DOI 10.1007/s10946-019-09804-5
Journal of Russian Laser Research, Volume 40, Number 3, May, 2019

PASSIVE Q-SWITCHED OPERATION OF A c-CUT $Tm,Ho:LuVO_4$ LASER WITH A FEW-LAYER WSe_2 SATURABLE ABSORBER

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Abstract

We demonstrate experimentally a passive Q-switched (PQS) operation of 2 μm c-cut $Tm,Ho:LuVO_4$ laser with a WSe_2 saturable absorber (SA) mirror. We obtain an average output power of 500 mW with a pulse width of 3.5 μs at 116.6 kHz and a pump power of 13.03 W. We measure the output wavelengths of the $Tm,Ho:LuVO_4$ laser to be 2,075.8 nm at the continuous-wave (CW) mode operation and 2,056.9 nm at the PQS mode operation. The beam quality factors $M_x^2 = 1.11$ and $M_y^2 = 1.06$ are obtained in the PQS $Tm,Ho:LuVO_4$ laser.

Keywords: PQS, WSe_2 SA, $Tm,Ho:LuVO_4$ crystal.

1. Introduction

In recent years, an increasing number of pulse lasers operating at 2 μm have attracted much attention in the fields of medicine, optical communications, remote sensors, radars, and gas detection due to their strong absorption properties in water and human tissue [1–4]. Active and passively Q-switched technologies are commonly used to achieve pulse laser generations. Compared with active Q-switched technology, the PQS technology with a SA has been shown to be an inexpensive, simple, and efficient method to acquire the pulse laser. Since the appearance of graphene, many new two-dimensional (2D) materials with good optical performances, for example, BP, MoS_2, WS_2, and WSe_2, have been prepared

Manuscript submitted by the authors in English on May 26, 2019.

as SAs to replace the conventional SAs; they have been demonstrated in the infrared laser range at wavelengths of 1–3 μm.

In 2015, a PQS Yb:CYA laser with a BP-SAM was developed; it had a pulse width of 620 ns and an average output power of 37 mW at 113.6 kHz with an output wavelength of 1,046 nm [5]. In 2018, a PQS Tm,Ho:YAP laser with a MoS_2 SA was proved to have the beam quality factors $M_x^2 = 1.06$ and $M_y^2 = 1.06$, an average output power of 3.3 W, and a per pulse energy of 23.31 μJ was achieved at 2,000.4 nm with a narrowest pulse width of 1.64 μs at 110 kHz [6]. A PQS Tm,Ho:YAP with a WS_2 SA mirror has also been demonstrated with a 696-mW average output power and a 1.79 W peak power corresponding to pulse widths of 5.6 μs [7]. A PQS fiber laser based on the WSe_2 SA also showed a 26.7 mW average output power and a 1.2 μs pulse width at 242 kHz with a pulse energy of 110 nJ [8].

$LuVO_4$ is of particular interest as a laser host material because it is suitable for doping or codoping of rare earth ions, such as Ho:LVO_4 and Tm,Ho:$LuVO_4$ [9]. Compared with other vanadate crystals, $LuVO_4$ crystals have larger absorption and emission cross sections in the range of 800 nm and 1.064 μm, respectively [10]. Also, various Ho:$LuVO_4$ lasers, for example, CW, Q-switched, actively mode-locked and single-longitudinal mode Ho:$LuVO_4$ lasers, have been proposed [9, 11–13], which shows that $LuVO_4$ crystals are an attractive host material in the 2 μm wavelength range.

In 2018, we demonstrated an AO Q-switched Tm,Ho:$LuVO_4$ laser [14]. An average output power of 3.77 W was achieved at 10 kHz with a 14.7 W pump power, and a 2.54 mJ pulse energy was obtained at 1 kHz with a pulse width of 69.9 ns. Also, we have demonstrated a PQS Tm,Ho:$LuVO_4$ laser with a graphene SA [15]. An average output power of 1,034 mW was obtained at 2,057.03 nm with a narrowest pulse width of 300 ns at 54.5 kHz.

In this work, we prepared a SA mirror with the 2D material of WSe_2 and presented a high beam quality PQS Tm,Ho:$LuVO_4$ laser with a WSe_2-based SA mirror. In the PQS operation mode, we obtained an average output power of 500 mW with a 3.5-μs pulse width at 116.6 kHz with a pump power of 13.03 W. Also, we achieved an output wavelength of 2,075.8 nm in the CW operation mode and an output wavelength of 2,056.9 nm in the PQS operation mode from the Tm,Ho:$LuVO_4$ laser in our experiments. The beam quality factors $M_x^2 = 1.11$ and $M_y^2 = 1.06$ were obtained in the PQS operation mode.

