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Passively Q-switched diode-pumped Tm, Ho:$LuVO_4$ laser with a black phosphorus saturable absorber*

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We presented a passively Q-switched (PQS) diode-pumped c-cut Tm, Ho:$LuVO_4$ laser with a black phosphorus saturable absorber for the first time. Under PQS mode, an average output power of 0.86 W and a peak power of 2.32 W were acquired from the Tm, Ho:$LuVO_4$ laser with the pump power of 14.55 W, corresponding to a pulse width of 2.89 μs, a pulse repetition rate of 71.84 kHz, and a pulse energy of about 6.70 μJ.

Keywords: passively Q-switched (PQS) technology, Tm, Ho:$LuVO_4$ crystal, pulse width

PACS: 42.60.Gd, 42.55.Rz, 42.70.Hj **DOI:** 10.1088/1674-1056/ab33f1

1. Introduction

The 2-μm laser radiation has high atmospheric transmittance and overlaps with the absorption bands of many molecules. Hence 2-μm lasers could be used in many application fields such as ranging, material processing, lidar, and space optical communication.[1–5] Especially, pulsed 2-μm laser can pump the optical parametric oscillators (OPOs) to obtain the middle infrared laser.[6] The Q-switching technology is an excellent way to obtain high density and efficiency pulsed laser radiations. It has been widely researched and applied in various technical fields. Among many Q-switching methods, the passively Q-switched (PQS) technology is an efficient and compact approach to generate the pulsed laser radiations. Therefore, PQS 2-μm lasers have been widely investigated in the past few years.

Recently, many two-dimensional (2D) materials such as graphene,[7] transition metal disulfides,[8–11] and topological insulators[12] were employed as the saturable absorber (SA) to achieve Q-switching thulium (Tm) or holmium (Ho)-doped lasers at 2-μm. Compared with the above materials, black phosphorus (BP) with distinctive structure and properties[13,14] is an attractive and promising 2D material as a passive Q-switch SA. Furthermore, it has a wide transmission range, which is very suitable to apply in mid-infrared laser.[15,16] Moreover, BP has an adjustable band gap and a high light absorption.[17] The direct bandgap structure of BP does not change with the number of layers, resulting in strong photon absorption and great modulation depth.[18]

In this work, we presented a diode-pumped 2-μm Tm, Ho:$LuVO_4$ laser passively Q-switched by a few-layer BP SA for the first time. Under an absorbed pump power of 14.55 W and an output transmittance of 2%, the passively Q-switched Tm, Ho:$LuVO_4$ laser produced a maximum average output power of 860 mW, a pulse width of 2.89 μs, and a pulse repetition rate of 71.84 kHz, corresponding to the calculated pulse energy of 6.70 μJ and peak power of 2.32 W.

2. Experimental setup

We used an 800 nm fiber-coupled laser diode (LD) as the pump source which has the core diameter of 400 μm and the numerical aperture of 0.22, and pump wavelengths in different pump powers are shown in Fig. 1. Figure 2 schematically illustrates the experimental setup of the passively Q-switched c-cut Tm, Ho:$LuVO_4$ laser end-pumped by a LD. A telescope consisted of two lenses L1 and L2 with focal lengths of 25 mm and 50 mm. The Tm, Ho:$LuVO_4$ crystal with doping concentration of Tm 5 at.% and Ho 0.5 at.% was used in this experiment. Its dimensions were 4 mm×4 mm in cross section and 8 mm in length. The laser crystal was wrapped with 0.1 mm-thick indium foils in a copper heat sink. The temperature of the heat sink was controlled at 77 K by a dewar with liquid nitrogen. The L-shaped cavity included 0° dichromic mirror M1, 45° dichromic mirror M2, and an output coupler M3 to filter out the pump light that was not absorbed by the laser crystal. The mirror M1 was a plano-concave mirror with a curvature radius of 400 mm, which was coated for high transmission at

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the pump wavelength and high reflectivity at the resonating wavelength. The flat mirror M2 was coated for high transmission at the pump wavelength and high reflectivity at the resonating wavelength. The output coupler M3 was a flat mirror with an output transmittance of 2%. The BP SA was inserted into the cavity close to the output coupler M3. The stable passively Q-switching pulse could be obtained by adjusting the position and incident angle of the SA. The physical length of the whole cavity was 23 mm. The pump diameter of 0.8 mm was focused into the laser crystal by L1, L2, and M1. The single-pass pump absorption of 95% in the Tm, Ho:$LuVO_4$ crystal was measured at 77 K.

