Introduction

Owing to their outstanding optical and electronic properties, novel two-dimensional (2D) modulators have been utilized in both passively Q-switched and mode-locked laser operations. Compared with conventional saturable absorbers, such as V3+-doped crystals and semiconductor saturable absorber mirrors; 2D materials, transition metal dichalcogenides (TMDs) [1] and topological insulators (TIs) [2] have been proved to be more attractive in experiments for their broadband modulation properties, controllable modulation depth and ultrafast recovery time [3]. In between, for an easy low-cost fabrication, TMDs are even more competitive candidates than TIs in practical applications.

Similar to MoS2, one of the most famous TMD materials [4], MoTe2 also possess different bandgaps between monolayer and bulk samples, which depend on their composition, structure and dimensionality. Furthermore, the band-gap decreases with the increasing layers, the monolayer MoTe2 holds a direct band-gap of 1.1 eV [5], while the bulk has an indirect band-gap of 0.9 eV [6]. Bulk MoTe2 is composed of a hexagonal sheet of molybdenum atoms and tellurium atoms; each atom of molybdenum is sandwiched between two tellurium atoms, and each Te–Mo–Te unit is combined by a strong covalent bond. However, it is a weak van der Waals force between layers [7].

The laser radiations at ~1.6 μm locating at an eye-safe wavelength are widely used in laser medicine, remote sensing and optical communications. Such laser radiation could be generated by electrons transmitting from 4I13/2 to 4I15/2 in Er3+-ion. Owing to the high damage threshold and the outstanding thermal conductivity, Erbium-doped yttrium aluminum garnet crystal (Er:YAG) is a reliable material for high-power laser
operations at ~1.6 μm [8]. To achieve a high-efficiency laser operation, in-band pumping was employed, which can effectively decrease the non-radiative transition and the thermal effect.

Based on the outstanding properties of MoTe2, we exfoliated the multi-layer MoTe2 samples with the method of liquid phase exfoliation (LPEx) in ethanol, and the MoTe2-SA was fabricated by dropping the supernatant on a Y AG plate. By inserting the MoTe2-SA into the cavity of a stable in-band pumped Er:Y AG CW laser, a stable Q-switched laser operation at ~1645 nm was realized. Under the absorbed pump power of 10.51 W, stable pulse trains with a maximum average output power of 1.14 W was obtained, the shortest pulse duration was 1.048 μs with a repetition rate of 41.59 kHz, corresponding to a pulse energy of 27.4 μJ and a peak power of 26.14 W.

Preparation and characterization of MoTe2-SA

In order to fabricate a high quality MoTe2-SA, we used the method of LPEx to get the MoTe2 supernatant. This method was proved to be a universally applicable method in mounts of high-quality layer-structure materials exfoliation processes [9–11]. In our experiment, the multi-layer MoTe2 dispersion was first exfoliated through a 6h ultrasonic bombarding process, then with a 10min centrifugalizing treatment at a rotational speed of 1500rpm. By then, the MoTe2 multi-layer samples were distributed in the top 2/3 section of the turbid fluid, and we collected the supernatant for further measurement.

The characterizations of the physical structure for our MoTe2 specimen were identified by a transmission electron microscopy (TEM) measurement. The TEM image shown in figure 1(a) displays the thickness of the exfoliation with the dimensions of a sub-micrometer. To further identify its laser modulation performance and characterize its spectrum...
transmittance property, we also took the Raman spectra and optical spectrum transmittance measurements for the sample. The Raman spectrum measurement result is shown in figure 1(b). Under the excitation of a 632.8 nm He–Ne laser, a stokes-shift peak of specimen was observed clearly, including the in-plane $E_{1g}^1$ and the out-of-plane $A_{1g}$ modes [12]. Meanwhile, some small peaks emerged on the spectrum, and we attribute them to the second-order nonlinear processing and edge effect [13].

The thickness of our MoTe$_2$ samples was further analyzed by atomic force microscopy (AFM). Both the AFM image and the height of the fabrications are shown in figure 1(c), the thickness of our sample mainly varies from 10 to 20 nm. Considering the thickness of the monolayer structure is 0.65 nm [5], the values of the layers’ number for the MoTe$_2$ samples were in the range from 15 to 30.

The optical transmittance measurement of the MoTe$_2$ multilayers was measured by a UV/VIS/NIR spectrophotometer (U-4100, Hitachi, Japan). As shown in figure 2, the transmittance measurement result of the multi-layer specimen is around 98% and smoothly increases with an increasing wavelength in the range of 1400 to 1800 nm.

MoTe$_2$-SAa were fabricated by dropping the supernatant on a YAG substrate and dried in the air for 10 h. An active Q-switched Er:YAG lasing at ~1645 nm with a repetition rate of 4 kHz was utilized to measure the nonlinear absorption property of our homemade SA. As shown in the inset of figure 2, the experimental data fits the theoretical function well [14], where the function is described as:

$$ T = 1 - \Delta R \cdot e^{(-I/I_s)} - T_{ns}. $$

In this function, $T$ is the transmittance of the spacer and varies with the incident beam power $I$. Fitting parameters $\Delta R$, $I_s$, $T_{ns}$ are the modulation depth, the saturable absorption intensity and the nonsaturable losses, respectively. For our MoTe$_2$ samples, the modulation depth was fitted to be 1.3%, the saturable absorption intensity to be 6.87 mJ cm$^{-2}$ and the nonsaturable losses to be 99%.

