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High Power 1443.5 nm Laser with Nd:YAG Single Crystal Fiber

Han Rao, Zhaojun Liu *, Zhenhua Cong, Yang Liu, Yongyao Xie, Wenrui Li and Xingyu Zhang

School of Information Science & Engineering and Shandong Provincial Key Laboratory of Laser Technology and Application, Shandong University, Jinan 250100, China; raohan1992@163.com (H.R.); congzhenhua@sdu.edu.cn (Z.C.); yang890301@163.com (Y.L.); xieyongyao1@163.com (Y.X.); m15853278080_1@163.com (W.L.); xyz@sdu.edu.cn (X.Z.)

* Correspondence: zhaojunliu@sdu.edu.cn

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Abstract: A high-power eye-safe 1443.5 nm laser was demonstrated with an Nd:YAG single crystal fiber (SCF) as the gain medium. For continuous wave (CW) operation, a maximum output power of 13.3 W was obtained under an absorbed pump power of 95.0 W, corresponding to an optical-to-optical conversion efficiency of 14.0%. For acousto-optically (AO) *Q*-switched regime, an output power of 1.95 W was obtained at a pulse repetition frequency (PRF) of 10 kHz. The pulse duration was 69.5 ns. The pulse energy and peak power were calculated to be 195 μJ and 2.81 kW, respectively.

Keywords: single crystal fiber; Nd:YAG; eye-safe 1443.5 laser; laser diode

1. Introduction

The wavelength of 1.44 μm is located in the eye-safe wavelength region of 1.4–2.1 μm. In particular, the 1.44 μm is one of the absorption peaks of liquid water, with a high water absorption coefficient of 31 cm^{-1} [1]. Therefore, we call lasers operating at 1.44 μm eye-safe lasers because they will be absorbed by the frontal parts of the eye before they cause retina damage, and they can be used in the field of lidar [2]. In addition, they also have many important applications in the field of medicine, such as treatment of lipomas, as well as surgical and dermatological applications [3–7].

1.44 μm laser can be obtained directly from the $^4F_{3/2}$–$^4I_{13/2}$ transition of Nd^{3+}. So Nd:YAG crystal [8–14], Nd:YAP crystal [9], Nd:YAG ceramic [15], Nd:LuAG crystal [16], and so on are all good candidates for 1.44 μm laser operations. The first operation of diode-pumped 1.44 μm Nd:YAG laser was reported in 1994 by V. Kubecek [8]. A maximum CW output power of 69 mW at 1443 nm was obtained under an absorbed pump power of 2.39 W. In 1997, H.M. Kreschmann et al. demonstrated a 1444 nm Nd:YAG laser and a 1430 nm Nd:YAP laser with output powers of 4.9 W and 2.2 W, respectively [9]. To the best of our knowledge, this is the highest output power of a laser diode (LD) pumped 1.44 μm Nd:YAG laser. In 1998, A. Agnesi et al. reported a 1444 nm Nd:YAG laser with watt level output [10]. When pumped by a 10 W-808 nm LD, it generated 1 W CW and 560 mW active *Q*-switching output. In 2013, H.N. Zhang et al. reported a diode-pumped 1442.8 nm Nd:YAG ceramic laser for the first time [15]. They obtained a maximum output power of up to 3.96 W under a pump power of 20.7 W with an optical-to-optical efficiency of 19.1%. Recently, a passively *Q*-switched Nd:LuAG laser at 1442.6 nm was demonstrated by C. Guan et al. [16]. The maximum output power of the CW operation was 1.83 W with, by using a V^{3+}:YAG crystal wafer as the saturable absorber, a passively *Q*-switched output power of up to 424 mW. Since the stimulated emission cross section and quantum defect of the 1.44 μm are both far lower than that of the 1.06 μm, so the output power of most experiments is not very high at 1.44 μm.

