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High beam quality passively Q-switched operation of a slab Tm:YLF laser with a MoS_2 saturable absorber mirror

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HIGHLIGHTS

- A PQS slab Tm:YLF laser based on a MoS_2 SA with a high output power, high peak power, and high beam factor was demonstrated in the experiment.
- Under PQS mode, an average output power of 6.3 W and a per pulse energy of 85.2 μJ were obtained at 1905.9 nm with a pulse width of 3.1 μs, corresponding to a peak power of 27.5 W.
- The beam quality factors of $M_x^2 = 1.06$ and $M_y^2 = 1.01$ from Tm:YLF laser were achieved in the PQS regime.

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MoS_2 SA
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ABSTRACT

A passively Q-switched (PQS) slab Tm:YLF laser based on a MoS_2 saturable absorber (SA) with the beam quality factors of $M_x^2 = 1.06$ and $M_y^2 = 1.01$ was experimentally demonstrated for the first time. An average output power of 6.3 W was achieved in PQS mode operation of Tm:YLF laser, corresponding to a slope efficiency of 10.0%. Also, up to 85.2 μJ pulse energy was obtained from laser with a pulse width of 3.1 μs and a peak power of 27.5 W.

1. Introduction

Pulsed laser sources with peak powers over ten watts based on Tm^{3+}-ion and emission around 2 μm, play an important role in spectroscopy, laser ranging, high-field physics, photo-medicine, and metrology. The Tm^{3+}-ion, owning large absorption band around 800 nm, matches the emission of commercial AlGaAs laser diodes. Typically, Q-switching is an attractive way to achieve pulses with short pulse width and high peak power. In particular, passively Q-switched (PQS) lasers combined with SAs, enjoying simplicity, compactness and flexibility of implementation, have been extensively used to produce the ultra-short pulse lasers, such as nanosecond or picosecond laser. An availably suitable SA, possessing the capabilities of high damage threshold, ultrafast recovery time, moderate saturation intensity and broadband saturable absorbtion, plays the most important role on the passively Q-switched lasers. To date, many various SAs, such as semiconductor saturable absorber mirrors (SESEMs), carbon nanotubes, black phosphorus, graphene, and topological insulators have been employed in the passive Q-switching regime [1–6]. The SESEMs have narrow operation bandwidth and complex fabrication process, which limit its application in IR laser fields. Graphene, a two-dimensional (2D) zero-bandgap material, has been confirmed as an excellent SA in passive Q-switching regime, but it has weak absorption and low damage threshold.

Transition metal dichalcogenides (TMDs) [7], a new class of 2D materials, have attracted extensive attention due to its thickness-dependent electronic and optical properties. The Molybdenum disulfide (MoS_2) [8,9], owning with Hexagonal structure of molybdenum atoms sandwiched between two layers of chalcogen atoms, is a typical

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example of TMDs. Having an ultrathin layered structure and an appreciable direct band gap of 1.9 eV in the monolayer regime, the MoS_2 is inspiring and compensates for the weakness of the gapless graphene [10].

Recently, monolayer or few-layer MoS_2 structures as SAs were employed in Q-switched or mode-locked bulk and fiber lasers [11–14]. In 2014, Han Zhang et al. have demonstrated a few-layer MoS_2-based mode-lock laser with a stable mode-locked laser pulse duration of 800 ps and a 3-dB spectral bandwidth of 2.7 nm [15]. Ytterbium-doped fiber laser with a new type of MoS_2 as SA was reported by Juan Du et al. in the same year, and the SA was first designed as a MoS_2-taper-fiber device used as a Q-switching SA and a polarization sensitive optical modulating component [16]. A PQS diode-pumped Tm,Ho:YAP laser at 2 μm based on MoS_2 SA was presented by C. Luan et al. in 2015, producing a peak power of 11.3 W [17]. With MoS_2 as a SA, a passively Q-witched Tm:CLNGG laser with a maximum output power of 62 mW and pulse energy of 0.72 μJ was also reported in 2015 [18]. We have demonstrated a PQS Tm,Ho:YAP laser with a MoS_2 SA in 2018, and a 3.03-W average output power was achieved with a per pulse energy of 23.31 μJ and a peak power of 9.74 W. Based on the above investigation, the pulsed bulk and fiber lasers with MoS_2 as a SA have been demonstrated. However, the average output power of over 5 W and peak power of over 10 W from PQS lasers at 2 μm wavelength range with a MoS_2 SA have never been reported.