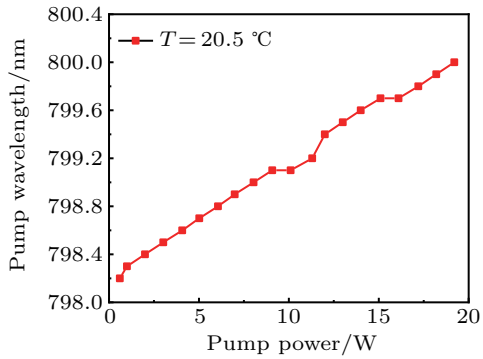


Fig. 1. Pump wavelengths of the LD in different pump powers.

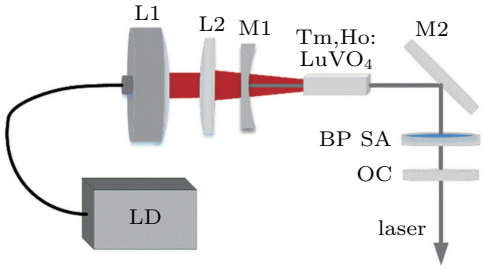


Fig. 2. The schematic of the PQS Tm, Ho:$LuVO_4$ laser.

3. Experimental results and discussion

A power meter (PM30) was used to measure the output powers of the Tm, Ho:$LuVO_4$ laser. Fisrtly, without SA, the CW output power was instigated, as shown in Fig. 3. The maximum output power of 1.87 W was achieved at the absorbed pump power of 14.55 W, corresponding to the slope efficiency of 14.6%. Then, with the BP SA, the maximum average output power of 0.86 W and the slope efficiency of 6.5% were obtained in the passively Q-switched Tm, Ho:$LuVO_4$ laser.

The output spectra of the diode-pumped Tm, Ho:$LuVO_4$ laser under both CW and PQS regimes were recorded by a spectrum analyzer (Bristol 721 A), as shown in Fig. 4. Under CW regime, the output wavelength was centered at 2075.8 nm. With the BP SA, the output wavelength shifted to 2056.5 nm. This phenomenon was mainly caused by the insertion loss of the BP SA. The central wavelength of the CW laser was longer than that of the PQS laser, which was attributed to the stimulated emission cross section in the PQS operation becoming a key factor because the energy stored in the crystal far exceeded the CW operation threshold.

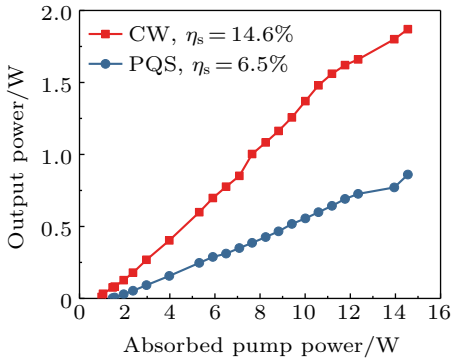


Fig. 3. The CW and PQS powers of diode-pumped Tm, Ho:$LuVO_4$ laser at 77 K.

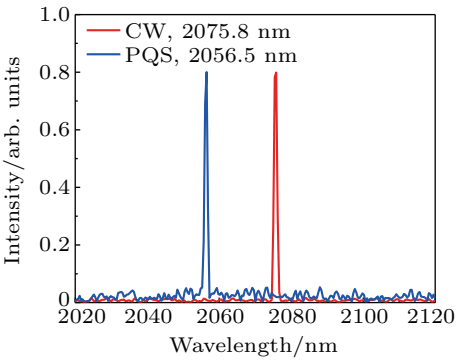


Fig. 4. The CW and PQS output spectra of diode-pumped Tm, Ho:$LuVO_4$ laser at 77 K.

