher pump energies. The pulse duration is 70-90ns for pump energies between 30mJ and 130mJ. For an aerosol backscatter lidar application pulse duration of less than 100ns will permit range resolution better than 15m. The build-up time and the pulse duration can be further decreased by using a shorter and more efficient laser resonator.

5. OUTLOOK

Further optimization of the Cr^{4+}:YAG resonator has to be performed. We plan to build a linear resonator with curved output coupler with 2-3m radius of curvature. This design will insure better mode matching between the pump and laser beams in the crystal. The spot size of the laser wavelength will be between 1.4mm and 1.6mm. The optimal reflectivity of the output coupler has to be found experimentally. Demonstration of the tunability of the laser output over water vapour absorption lines is also planed using a 3-plate-birefringent filter.

6. CONCLUSION

Recent laboratory progress toward the development of a Cr^{4+}:YAG laser for lidar applications was presented. Further steps in the optimization of the laser performance were outlined and will be presented at the conference. In its final configuration, the laser transmitter will be tunable by means of intracavity frequency selective components and/or injection-seeding. The potential of this laser as eye-safe water vapour DIAL transmitter will be investigated by atmospheric measurements.

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