**Figure 3.** Schematic diagram of the passively Q-switched Er:YAG laser with MoTe$_2$-SA.

**Laser experiment**

**Experiment setup**

The schematic diagram of our laser experiment setup is shown in figure 3: a laser diode (LD) lasing at 1532 nm was employed as the pumping source. An optical fiber with a core diameter of 400 $\mu$m and numerical aperture of 0.22 was used to couple the laser beam out from the LD. To efficiently utilize the pump energy, a lens system was introduced to converge the divergent laser beam exported from the fiber. This lens system was composed of two properly coated convergent lenses and with an equivalent focal length of 100 mm. The convergent beam was then focused into the laser gain medium sited in the cavity. In our setup, we used an uncoated Er:YAG crystal with a doping concentration of 0.25 at.% as the gain medium, and an 8 cm-long plane-plane cavity constituted by plane mirrors M1 and M2 as shown in the figure. For the cavity, M1 worked as the input coupling mirror holding the transmittance of 90% at a pumping wavelength of 1532 nm and a reflection efficiency of 99%, ranging from 1.6 $\mu$m–1.7 $\mu$m, while M2 worked as the output coupler, which was in fact three different mirrors with transmittances of 2%, 5% and 10% around 1.6 $\mu$m, in order to characterize the laser operations under different optical loss conditions.

**Results and discussion**

Both stable CW and Q-switched laser operations were realized with this type of laser scheme. The output powers were measured with a power meter (photodiode sensor of PM100 together with a power meter S314C Thorlabs Inc., USA), which are shown in figure 4. For the CW operations, the lasing thresholds of our laser system were measured to be 5.09 W, 5.67 W and 5.74 W, with the couplers of different transmittance at 2%, 5% and 10%, respectively. Under the maximum absorbed pump power of 10.51 W, the measured output powers of our laser system were 1.29 W, 1.87 W and 2.24 W, corresponding to slope efficiencies of 23.85%, 38.72% and
46.91\%, respectively, with the different output couplers mentioned above. By inserting the MoTe\textsubscript{2}-SA into the cavity, stable Q-switched laser operations were achieved. In this condition, the lasing thresholds were altered to be 5.64 W, 5.88 W and 7.27 W. By keeping the absorbed pump power the same, the measured average output powers varied between 0.57 W, 1.04 W and 1.16 W, corresponding to the slope efficiencies of 10.38\%, 22.53\% and 36.60\%, with the output couplers above. As shown in figures 4(a) and (b), the output powers increase almost linearly with the pump power increasing both in CW and Q-switched operations. The measured lasing wavelengths are almost the same at 1.645 \( \mu \)m in both cases, as seen in figures 4(c) and (d).

Previous passively Q-switched studies indicate that the pulse duration decreases while the repetition rate increases with an increase in the pump power \[1, 2, 14\]. In our Q-switched measurement, similar tendencies for the pulse duration and repetition rate were found as shown in figures 5(a) and (b). Among these three different transmittance output couplers (OCs), the 10\% one held the shortest pulse duration under the same pump energy while the highest lasing pump threshold was 7.27 W. The 2\% and 5\% transmittance OCs had a much lower pump threshold but also much longer pulse durations. The shortest pulse duration of 1.048 \( \mu \)s was obtained with a 10\% transmittance OC under a pump power of 10.51 W. The highest measured repetition rate was 46.92 kHz with a 5\% transmittance OC under the same pump power.

The pulse train signal was detected by an InGaAs photodetector with a rising time of 1 \( \text{ns} \) (New Focus) and synchronously visualized by the oscilloscope with a 1 GHz bandwidth and a 5 GS/s sampling rate (Tektronix DPO 7102, USA). We show in figures 5(c) and (d), with the 10\% transmittance of the OC, the stable passively Q-switched pulse train with a pulse duration of 1.048 \( \mu \)s and a repetition rate of 41.59 kHz.

Figure 4. Dependence of average output power on absorbed pump power in (a) CW and in (b) Q-switched laser operation; spectrum of (c) CW (peak 1645.94 nm) and (d) Q-switched (peak 1645.26 nm) laser operations.

Figure 5. Dependence of (a) pulse durations and (b) repetition rates of Q-switched laser operations versus absorbed pump power; (c) typical Q-switched pulse train and (d) temporal pulse profile.
Figure 6 shows the dependence of the peak power and pulse energy of Q-switched operations with different coupling transmittances under variations of the absorbed pump power. As shown in figures 6(a) and (b), the slopes of both line clusters of pulse energy and peak power increase with the increasing transmittance of the OCs under a certain range of pump power. This means that under certain absorbed pump power, we are able to obtain a Q-switched laser with both a higher peak power and pulse energy by employing an OC with a relatively higher transmittance in a certain range. In our experiment, under the maximum absorbed pump power of 10.51 W, the maximum pulse energy of 27.4 µJ and peak power of 26.2 W was obtained with the OC transmittance of 10% among all three stable pulsed laser operations.

Conclusion

In conclusion, a YAG-based multilayer MoTe₂-SA was fabricated and an in-band pumped passively Q-switched 1645 nm Er:YAG laser was realized by introducing such an SA into the cavity. When the absorbed pump power reached 10.51 W, a stable pulsed laser with an average output power of 1.14 W was achieved. The shortest pulse duration obtained was 1.048 µs with a repetition rate of 41.59 kHz, corresponding to a pulse energy of 27.4 µJ and a peak power of 26.14 W. The experiment result demonstrated that multilayer MoTe₂ has the potential to be an SA at a wavelength of 1.6 μm.

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