2. Experimental Setup

The experimental schematic diagram of a PQS Tm,Ho:$LuVO_4$ laser is shown in Fig. 1. A straight-type laser resonant cavity with a physical length of 45 mm was used; it consisted of a high-reflectivity laser mirror (HR), a laser crystal, and an output couple (OC) mirror. These components were designed to achieve a compact and stable structure. The $^5I_7 \rightarrow ^5I_8$ laser transition of Ho^{3+} in the Tm,Ho:$LuVO_4$ crystal was used to achieve a 2 μm wavelength-range laser emission in the experiment. The laser crystal used was grown in the Institute of Optics and Fine Mechanics in Shanghai, China and was codoped with 5 at.% Tm^{3+} and 0.5 at.% Ho^{3+}. The crystal was cut along with the c axis with a length of 7 mm and had a cross section of 4×4 mm.

The laser crystal was put in a Dewar filled with liquid nitrogen to alleviate the thermal effect of the crystal. HR was a flat–concave mirror with a 300-mm radius of curvature, the double faces of which were coated with a high transmittance material at 790–810 nm. The concave face was also coated with a high-reflectivity material at 2,000 − 2,100 nm. OC was a flat mirror, one face of which was coated with a low transmittance film (2% transmittance) at 2,000 − 2,100 nm. The pump light was from a laser diode (LD, nLight Corp. NL-PPS50-10030) with a center output wavelength of 800 nm, which was coupled by a fiber with a core diameter of 400 μm and a numerical aperture of 0.22. In the experiment, the LD temperature was set to be 303.15 K to achieve the optimum pump wavelength.

The collimator lens (L1) had a focal length of 25 mm, and the focus lens (L2) had a focal length of 50 mm, which were chosen to obtain the optimum pump-spot size at one end face of the laser crystal (0.8 mm). The laser beam radius in the two mirrors (HR and OC) and laser crystal were calculated to be 287.4, 264.8, and 271.8 μm, respectively, in view of the ABCD matrix at a physical cavity of 45 mm. The WSe_2-based SA mirror prepared was put into the laser cavity located between the laser crystal and OC (near OC) with a laser beam radius of 264.8 μm at the surface of the WSe_2 SA mirror. The mirror made from CaF_2 crystal was used as the SA substrate, and a WSe_2 crystal was chosen as the SA material. The WSe_2 material, dissolved in ethyl alcohol, was coated onto the surface of one face at the CaF_2 mirror using a spin coating machine (KW-4A, Chinese Academy of Sciences).

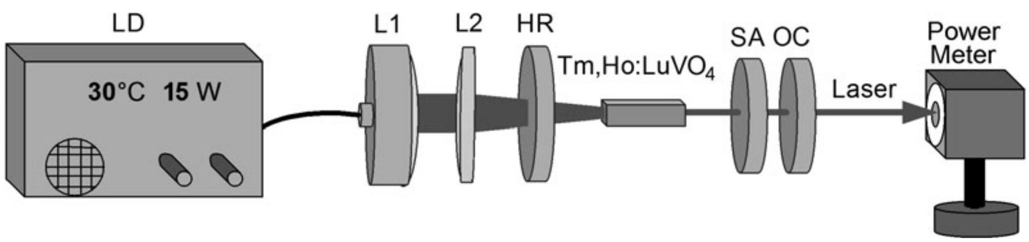

Fig. 1. LD-pumped PQS Tm,Ho:$LuVO_4$ laser with WSe_2 as a SA.

3. Experimental Results and Discussion

An OC with a transmittance of 2% was used in the experiment with a pump power of 13.03 W. Figure 2 shows the output power of Tm,Ho:$LuVO_4$, equal to 1.29 W in the continuous-wave (CW) operation mode. A 0.5 W average output power in the PQS-operation mode was achieved from the Tm,Ho:$LuVO_4$ laser with optical–optical conversion efficiencies of 9.9% and 3.8%, respectively.

