Compact $Q$-switched 2 μm Tm:GdVO$_4$ laser with MoS$_2$ absorber

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A molybdenum disulfide (MoS$_2$) saturable absorber was fabricated by thermally decomposing the ammonium thiocyanate (ATC) at 500°C for an hour in the growth process. Finally, a stable $Q$-switched laser with repetition rates from 25.58 to 48.09 kHz was achieved. Maximum average output power was 100 mW with the shortest pulse duration of 0.8 μs. Maximum pulse energy is 2.08 μJ at center of 1902 nm. © 2015 Chinese Laser Press

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1. INTRODUCTION

Two-dimensional (2D) nanomaterials have attracted much attention recently due to their remarkable electronic and optical properties. A well-known 2D nanomaterial, graphene, has a direct bandgap of 0.26 eV in its bulk form [1] and a direct bandgap of 1.29 eV in a single layer [2]. Due to its thickness-dependent electronic and optical properties, graphene has been widely investigated as an excellent saturable absorber (SA) for pulsed lasers [3,4]. With the wide application of graphene-based SAs, other 2D materials also have attracted extensive attention. Recently, molybdenum disulfide (MoS$_2$), a new type of 2D material, transition metal dichalcogenides [6], has received attention due to its thickness-dependent electronic and optical properties. MoS$_2$ is composed of a hexagonal structure of molybdenum atoms sandwiched between two layers of chalcogen atoms [6]. Reference [7] demonstrated that the MoS$_2$ has a nonlinear optical response stronger than that of graphene. Furthermore, the thermal conductivity of MoS$_2$ is 11.7 W m$^{-1}$ K$^{-1}$ at 300 K, larger than that in YAP and YLF, which is more efficient cooling the crystal. A maximum output power of 2.6 W at 1910 nm in a diode-pumped continuous wave (CW) Tm:GdVO$_4$ laser had been reported by Cerny et al. [8]. An acousto-optical (AO) Q-switch output has also been proved in Tm:GdVO$_4$ [9]. However, a diode-pumped passively $Q$-switched Tm:GdVO$_4$ laser has not been reported.

In this paper, the MoS$_2$ SA is fabricated by thermally decomposing ammonium thiocyanate dip coating the mica and successfully realizing a stable $Q$-switched Tm:GdVO$_4$ laser at 1902 nm. A maximum output power of 100 mW was achieved at 1902 nm, corresponding to the maximum single pulse energy of 2.08 μJ.

2. FABRICATION OF MoS$_2$ SA

Figure 1 schematically illustrates a convenient and cost-effective approach by thermally decomposing the ammonium thiocyanate dip coating onto the fresh surface of mica of just dissociation with a drop and using a spin coater to ensure uniformity of solution on the mica. The sample should be placed in the hot zone of the furnace for drying naturally horizontally. After this, the annealing process was carried out in the quartz tube. First, the quartz tube was pumped to low pressure accompanied by a flow of H$_2$ and Ar (20/80 sccm). Subsequently, a temperature of 500°C was kept for an hour in the growth process. Finally,
the furnace was quickly cooled to room temperature by opening the furnace.

The XRD results of exfoliated MoS$_2$ NPs in Fig. 2(a) are in good fit the hexagonal structure of MoS$_2$ (PDF Card 04-0880). Several diffraction peaks are easily indexed, assigned to (110), (100), (102), and (106) reflection.

Figure 2(b) exhibits the SEM image of the MoS$_2$ membrane after the decomposition of ammonium thiomolybdate on mica substrate. A large area continuous MoS$_2$ layer is obtained. As shown in the SEM image, the surface of the sample is uniform and compliant.

Figure 2(c) shows the Raman spectroscopy on trilayered MoS$_2$. The characteristic peaks of the two samples at 382.9 and 405.4 cm$^{-1}$ are assigned to the $E_{2g}^1$ and $A_{1g}$ modes of MoS$_2$, respectively, while the two characteristic peaks $E_{2g}^1$ and $A_{1g}$ of the bulk MoS$_2$ occur at 380 and 410 cm$^{-1}$ [21]. Compared with the thickness-related distance value of bulk MoS$_2$ between the two peaks is ~30 cm$^{-1}$, the thickness-related distance value of the trilayered MoS$_2$ between the two peaks in ~22.5 cm$^{-1}$. The frequency difference of the two modes can be used to determine the layer thickness of MoS$_2$. In our result, the thickness-related distance of ~22.5 cm$^{-1}$ corresponds to three or four layers of MoS$_2$ [22,23].