In this paper, we demonstrate a PQS slab Tm:YLF laser base on a MoS_2 SA with a high output power, high peak power, and high beam factor. Under PQS mode, an average output power of 6.3 W and a per pulse energy of 85.2 μJ were obtained at 1905.9 nm with a pulse width of 3.1 μs, corresponding to a peak power of 27.5 W. The beam quality factors of $M_x^2 = 1.06$ and $M_y^2 = 1.01$ from PQS Tm:YLF laser were achieved for the first time.

2. Experiment setup

The schematic of the passively Q-switched Tm:YLF laser was shown in Fig. 1. An L-folded cavity was employed in the experiment to achieve high beam quality and average output power. A Tm:YLF slab crystal, which had a length of 35 mm and a cross-section of 1.5 × 6 mm^2, was used in the resonator. Two flat 45° dichroic mirrors (M1 and M2) with high reflectivity (R > 99.98%) in the wavelength around 1.91 μm and high transmission (T > 99.8%) at the pump wavelength were used in the folded resonator. A Volume Bragg Grating (VBG, OptiGrate Corp.) or a plane high reflectivity (HR) mirror was employed as a back-reflector mirror, and the VBG had a clear cross section of 6 × 6 mm^2 and a length of 5.5 mm. The output coupler was a plano-concave mirror with a 200 mm curvature radius and coated for three different transmittance (10%, 40% and 50%) around at 1.91 μm. The physical length of the resonator was 135 mm. The slab crystal had a doping concentration of 2.0 at. %, and was c-cut with the c-axis along the 1.5 mm direction. Both end faces of the Tm:YLF slab were antireflection coated with the laser wavelengths in the range 1.9–2.0 μm and the diode-pump wavelength around 790 nm. The slab crystal was wrapped in 0.05-mm-thickness indium foils and mounted in a water-cooled copper heat sink kept at the temperature of 290 K. A MoS_2 SA with the transmittance of 90% at 1.91 μm was used in our experiment, which was placed next to the M2 as close as possible. The beam radius on the MoS_2 SA was calculated to be 310 μm by ABCD matrix.

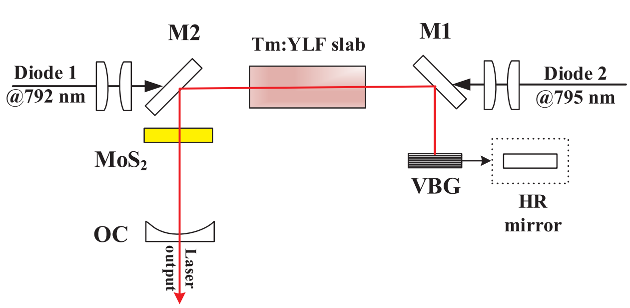

Fig. 1. Layout of the dual-end-pumped passively Q-switched slab Tm:YLF laser with MoS_2 as a SA.

The two laser diodes had a fiber diameter of ω_p = 400 μm and a numerical aperture of 0.22 ($M_p^2 \sim 175$). The one laser-diode central wavelength (λp) was measured to be 791.7 nm (The absorption efficiency for the laser crystal was 94.3%) at the maximum output power of 50 W, and the other one λp was 794.8 nm (The absorption efficiency for the laser crystal was 77.9%), resulting in the Rayleigh length zr ($zr = \pi\omega_p^2 n/\lambda_p M_p^2$) of ∼5.22 and 5.20 mm inside the crystal with refraction index $n = 1.44$ [19]. The spectral widths of the two laser diodes were all approximately 2.5 nm. A pair of collimating and focusing lens with f = 25 and 50 mm was used to focus the pump beam into the crystal, resulting in a diameter of about 800 μm. The pump beam was end pumped into the crystal from the 1.5 mm × 6 mm plane surface, and the pump waist was positioned at 11 mm inside the crystal.