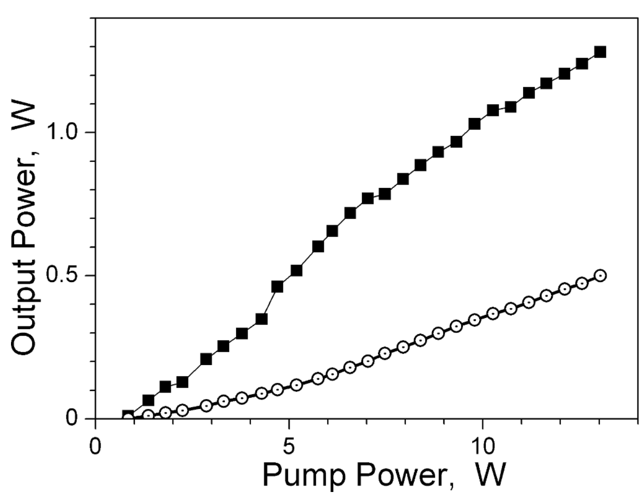

Fig. 2. The output power of the Tm,Ho:$LuVO_4$ laser in CW (■) and PQS (⊙) modes.

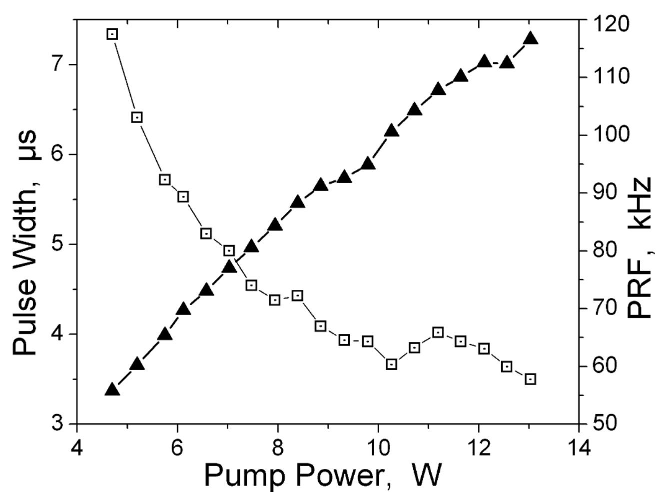

Fig. 3. The pulse width (⊡) and PRF (▲) of the PQS Tm,Ho:$LuVO_4$ laser.

In the PQS operation mode, the pulse width and pulse repetition frequency from the Tm,Ho:$LuVO_4$ laser are shown in Fig. 3. In Fig. 3, we see that the pulse width decreases with increase in the pump power, but the pulse repetition frequency (PRF) increases. We employed an oscilloscope (Tektronix, DPO4104) with a 1 GHz bandwidth and a detector (Thorlabs, PDA10PT-EC) with a bandwidth up to 1600 kHz to measure the pulse width and the PRF of the PQS Tm,Ho:$LuVO_4$ laser. When the pump power was 13.03 W, a pulse width of 3.5 μs was obtained, which corresponded to a PRF of 116.6 kHz. In Fig. 4, we show two typical pulse trains captured in the experiment. When the average output power of the PQS Tm,Ho:$LuVO_4$ laser was 229 mW with a pump power of 7.47 W, time scales were recorded at 20 and 40 μs with a pulse width/PRF of 4.59/80.13 and 4.5/80.52 μs/kHz, respectively.

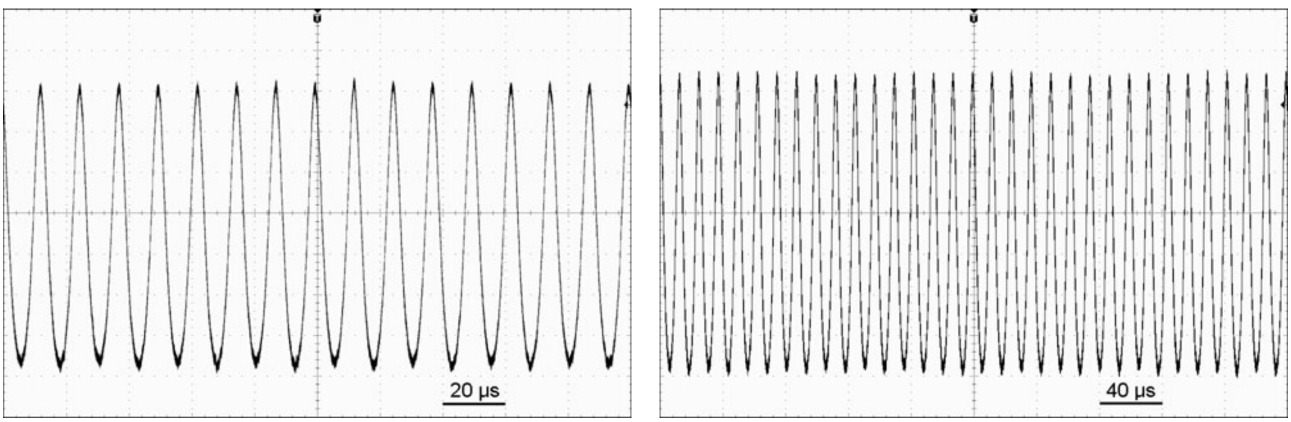

Fig. 4. Typical pulse trains of the Tm,Ho:$LuVO_4$ laser at 20 μs (left) and 40 μs (right) time scales.