To obtain higher output power at 1.44 μm, we put our focus on a novel geometry of Nd:YAG crystal, i.e., Nd:YAG single crystal fiber (SCF). The SCF is an end-pumped long and thin rod crystal, and is able to confine the pump radiation by guiding it with free-propagating signal. This geometry can easily be used to produce compact, high-power and highly efficient solid-state lasers. In recent years, scientists have done much research on 1064 and 946 nm lasers and amplifiers of Nd:YAG SCF [17–22]. While, Nd:YAG SCF laser emitting at 1.44 μm has not been reported yet.

In this paper, we demonstrated a high power 1443.5 nm laser by using Nd:YAG single crystal fiber as the laser medium. The maximum output power of the CW regime was as high as 13.3 W. It is 2.7 times as high as 4.9 W which is the highest output power ever reported at 1.44 μm. The absorbed pump power was 95.0 W, corresponding to an optical-to-optical conversion efficiency of 14.0%. In the experiment, we also studied output characteristics of AO *Q*-switched with three different pulse repetition frequencies (PRF). The maximum output power of 2.2 W was obtained at a PRF of 30 kHz. The highest peak power was achieved at a PRF of 10 kHz. The shortest pulse duration of 69.5 ns with single-pulse energy of 195 μJ and peak power of 2.81 kW were achieved at 10 kHz.

2. Experimental Setup

Figure 1 shows the experimental of the Nd:YAG SCF laser. The pumping source was a fiber-coupled CW 808 nm laser diode with a fiber core diameter of 400 μm and numerical aperture of 0.22. The maximum output power of the LD was 200 W. With an optical coupling system of 1:1 magnifying ratio, the pump beam was focused into the Nd:YAG SCF. The rear mirror (M1) coated for high-reflection (HR) at 1300–1500 nm ($R > 99.8\%$) and high transmission (HT) at 808 and 1064 nm ($T > 99.0\%$). The output coupler (OC) M2 was partial reflection (PR) coated at 1443.5 nm ($T = 10\%$) and HT at 1000–1350 nm ($T > 99.5\%$). The Nd:YAG SCF (0.2 at. % Nd-doped) was 50-mm-long with a diameter of 1 mm, and was fabricated by the micro-pulling down technique. Both incident and exit surfaces of the Nd:YAG SCF were HT coated at 808 nm. The Nd:YAG SCF was water cooled and the temperature was maintained at 20 °C.

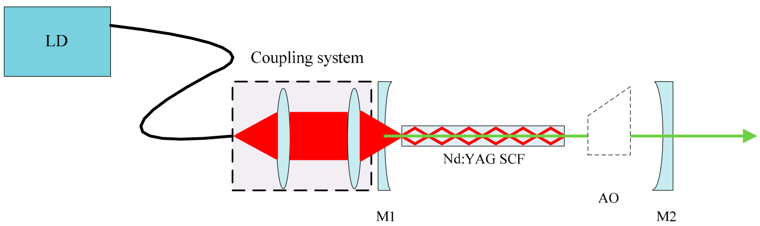

Figure 1. Schematic diagram of the 1443.5 nm Nd:YAG SCF laser.

3. Results and Discussion

To begin with, we studied the Nd:YAG SCF's absorption for the 808 nm pump laser. By measuring the power before and behind the SCF, the absorbed pump power was calculated; the results are shown in Figure 2. At an incident pump power of 162.0 W, the absorbed pump power was 121.0 W. The absorption efficiency was about 74.4%. The pump laser was not absorbed completely, primarily due to the low Nd^{3+} ion doping (0.2 at. %).

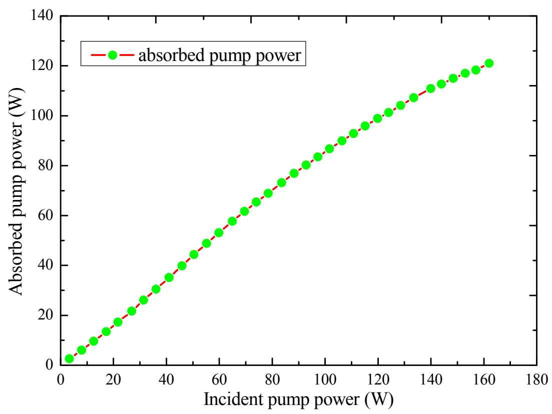

Figure 2. The Nd:YAG SCF's absorption for 808 nm pump laser.

