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Passively Q-switched Nd:$GdYTaO_4$ laser based on two-dimensional MoS_2 saturable absorber

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ABSTRACT

We presented a LD-pumped passively Q-switched Nd:$GdYTaO_4$ laser based on the two-dimensional (2D) MoS_2 for the first time. The continuous-wave (CW) Nd:$GdYTaO_4$ laser without the MoS_2 was firstly investigated. The highest output power reached 5.24 W with the slope efficiency of 41%. Next, by using the 2D MoS_2 nanosheet as the saturable absorber, the passively Q-switched Nd:$GdYTaO_4$ laser was researched. The maximum average output power of the pulse laser was 112 mW at 1066 nm. The corresponding pulse width, repetition rate, pulse energy, and pulse peak power were 2.2 µs, 250 kHz, 0.39 µJ, and 0.18 W, respectively.

1. Introduction

For the diode pumped solid state lasers (DPSSLs), Nd^{3+} doped crystal is widely used for near infrared laser generation [1–6]. In these crystals, Nd:$GdTaO_4$ has proven itself as a brilliant laser material operating at 1066 nm [7–9]. To improve the laser performance of Nd:$GdTaO_4$, the mixed crystal of Nd:$GdYTaO_4$ was grown successfully by Peng et al. in 2015 [10]. The disordered characteristic of mixed crystal leads to an obvious broadening in the absorption bandwidth. Therefore, it could improve the laser efficiency. Nd:$GdYTaO_4$ mixed crystal has a absorption bandwidth of 12 nm. For comparison, the absorption bandwidth of Nd:$GdTaO_4$ and Nd:YAG crystals were 6 nm and 0.8 nm, respectively [10,11]. Furthermore, Nd:$GdYTaO_4$ mixed crystal has a upper-level lifetime of 182 µs and an emission cross section of 2.2×10^{-19} cm^2. From above, we can see that Nd:$GdYTaO_4$ mixed crystal has some attractive advantageous to be used as laser medium. Peng et al. demonstrated the continuous-wave (CW) operation of the 808-nm-pumped Nd:$GdYTaO_4$ laser and achieved up to 2.37 W of CW laser at 1066.5 nm, corresponding to a slope efficiency of 38% [10]. Further, by using actively electro-optical cavity-dumped *Q*-switched technique, Wu et al. realized an 879-nm laser diode (LD) pumped pulsed Nd:$GdYTaO_4$ laser. The pulse width of 3.4 ns was obtained at a *Q*-switching repetition rate of 20 kHz [12].

Compared with actively Q-switching technology, passively Q-switching method has the merits of obviously simplicity, compactness and lower cost [13–16]. Ma et al. presented the passively *Q*-switched operations of the Nd:$GdYTaO_4$ laser. By using the Cr^{4+}:YAG saturable absorber, an average output power of 2.26 W was obtained under a pumping power of 16.2 W in the passively *Q*-switched operation [17]. Recently, the two-dimensional (2D) material has shown great interest in lasers due to their ultrafast recovery time, wide operation spectral range and ultrathin thickness [18–21]. Among the 2D materials, compared with the commonly used graphene, MoS_2 (molybdenum disulfide) has larger modulation depth at broadband wavelength and naturally controllable bandgap [22], which is suitable as the saturable absorber for passively Q-switched laser [23,24].

In this paper, a novel passively Q-switched 808-nm LD-pumped Nd:$GdYTaO_4$ laser based on the 2D MoS_2 nanosheet was presented for the first time to the best of knowledge. We firstly investigated the continuous-wave (CW) Nd:$GdYTaO_4$ laser without the MoS_2 saturable absorber. Via optimizing the transmission of the output coupler, the maximum CW power reached 5.24 W at 1066 nm with a high slope

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efficiency of 41%. Subsequent experiments are carried out to explore the characteristics of the passively Q-switched Nd:$GdYTaO_4$ laser. The 2D MoS_2 nanosheet was adopted as the saturable absorber. With the maximum absorbed pump power of 4.39 W, the average output power, repetition rate, pulse energy, and pulse peak power achieved maximum and the values were 112 mW, 250 kHz, 0.39 µJ, and 0.18 W, respectively. And the corresponding pulse width reached the minimum value of 2.2 µs.

2. Experimental setup

The pumping source was a fiber-coupled laser diode (LD) emitting at 808 nm. The core diameter of fiber was 400 µm and the N.A. was 0.22. L_1 and L_2 were plano-convex lenses with focal length of 26.7 mm and 42.7 mm, respectively, which were used for coupling the pump beam into the Nd:$GdYTaO_4$ mixed crystal with a beam waist of 320 µm. The Nd^{3+} doping concentration in gain medium of Nd:$GdYTaO_4$ mixed crystal was 1%. The crystal had a dimension of $2 \times 2 \times 5\ mm^3$. Two plano-plano mirrors of M_1 and M_2 were used to construct the laser resonator and the cavity had 40 mm in length. The M_1 was antireflection-coated at 808 nm and high-reflection-coated at 1066 nm. The M_2 output coupler had different transmissions at 1066 nm. The whole system was presented in Fig. 1.

