A 3.3-W passive Q-switched 2-\(\mu\)m laser with a MoS\(_2\)-based saturable absorber

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Abstract. Using a new MoS\(_2\)-based nanosheets as a saturable absorber (SA), a passively Q-switched (PQS) Tm,Ho:YAP laser at 2000.4 nm was proved in the paper. Under PQS mode, an average output power of over 3 W and per pulse energy of over 23 \(\mu\)J were obtained in the experiment. Also, the beam quality factors were less than 1.1 in PQS mode.

1. Introduction
Pulses laser emitted at 2 \(\mu\)m waveband range have been explored due to their excellent energy density. Also, they are suitable for quartz fiber transmission with strong absorption in water and human tissue, and they are in visual security waveband. So, 2-\(\mu\)m solid-state lasers with high energy density will be particularly promising for application in material processing, urethral lithotripsy, surface wave detection surgery and infrared remote sensing [1-4]. PQS technology is an inexpensive and simple method to acquire short pulse laser at 1-3 \(\mu\)m, SAs are key optical components in the process. Two-dimensional (2D) materials with many excellent optical characteristics, are fascinated to be used as SAs for PQS laser [5-7].

Transition metal dichalcogenides (TMDCs) with excellent modulation depth, wide waveband absorption, and non-linear effects, are widely followed as SAs [6-7]. MoS\(_2\), is a new 2D material of TMDCs, which have broad prospects in SA [6-9]. The electronic band structure of MoS\(_2\) was decided by the thickness of material, and this feature greatly compensates for the bandgap structure of the material which let it to certain some new optical properties and be used in the optoelectronic devices and next generation switching [10-11].

In this work, we proved a PQS Tm,Ho:YAP laser with a MoS\(_2\)-based SA at 2000.4 nm. An over 3.0-W average output power and an over 23 \(\mu\)J per pulse energy were firstly obtained from a PQS Tm,Ho:YAP laser, and the beam quality factors were less than 1.1 in PQS mode.

2. Experimental Setup
A compact experimental schematic is shown in Fig. 1. A Tm,Ho:YAP crystal, was grown in Czochralski method, was used to emit laser at 2 \(\mu\)m waveband. An L-Type cavity with a physical cavity length of 155 mm was chosen. A dual-end-pumped laser configuration was select to relieve the thermal loading of the Tm,Ho:YAP crystal. The Tm,Ho:YAP crystal, was co-doped with 5 at.% Tm\(^{3+}\) and 0.3 at.% Ho\(^{3+}\), was cut along its b-axis with the cross-sectional area of 4 mm\(^2\)×4mm and the length of 8 mm. A high transmittance film at 790-800 nm and 1.9-2.2 \(\mu\)m
was coated at both cross-sectional area of the crystal and a Dewar with 500 mL liquid nitrogen was chosen a refrigeration device for the laser crystal.

Double laser diodes (LDs) with both center output wavelengths about 794.0 nm and output powers about 20.0 W were selected to pump laser crystal. A fiber of 400-μm core diameter and 0.22 numerical aperture was coupled output the power of each LD. The pumped laser from one LD passed a 35-mm collimating mirror (L1 or L4) and a 75-mm focus lenses (L2 or L3) was refocused on end face of the laser crystal. A pump spot with a radius of 428.55 μm was focus at the input surface of the laser crystal. A flat mirror, was coated with a 5% (7% or 10%) transmittance at 1.9-2.2 μm, which was used as output coupler (OC) for the laser. A flat concave mirror (M1) with a 300-mm radius of curvature, was coated at 790-798 nm with a low reflectivity (R<2.0%) coating on the both faces, which was coated at 1.9-2.2 μm with a low transmission (T <0.5%) material on its concave face. A plano mirror with a 45°coating was chosen as a dichroic mirror (M2), which was coated at 790–810 nm with a low reflection (R<1.0%) material in both end faces and 1.9-2.2 μm with a low transmission (T <2.0%). A MoS2-based SA mirror was used for the PQS experiments, and the mirror made from CaF2 crystal was used as the substrate of MoS2-based SA. MoS2 material dissolved in ethyl alcohol was coated onto the surface of one face at the CaF2 mirror with a spin coating machine (KW-4A, Chinese Academy of Sciences).

![Fig. 1. An experimental set-up of PQS Tm,Ho:YAP laser](image)

3. Results and discussion
Under PQS mode, the output performances of the Tm,Ho:YAP laser are shown in Fig. 2. An average output powers of 550.0 (688.0 or 3300.0) mW was achieved with a 5% (7% or 10%) transmittance of OC at 1.9-2.2 μm waveband, and per pulse energy of 4.23 (6.25 or 23.31) μJ was obtained with a pump power of 20.1 (18.1 or 26.1) W.

![Fig. 2. The output performance of the Tm,Ho:YAP laser](image)

The pulse widths of PQS Tm,Ho:YAP laser are shown in Fig. 3. Under PQS operation with a 5% (7% or 10%) transmittance of OC at 1.9-2.2 μm waveband, the pulse width of 2.61 (1.64 or 2.37) μs was acquired at a PRF of 133.6 (110 or 133.2) kHz. The PRF of each kind of OC was increased with the pump power increased, and the pulse width of each kind of OC was reduced. A detector (PDA10PT-EC) with a 28 ps rise time and a oscilloscope (DPO4104) with 1 GHz bandwidth were selected to measure the pulse train of Tm,Ho:YAP laser, the typical pulse trains were recorded in 4.0 μs and 100 μs time scales, and the dates is shown in Fig. 4.
Fig. 3. The pulse widths and PRF of the laser in PQS mode.

Fig. 4. The pulse train in 4.0 μs and 100 μs time scale

The output wavelengths of CW and PQS Tm,Ho:YAP laser were measured by a 721A-IR laser wavelength meter, and dates are shown in Fig. 5. The output wavelengths were acquired at 2119.5 nm from CW Tm,Ho:YAP laser and 2000.4 nm from PQS Tm,Ho:YAP laser.

Fig. 5. The output wavelengths of CW and PQS Tm,Ho:YAP laser

A 2D and 3D laser profile of the output beam from PQS Tm,Ho:YAP laser were measured by a slit scanning beam profiler, and the dates are shown in Fig. 6. Also, the beam quality factor was less than 1.1 from the PQS Tm,Ho:YAP laser.

Fig. 6. 2D and 3D laser profile of PQS Tm,Ho:YAP laser
4. Conclusions

In PQS operation, a MoS₂-based material was selected as the SA, and an over 3.0 W average output power and an over 23.0 μJ per pulse energy were firstly acquired. A beam quality factor of less than 1.1 was obtained.

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