The rear mirror and OC we selected were both HT at 1.06 and 1.1 μm to increase their loss in the cavity, while the OC was also HT coated at 1.3 μm. Therefore, in the experiment, we only observed 1.44 μm laser oscillation. Other possible wavelengths, such as 1.06, 1.1 and 1.3 μm, were suppressed successfully. The laser spectrum was studied with an Ando AQ-6370C analyzer. A resolution of 0.5 nm was selected for the equipment. The results at the highest output powers of 13.3 W are shown in Figure 3. Only the 1443.5 nm laser was observed.

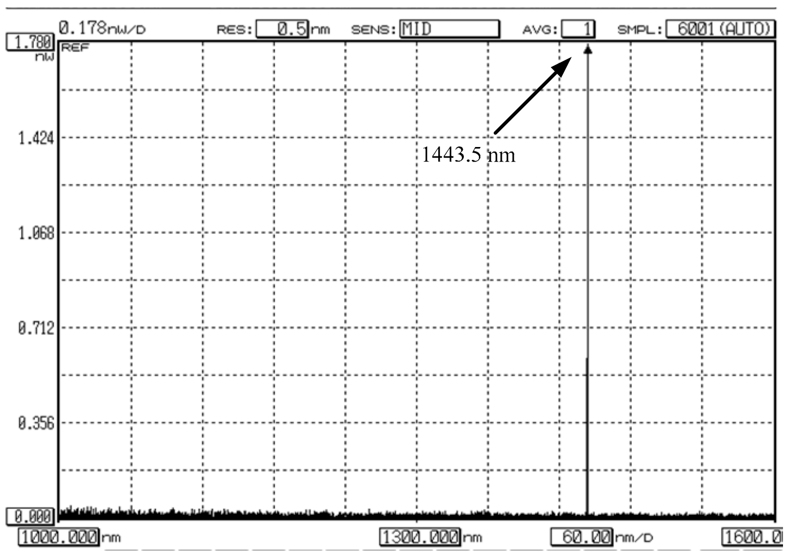

Figure 3. The optical spectrum of the Nd:YAG SCF laser.

We studied the CW output characteristics of the 1443.5 nm laser. The overall cavity length was 55 mm. By using a plane rear mirror, we studied the output characteristics with four different OCs at a certain transmission of 10%. The output powers are shown in Figure 4. The horizontal axis shows absorbed pumping power. The output powers were measured using an EPM2000 power meter and a PM200 detector. A dichroic mirror coated for HR at 1.44 μm ($R > 99.5\%$) and HT at 0.8 μm ($T > 99.0\%$) was used to separate the 1.44 μm laser from the 0.8 μm pump laser.

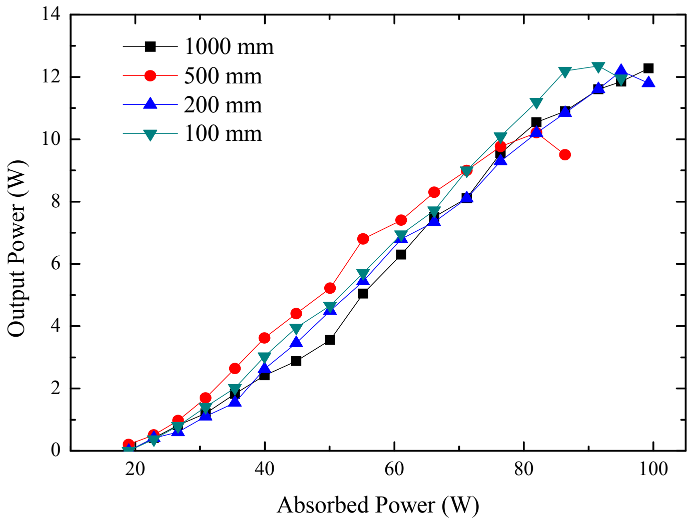

Figure 4. Output power of the Nd:YAG SCF laser with four different OCs; (Curvature radius: 1000, 500, 200 and 100 mm).