3. EXPERIMENT SETUP

A schematic of the experimental arrangement is shown in Fig. 3. A fiber-coupled diode laser was used as the pump resource, whose emission wavelength was around 803 nm at 25.4°C. The pump core diameter and the numerical aperture were 400 μm and 0.22, respectively. By using a couple of convex lens (1:0.5), the pump beam was focused on the laser crystal with the radius of 100 μm. The laser crystal was a-cut Tm:GdVO$_4$ crystal with the Tm$^{3+}$ doping concentration of 0.5 at. % and the dimension of 3 mm × 3 mm × 3 mm, which both surfaces were antireflection coating at the pump and laser wavelengths. It was wrapped with an indium foil and then mounted on a water-cooled copper crystal holder with the cooling water temperature set at 15°C to preserve the laser crystal from thermal fracture. The absorption efficiency of the diode pump by the crystal was 77.86%. The input mirror M1 was a plane-concave mirror with radius of 100 mm, which was high-transmission coated at 780–810 nm and high-reflection coated at 1900–2000 nm. A flat mirror M2 with the transmittance of 2% was used as the output coupler (OC). A compact concave-plane resonator was designed to keep the mode matching in crystal between the pump beam and the fundamental resonant mode. The laser pulse trains was recorded by a 1 GHz digital oscilloscope (Tektronix DPO 4104) and a fast photodiode detector (ET-5000) with a rising time of 250 ps. The average output power was measured by a laser power meter (30A-SH-V1, made in Israel).

4. RESULTS AND DISCUSSION

The average output powers of the CW and passively Q-switched Tm:GdVO$_4$ laser versus absorbed pump power are shown in Fig. 4. In the CW operation, the laser threshold pumping power was 2.12 W without inserting MoS$_2$ SA. When the absorbed pump powers were increased to 3.08 W, the maximum output power of 304 mW was obtained with corresponding slope efficiency of 19%. In the passively Q-switched operation, the MoS$_2$ SA was positioned close to the M2. The radius of the laser beam at the MoS$_2$ SA was...
calculated to be about 125 μm by ABCD matrix. By carefully aligning the laser cavity, the passively Q-switched pulse train was searched. The laser threshold pumping power was 2.41 W. The maximum output power of 100 mW was obtained with a corresponding slope efficiency of 7.3% with the absorbed pump powers of 3.08 W. To avoid damage to the laser crystal and MoS$_2$, the pump power was not increased more than 4.0 W.

The CW and Q-switched pulse spectrum were measured by an optical spectrum analyzer (AvaSpec-NIR256–2.2-RM) with a resolution of 10 nm. Figure 5 shows the CW and Q-switched spectra under the absorbed pump power of 3.08 W. We can see the central wavelengths were 1938 and 1902 nm. The central wavelength of Q-switching was shorter than that of the CW, which was attributed to the stimulated emission cross section in the Q-switched operation becoming a key factor because the energy stored in the crystal far exceeds the CW operation threshold [24].

The pulse width and the repetition rate of the passively Q-switched operation as the function of the absorbed pump power are shown in Fig. 6. It can be seen that the repetition increases as the pulse width decreases rapidly. In Fig. 6, we can see that, when the absorbed pump power is increased from 1.88 to 3.08 W, the pulse duration decreased from 2 to 0.8 μs with the pulse repetition rate increasing from 25.58 to 48.09 kHz. The maximum repetition rate of 48.09 kHz and the minimum pulse width of 0.8 μs were achieved under the absorbed pump power of 3.08 W, corresponding to the maximum single pulse energy of 2.08 μJ.

Figure 7 gives a recorded typical oscilloscope pulse train with the time of 40 and 2 μs/div. The experimental result was obtained at the absorbed pump power of 3.08 W. The pulse-to-pulse amplitude fluctuation of the Q-switched pulse train was less than 5%. In order to protect the laser crystal and MoS$_2$ from damage, we no longer increased the pump power. In future experiments, we will continue to optimize cavity type to obtain excellent Q-switching stability and Q-switch mode-lock.

5. CONCLUSIONS

In conclusion, using a MoS$_2$ as a SA, which was fabricated by thermally decomposing the ammonium thiomolybdate, a passively Q-switched Tm:GdVO$_4$ laser was realized. A maximum output power of 100 mW and pulse duration of 0.8 μs were achieved at 1902 nm, corresponding to the slope efficiency of 7.3%, and the single pulse energy was 2.08 μJ. As far as we know, this is the first report on diode-pumped passively Q-switched Tm:GdVO$_4$ lasers with the MoS$_2$. With further optimization of the MoS$_2$-SA, the higher output power and CW mode-locking laser performance can be anticipated.

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