The 2D MoS_2 nanosheet was used as the saturable absorber, whose substrate was sapphire. The modulation depth of MoS_2 was 16.7%, and corresponding saturation power intensities and non-saturable losses were 121.3 MW/cm^2 and 8.9%.

3. Results and discussion

3.1. CW operation

Without the 2D MoS_2 nanosheet, the CW Nd:$GdYTaO_4$ laser was investigated firstly. The dependence of the CW output power on the absorbed pump power was shown in Fig. 2. The transmission of the output couplers T was varied as 2%, 5%, and 10% at 1066 nm. It can be found that the threshold absorbed pump power was 1.92 W, 1.71 W and 2.53 W, respectively. Linear fit of the measured data showed that the slope efficiency η_s was 30%, 41% and 40% for output coupler transmission of 2%, 5%, and 10%, respectively. Results indicated that the optimal output coupler transmission was 5%. When the absorbed pump power is 14.2 W, the maximum CW output power of 1066 nm laser reached 5.24 W with the optical-optical conversion efficiency of 37%, which proved the high efficiency of the Nd:$GdYTaO_4$ mixed crystal. The laser beam quality factor M^2 was measured to be 4.1 at the maximum output power.

3.2. Passively Q-switched operation

As a next step, the passively Q-switched operation of Nd:$GdYTaO_4$ laser was investigated in our experiments. The 2D MoS_2 nanosheet was employed as the saturable absorber and the output coupler transmission was set to 5%. The other experimental conditions were the same as in the previous case. The average output power of the pulsed Nd:$GdYTaO_4$ laser as functions of the absorbed pump power was shown in Fig. 3. The maximum average output power of 112 mW was achieved when the absorbed incident pump power was 4.39 W with the slope efficiency of

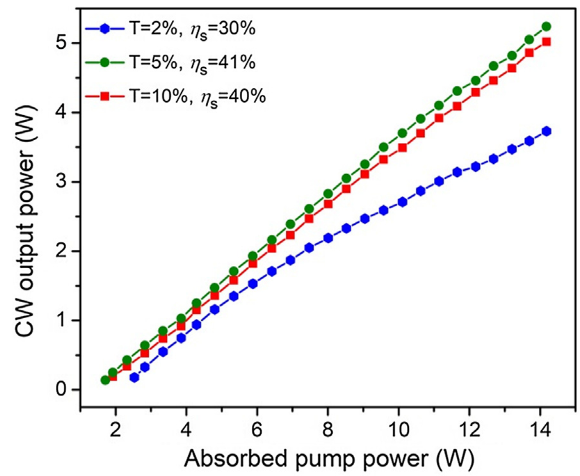

Fig. 2. Continuous-wave (CW) output power on the basis of absorbed pump power.

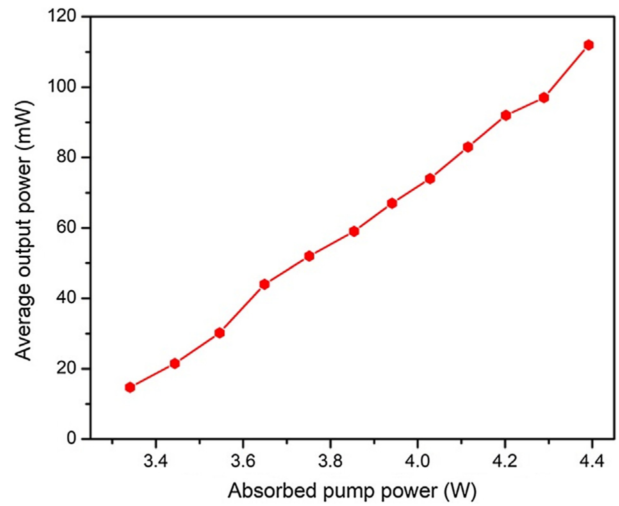

Fig. 3. The average output power on the basis of absorbed pump power.

9.5%. No roll-off in average output power was observed indicating that further power scaling might be possible with the availability of higher absorbed pump power. However, considering the low damage threshold of MoS_2 nanosheet, the pump power didn't continue to increase. The measured beam quality factor M^2 was ~1.8 at the maximum average output power of 112 mW. The laser power instability was less than 5% for both CW and passively Q-switched operations.