3. Results and discussion

The continuous wave passively Q-switched Tm:YLF laser with VBG was firstly investigated with different transmittance output couplers, and the output powers versus laser diode pump power was shown in Fig. 2. With no SA insertion, the absorbed threshold pumping power of CW Tm:YLF laser was about 5.7 W, 9.3 W, and 12.2 W, respectively, when the output coupler transmittance was 10%, 40%, and 50%. The maximum output power was 9.8 W, 16.8 W and 16.7 W respectively, corresponding to a slope efficiency of 12.6%, 24.5%, and 25.0%. The low efficiency could be attributed to the unmatched LD emission and the two long gain crystals. With the MoS_2 SA inserted in the resonator, the passively Q-switched operating was obtained when the absorbed pump power was over 13.3 W, 17.8 W, and 17.8 W. Up to 1.8 W, 5.1 W, and 5.7 W output power was achieved in PQS mode, which corresponded to a slope efficiency of 2.7%, 9.0%, and 12.7%, respectively. The emission wavelength of CW and PQS regime were all around 1908 nm, which could be attributed to the VBG causing the wavelength shift less than 1 nm.

To further study the emission wavelength in PQS regime, the PQS Tm:YLF laser with plane HR mirror was investigated. The results of output power and pulse energy were shown in Fig. 3. When absorbed pump power was over 13.3 W, 17.8 W, and 17.8 W, respectively, the PQS operation was starting with T = 10%, 40%, and 50% output coupler. Up to 2.2 W, 5.5 W, and 6.3 W output power was obtained at different transmittance of 10%, 40%, and 50%, which was a bit higher than the VBG regime, corresponding to a slope efficiency of 3.1%, 8.5%,

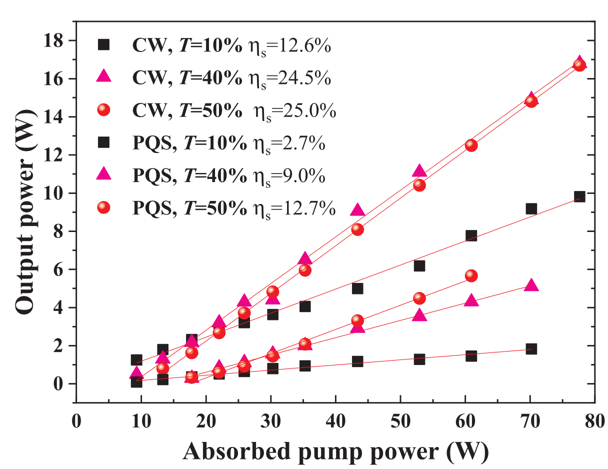

Fig. 2. The output powers of the Tm:YLF laser with VBG under CW and PQS modes.

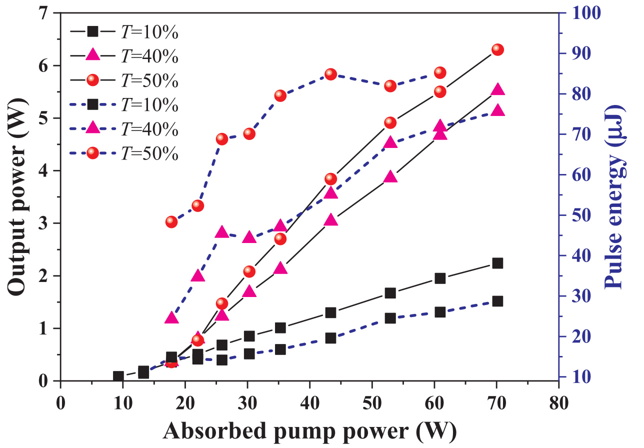

Fig. 3. The output performance of the PQS Tm:YLF laser with plane HR mirror.

and 10.0%. Best results were achieved with the T = 50% output coupler. A maximum output energy of 85.2 μJ was obtained at the absorbed pump power of 60.9 W. Due to the large pump beam waist, the output pulse energy remained almost constant, between 79.5 and 85.2 μJ with the absorbed pump power over 35.3 W.