We selected four plano-concave mirrors as the OC. The maximum output powers of 12.28, 10.21, 12.20 and 12.35 W were obtained with curvature radii of 1000, 500, 200 and 100 mm, respectively. It was found that the OC with a curvature radius of 100 mm was the most appropriate one. A saturation phenomenon was observed above 95.0 W of absorbed pump power. Thermal effects of the SCF could influence the stabilization of the resonating cavity. With pump power increasing, thermal effects became more and more serious. When the cavity came to a critical status, output power would show saturation.

By using the OC with a curvature radius of 100 mm and transmittance of 10%, we tried another two rear mirrors with different curvature radii. The output power results are shown in Figure 5.

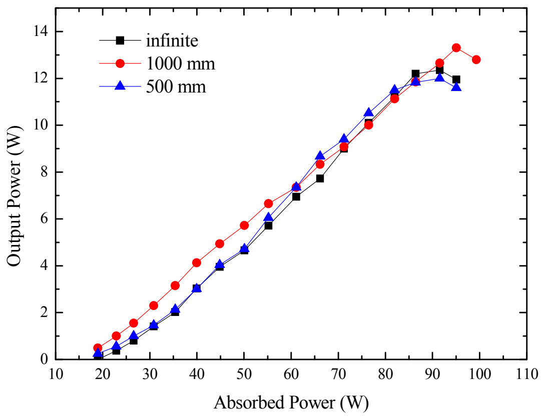

Figure 5. Output power of the Nd:YAG SCF laser with three different rear mirrors; (Curvature radius: infinite, 1000 and 500 mm).

From the results, we found that the increasing trend of output powers is similar. Output power saturation with different rear mirrors was not the same. The highest output power of 13.3 W was obtained with a curvature radius of 1000 mm. The optical-to-optical conversion efficiency was 14%, which was lower than the result of 19.1% in [15]. The Nd:YAG SCF we used was not HT coated at 1.44 μm on both surfaces, which may be the main reason for the lower efficiency. We believe that if both surfaces of the SCF were HT coated at 1.44 μm, the output power and efficiency would be further increased.

The same cavity of CW operations was employed for *Q*-switched laser. The only difference was that a 46 mm-long AO *Q*-switch was inserted between the SCF and OC. This AO *Q*-switch was designed for 1.3 μm laser. The overall cavity length was 100 mm. The laser pulse signal was detected by an InGaAs detector connected to an oscilloscope (Tektronix TDS 5032B). The peak power and average power as a function of the absorbed pump power for the different PRFs are shown in Figure 6.

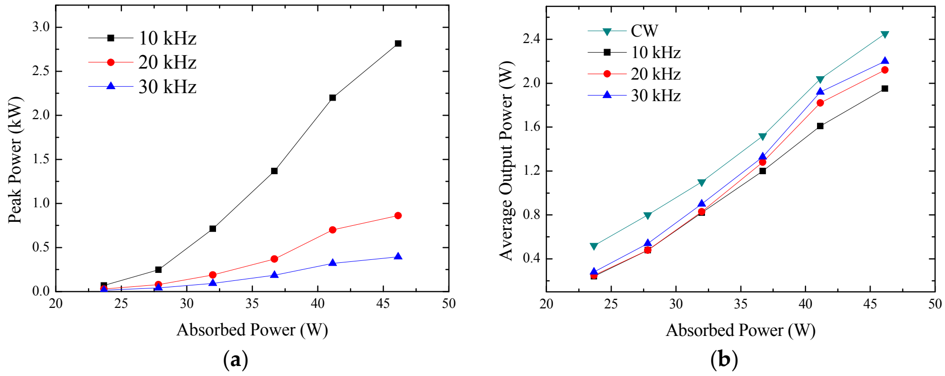

Figure 6. Peak power (**a**) and average power (**b**) versus absorbed power at different PRFs.