A laser wavelength meter (721A IR) was used to measure the output wavelength of the Tm,Ho:$LuVO_4$ laser. The output wavelengths of the Tm,Ho:$LuVO_4$ laser in the CW and PQS operation modes are shown in Fig. 5. An output wavelength of 2,075.8 nm was obtained in the CW operation mode, and an output wavelength of 2,056.9 nm was obtained in the PQS operation mode. The output wavelength of the Tm,Ho:$LuVO_4$ laser in the CW mode was longer than that of the same laser in the PQS operation mode, because the operation threshold of the energy stored in the crystal under the PQS mode far exceeded that under the CW mode.

A slit scanning beam profiler (BP109-IR2) was used to measure the beam quality of the Tm,Ho:$LuVO_4$ laser (Thorlabs Inc., USA); as a result we obtained the 2D and 3D laser profiles of the output beam from the Tm,Ho:$LuVO_4$ laser (Fig. 6). Also, the beam quality factors $M_x^2 = 1.11$ and $M_y^2 = 1.06$ were obtained from the PQS Tm,Ho:$LuVO_4$ laser.

4. Summary

In conclusion, we prepared for the first time a WSe_2 SA mirror and experimentally demonstrated a high-beam-quality Tm,Ho:$LuVO_4$ laser in the PQS operation mode. We achieved 500 mW average output power and 4.29-μJ per pulse energy with a pulse width of 3.5 μs at 116.6 kHz. Also, the beam quality factors $M_x^2 = 1.11$ and $M_y^2 = 1.06$ were obtained from the PQS Tm,Ho:$LuVO_4$ laser.

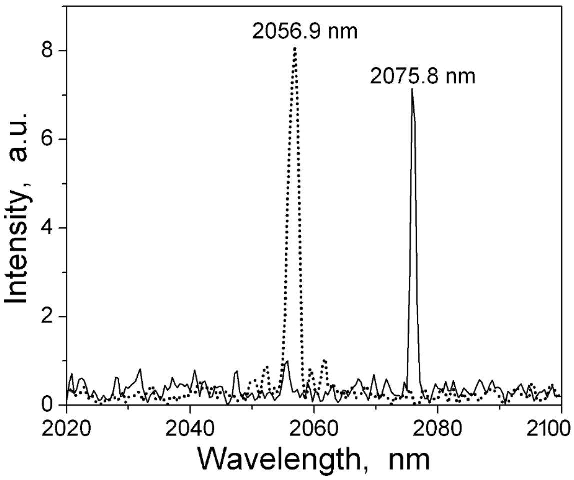

Fig. 5. The output wavelengths of Tm,Ho:$LuVO_4$ laser in the CW (solid curve) and PQS (dotted curve) operation modes.

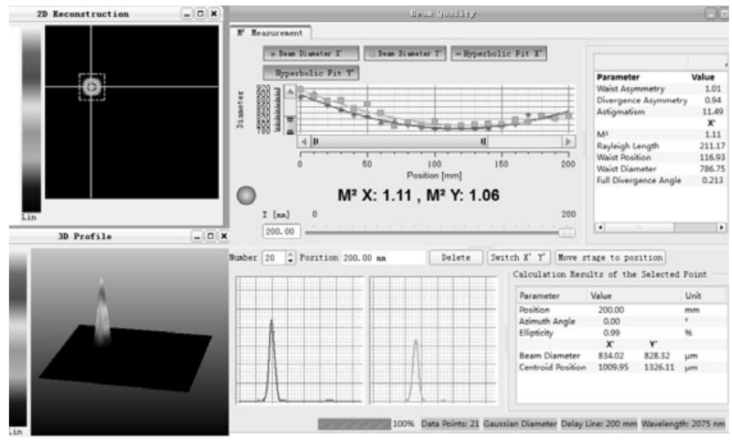

Fig. 6. The beam quality of the Tm,Ho:$LuVO_4$ laser.

Acknowledgments

This work was supported by the National Natural Science Foundation of China under Projects Nos. 61775053 and 51777046.

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