The pulse repetition frequency (PRF) and pulse width of the PQS Tm:YLF laser with HR mirror versus laser diode pump power were shown in the Fig. 4. The PRFs were 17 kHz, 15 kHz and 14.7 kHz near threshold, increasing with the LD pump power to 78 kHz, 73 kHz, and 76 kHz. The typical oscilloscope pulse trains in 40 μs and 100 μs time scales were shown in Fig. 5, implying that the pulse-to pulse amplitude fluctuation of the Q-switched pulse train was less than 10%. The oscilloscope traces were measured by an InAsSb temperature controlled amplified detector (THORLABS PDA10PT-EC, USA) and a 1 GHz digital oscilloscope (Tektronix DPO4104, USA). The pulse duration decreased from 6.5 μs to 3.7 μs (T = 10%), 5.0 μs to 3.3 μs (T = 40%), 4.7 μs to 3.1 μs (T = 50%). The high modulation depth of MoS_2 SA, which was caused by thick MoS_2 coating, was result in relatively broad pulse duration of the PQS Tm:YLF laser. The pulse duration remained almost constant when the absorbed pump power was over 35.3 W. The MoS_2 SA was damaged when the absorbed pump power was over 70.2 W.

As shown in Fig. 6, the output spectra of the Tm slab laser in CW and PQS regime was measured by a wavelength meters (Bristol instruments 721A-IR, USA,) with a measuring accuracy of 0.002 nm. The CW laser showed a peak at 1908.2 nm, corresponding with a full width at half maximum (FWHM) of about 0.9 nm. In the case of PQS regime, the central wavelength was 1905.9 nm shifted to short wavelength as compared to the CW regime, with a FWHM of approximate 2.6 nm. The

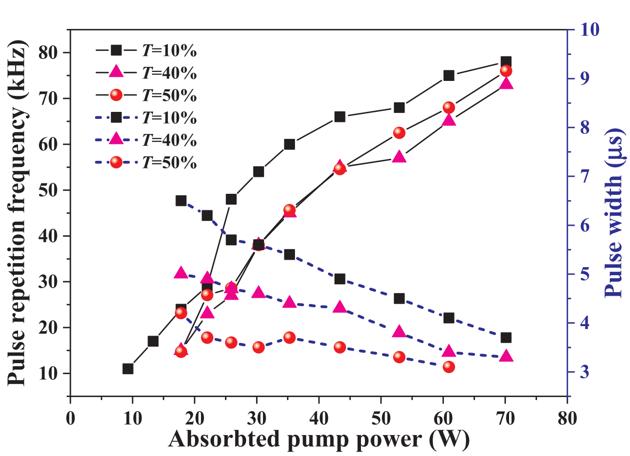

Fig. 4. The PRF and pulse width of the PQS slab Tm:YLF laser with a plane HR mirror.

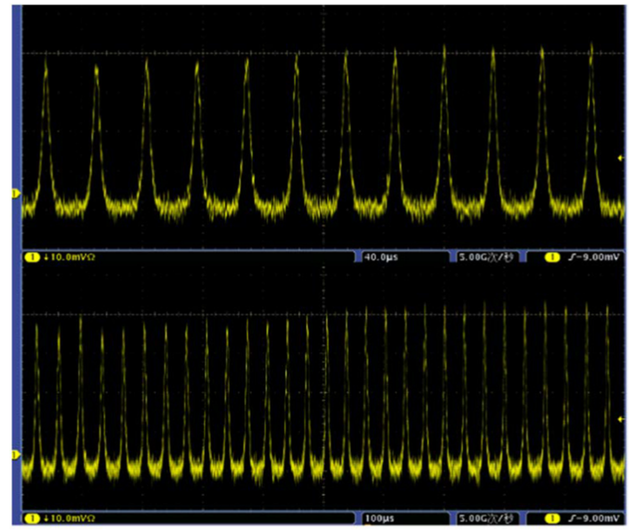

Fig. 5. The typical pulse trains of the PQS slab Tm:YLF laser with plane HR mirror in different time scales.