The pulse profiles of the passively Q-switched Tm, Ho:$LuVO_4$ laser were detected by a InGaAs photodetector (EOT ET-5000) and recorded by a digital oscilloscope (Tektronix DPO4104). Figure 5(a)) shows the pulse repetition rate and energy variations of the passively Q-switched Tm, Ho:$LuVO_4$ laser. As the absorbed pump power increased from 5.31 W to 14.55 W, the pulse repetition rate increased from 62.24 kHz to128.4 kHz. The maximum pulse energy of about 6.7 μJ was obtained at the maximum absorbed pump power of 14.55 W. Figure 5(b)) shows the pulse widths of the passively Q-switched Tm, Ho:$LuVO_4$ laser. It can be seen that the pulse width fluctuated between 3.04 μs and 2.83 μs, corresponding to the increase of the calculated peak power from 1.33 W to 2.32 W. The pulse trains of the passively Q-switched Tm, Ho:$LuVO_4$ laser were recorded at the average output powers of 0.35 W, 0.6 W, and 0.86 W, as shown in Fig. 6, corresponding to the pulse repetition rates of 81.5 kHz, 107 kHz, and 128.3 kHz. The temporal profile of the single Q-switched laser pulse at 2.92 μs was also acquired at an average output power of 0.3 W, as shown in Fig. 6.

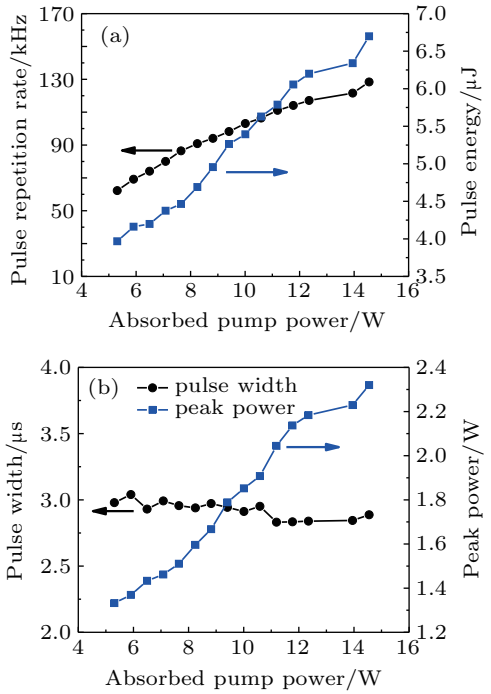


Fig. 5. The output performances of PQS Tm, Ho:$LuVO_4$ laser. (a) The pulse repetition rate and pulse energy versus the absorbed pump power. (b) The pulse width and peak power versus the absorbed pump power.

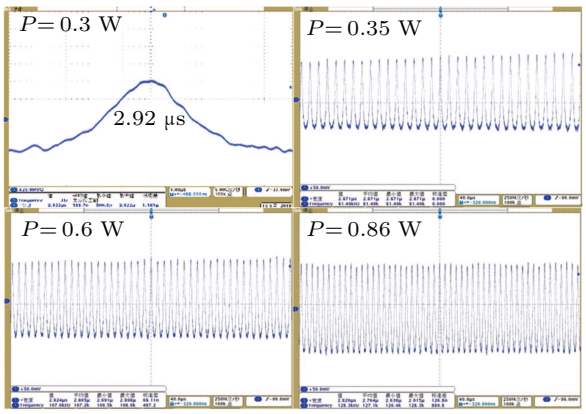


Fig. 6. The pulse trains of passively Q-switched Tm, Ho:$LuVO_4$ laser.

4. Conclusion and perspectives

In summary, a PQS Tm, Ho:$LuVO_4$ laser with a BP SA was demonstrated for the first time in this paper. In CW mode operation, a maximum output power of 1.87 W was achieved with an absorbed pump power of 14.55 W, corresponding to the slope efficiency of 14.6%. A pulse width of about 2.89 μs and a pulse repetition rate of 71.84 kHz were achieved under PQS mode operation. The maximum average output power of 0.86 W was obtained with an absorbed pump power of 14.55 W, corresponding to a maximum single-pulse energy of about 6.7 μJ.

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