The maximum peak powers for PRFs of 20 and 30 kHz were 0.86 kW and 0.39 kW, corresponding to pulse energies of 106 μJ and 73.3 μJ, respectively. The highest peak power of 2.81 kW and pulse energy of 195 μJ were obtained at 10 kHz. From Figure 5b, we can see that, at certain levels of absorbed power, the higher the PRF, the higher the average output power. The maximum average output power for PRFs of 10, 20 and 30 kHz were 1.95, 2.12 and 2.20 W, respectively. With the pump power increasing further, the thermal effects became serious, and an unstable *Q*-switching signal was observed.

Figure 7 shows the dependence of the pulse width on the absorbed pump power with different PRFs. The pulse widths decreased with increasing absorbed power. The shortest pulse of 69.5 ns was achieved at a PRF of 10 kHz. A typical pulse trace is shown as the inset of Figure 6.

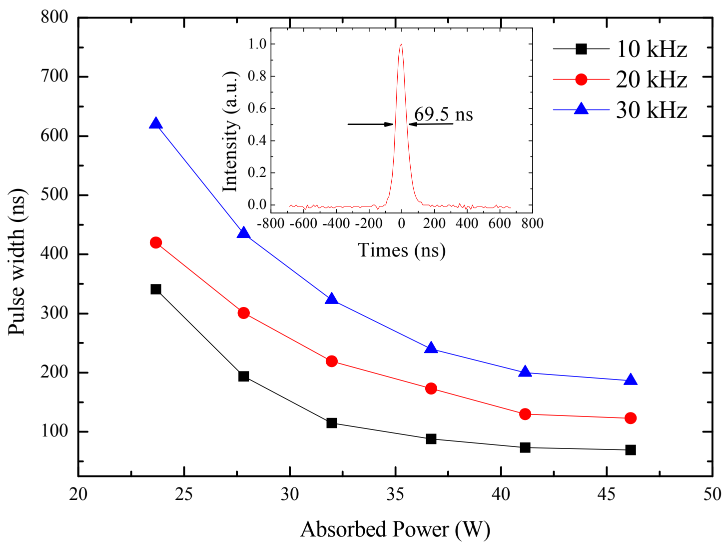

Figure 7. Pulse width versus absorbed powers for different PRFs. Inset: typical pulse trace.

We found that, even if the Nd:YAG SCF we used was not HT coated at 1.44 μm, we still achieved high output power. This could be attributed to the special structure of SCF. The relatively thin and long rod geometry of SCF could confine the pump beam by guiding. High pump power could be absorbed over a long distance, instead of within only several millimeters, as occurs in diode-end-pumped bulk crystals. This structure allowed low doping concentration, e.g., at only 0.2 at.% in this report, to realize high absorption. In our experiments, the quantum defect-induced thermal load was distributed throughout the crystal, which was, overall, 50 mm in length. This would help to guarantee good thermal management. Therefore, we were able to achieve a high output power laser. In future experiments, a Nd:YAG SCF with HT coated at 1.44 µm would make a contribution to higher output power, and we need an AO module designed for 1.44 µm for the *Q*-switched operation. In the experiments above, all the OCs we employed were coated for transmittance of 10%, and might not be the optimal transmittance for a 1.44 µm laser. Next, we could try various OCs with different transmittances, to obtain better results of 1.44 µm laser.

4. Conclusions

We demonstrated high power 1443.5 nm laser operations, both in CW and AO *Q*-switched regimes, based on a Nd:YAG SCF. The maximum CW output power of 13.3 W was obtained with an optical-to-optical conversion efficiency of 14.0%. During AO *Q*-switched operation, a maximum output power of 2.2 W was obtained at the PRF of 30 kHz. The highest peak power was achieved at a PRF of 10 kHz. The shortest pulse duration was 69.5 ns with single-pulse energy of 195 µJ and peak power of 2.81 kW, respectively.

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Conflicts of Interest: The authors declare no conflict of interest.

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