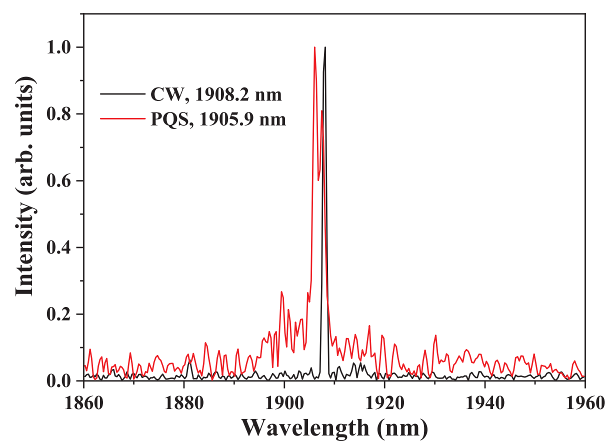

Fig. 6. The output spectra of the CW and PQS slab Tm:YLF laser with a plane HR mirror.

central wavelength of PQS was shorter than that of the CW, 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 exceeds the CW operation threshold. Also, the FWHM in PQS mode was wider than that in CW mode because emission wavelength in CW mode was in the range of diffraction wavelength from VBG.

To evaluate the beam quality of the PQS Tm:YLF laser, we measured the beam radius at the highest output power by M2 beam quality analysis system (THORLABS BP109-IR2, USA), as shown in Fig. 7. Two-dimensional (2D) and three-dimensional (3D) spatial power distribution were reconstructed. The beam quality factors of $M_x^2 = 1.06$ and $M_y^2 = 1.01$ were achieved at the highest output power in the PQS regime, corresponding to a far field divergence of x: 0.001° and y: 0.046°.

4. Conclusion

In conclusion, we have experimentally demonstrated a high beam quality Tm:YLF laser under PQS operations for the first time. In PQS operation, the MoS_2 material was used as the SA, and an average output power of 6.3 W and a per pulse energy of 23.1 μJ were firstly acquired with a per pulse energy of 85.2 μJ and a peak power of 27.5 W. The beam quality factors of $\boldsymbol{M_x^2} = 1.06$ and $\boldsymbol{M_y^2} = 1.01$ were achieved from PQS Tm:YLF laser at 1905.9 nm.

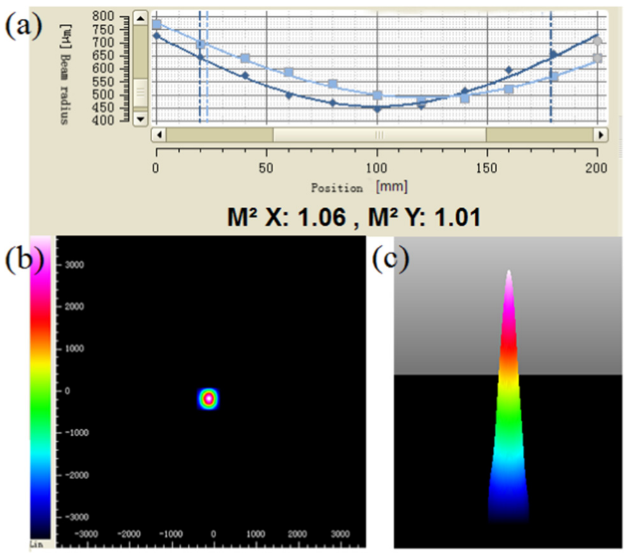

Fig. 7. Beam quality of the PQS Tm:YLF laser with a HR mirror. (a) The Beam radius of PQS Tm:YLF laser. (b) 2D laser profile of the output beam of PQS Tm:YLF laser. (c) 3D laser profile of the output beam of PQS Tm:YLF laser.

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