The pulse width and repetition rate of the passively Q-switched Nd:$GdYTaO_4$ laser were investigated and presented in Fig. 4. We observed that the pulse width decreased with the absorbed pump power improving. When the absorbed pump power exceeded 4.0 W, the pulse width was nearly unchanged. With the maximum absorbed pump power, the pulse duration of the passively Q-switched Nd:$GdYTaO_4$ laser was 2.2 µs and a temporal pulse profile with a pulse width of 2.2 µs was also shown in Fig. 4. Obviously, as pump power improved, the

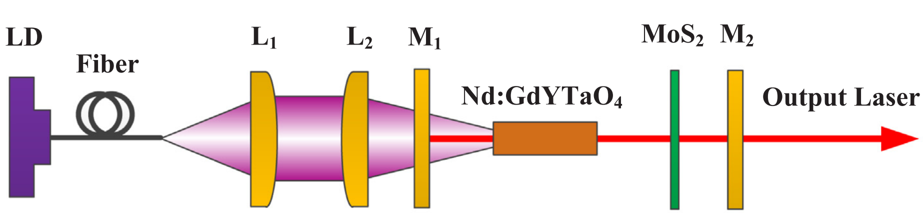

Fig. 1. Schematic of passively Q-switched 1066 nm Nd:$GdYTaO_4$ laser.

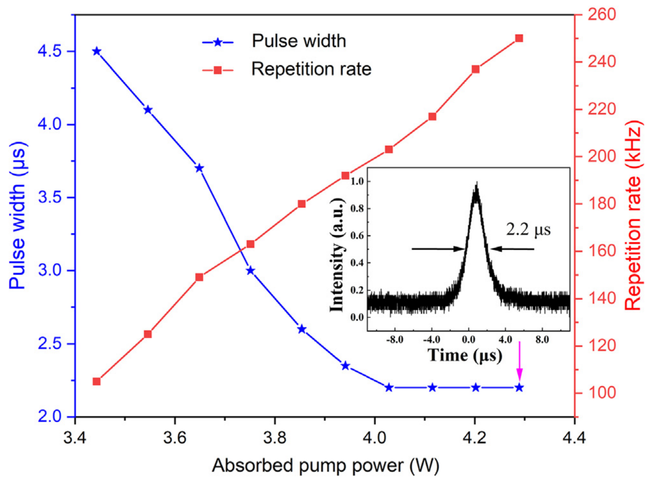

Fig. 4. The pulse width and repetition rate on the basis of absorbed pump power. Inset: the pulse shape at 4.39 W.

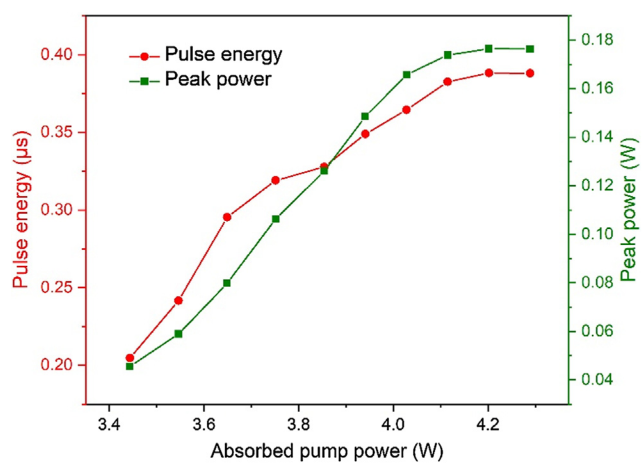

Fig. 5. The pulse energy and peak power on the basis of absorbed pump power.

repetition rate correspondingly increased linearly. The repetition rate grew from the minimum value of 105 kHz to the maximum value of 250 kHz when the absorbed pump power was 4.39 W.

We also studied the pulse energy and pulse peak power of the passively Q-switched Nd:GdYTaO$_4$ laser. The results were summarized in Fig. 5. It can be seen that both pulse energy and peak power increased with the growth of the absorbed pump power. And when the pump power was more than 4 W, the pulse energy and pulse peak power approached to saturation. When the absorbed pump power was 4.39 W, the maximum pulse energy and pulse peak power were 0.39 μJ and 0.18 W, respectively.

4. Conclusion

In summary, we demonstrated a passively Q-switched laser using novel Nd:GdYTaO$_4$ mixed crystal and MoS$_2$ saturable absorber for the first time. Firstly, in the study of CW Nd:GdYTaO$_4$ laser without the MoS$_2$ saturable absorber, the highest output power 5.24 W was obtained and the corresponding slope efficiency was 41% with the optimal output coupler transmission of 5%. This result indicated that the Nd:GdYTaO$_4$ mixed crystal had potential to be a high efficiency laser gain medium. And then the passively Q-switched Nd:GdYTaO$_4$ laser was investigated. The 2D MoS$_2$ nanosheet was adopted as the saturable absorber. With the absorbed pump power growing, the average output power, repetition rate and pulse peak power increased and the pulse width decreased. When the pump power is 4.39 W, the maximum average output power, repetition rate, pulse energy, and pulse peak power were 112 mW, 250 kHz, 0.39 μJ, and 0.18 W, respectively. And the minimum pulse width was 2.2 μs.

Declaration of Competing Interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

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