Passively Q-switched dual-wavelength Yb:LSO laser based on tungsten disulphide saturable absorber*

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(Received 4 November 2015; revised manuscript received 8 December 2015; published online 20 January 2016)

We demonstrate a passively Q-switched Yb:LSO laser based on tungsten disulphide (WS_2) saturable absorber operating at 1034 nm and 1056 nm simultaneously. The saturable absorbers were fabricated by spin coating method. With low speed, the WS_2 nanoplatelets embedded in polyvinyl alcohol could be coated on a BK7 glass substrate coated with high-refractive-index thin polymer. The shortest pulse width of 1.6 μs with a repetition rate of 76.9 kHz is obtained. As the pump power increases to 9 W, the maximum output power is measured to be 250 mW, corresponding to a single pulse energy of 3.25 μJ. To the best of our knowledge, this is the first time to obtain dual-wavelength Q-switched solid-state laser using few-layer WS_2 nanoplatelets.

Keywords: tungsten disulphide, Yb:LSO, Q-switching, dual-wavelength

PACS: 42.60.Gd, 42.70.Hj, 42.65.Re, 42.60.Lh **DOI:** 10.1088/1674-1056/25/3/034207

1. Introduction

Synchronous dual-wavelength pulsed laser is well suitable to generate coherent terahertz (THz) radiation[1] and applied in pump–probe processes,[2] nonlinear frequency conversion,[3] etc. It has been reported that difference frequency generation of two Q-switched near infrared laser pulses could generate high peak power THz radiation.[4,5] Passively Q-switched solid-state laser favored the advantages of compactness, flexibility for generation of dual-wavelength laser. In previous works, many saturable absorbers (SAs) such as carbon materials[6–8] (carbon nanotubes, graphene, and graphene oxide), two-dimensional materials including topological insulators[9] and molybdenum disulphide (MoS_2)[10] have been applied in solid-state lasers for Q-switching or mode locking. Recently, passively Q-switched dual-wavelength solid-state lasers have been realized based on graphene,[11] graphene oxide,[12] single-wall carbon nanotubes,[13] topological insulator,[14] and MoS_2 saturable absorber,[15] respectively.

In two-dimensional materials, graphene research has reached a mature stage. However, as saturable absorber, the optics damage threshold of single-layer graphene is as low as 14 mJ/cm^2.[16] Graphene-like material such as tungsten disulphide (WS_2) has attracted much attention for its physical properties.[17] Monolayers of tungsten disulphide are proved to be stable under ambient conditions (room temperature in air)[18] and have emerged as candidate materials for future saturable absorbers. Recently, WS_2 has been applied in fiber lasers. Mao *et al*. demonstrated an Er-doped mode-locked fiber laser with WS_2 nanoplatelets (NPs).[19] Yan *et al*. realized 1 GHz harmonic mode-locking with pulse duration of 452 fs at 1.5 μm.[20] Wu *et al*. obtained a mode-locked Er-doped fiber laser at 1550 nm.[21] Zhao *et al*. obtained passively Q-switched laser operation with 60 ns pulse width and ultrafast mode locking with 8.6-ps pulse width.[22] These research results proved WS_2 to be a potential high-power flexible saturable absorber for lasers.

In this paper, we demonstrate a Q-switched solid-state Yb:LSO laser based on WS_2 nanoplatelet film. Q-switched pulses as short as 1.6 μs were obtained at the pump power of 9 W. The Q-switched laser delivered dual-wavelength output at wavelength of 1034.3 nm and 1056.8 nm simultaneously. At the maximum pump power of 9 W, the average output power is 250 mW, corresponding to pulse energy of 3.25 μJ. To the best of our knowledge, this is the first time to realize a passively Q-switched, dual-wavelength solid-state laser using WS_2 as saturable absorber.

2. Experimental setup

WS_2 nanoplatelets could be fabricated by liquid-phase exfoliation due to the weak bonding between the WS_2 lay-

*Project supported by the National Scientific Research Project of China (Grant No. 61177047), Beijing Municipal Natural Science Foundation, China (Grant No. 1102005), and the Basic Research Foundation of Beijing University of Technology, China (Grant No. X3006111201501).

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ers, which made it possible to separate WS_2 bulk into single molecular layers.[23] In our experiment, solution of WS_2 nanoplatelets was fabricated by the liquid exfoliation.[24] The WS_2 powder was dispersed with ethanol and water at the volume ratio of 50:50, and then the mixture was ultrasonically agitated for about 200 min. After ultrasonication, the solution was centrifuged at 3000 r/min for several times to move out the larger WS_2 NPs. Hence, the WS_2 solution was completed as shown in Fig. 1(a). Figure 1(b) shows the atomic force microscope (AFM) image of WS_2 sample.

The thickness of WS_2 NPs ranges from 20 to 70 nm. The width and length of WS_2 NPs fall within the range of about 200 nm. We test the Raman spectra of WS_2 sample. The two characteristic peaks E^1_{2g} and A_{1g} appear at 352.2 cm^{-1} and 420.5 cm^{-1}, which are in agreement with the earlier reports.[17,19] The nonlinear transmission of the WS_2 film was measured by the near-field Z-scan technique shown in Fig. 2(a). The result is shown in Fig. 2(b) and the modulation depth of WS_2 film sample could be derived to be about 12.7%. Meanwhile, the saturable optical intensity of the WS_2 film is 0.106 mJ/cm^2, which is higher than reported typical values of graphene oxide,[25] carbon nanotubes,[26] or topological insulators,[27] which implies that such high saturable intensity entails large optical intensity for excitation and the threshold of Q-switching operation with the WS_2 film would be higher. The damage threshold of the WS_2/PVA film was measured to be 1.14 mJ/cm^2 by a picosecond Yb-doped fiber laser amplifer system with an output power up to 6.5 W.

To prepare the WS_2-SA, we used a BK7 glass substrate with high refractive index thin polymer of 96% at 1030 nm with a bandwidth of about 60 nm. After mixing WS_2 solution with polyvinyl alcohol (PVA), WS_2/PVA was spin coated on the substrate with low speed. Then the WS_2 saturable absorber mirror (SAM) was finished.

The WS_2 saturable absorber was inserted to a solid-state Yb:LSO laser and the schematic of the laser is shown in Fig. 3. The laser gain medium was a 5 at.%-doped Yb:LSO crystal size of 5 mm×6 mm×3 mm. For stable operation, the Yb:LSO crystal was wrapped with indium foil, mounted on a copper heat sink, and water cooled down to 15.3 °C. The pump source was a fiber-coupled diode laser at 976 nm. The core diameter of the tail fiber was 105 μm and the numerical aperture was 0.22. The pump laser beam was focused by two lenses with an imaging ratio of 1:2. The cavity was composed of three mirrors. M1 was a flat dichroic mirror with antireflection at 980 nm and high reflection at 1020–1100 nm. OC was an output mirror ($T = 2.5\%$) with a radius of curvature of 100 mm. WS_2-SAM was a high reflective mirror coated with WS_2, as shown in Fig. 3.

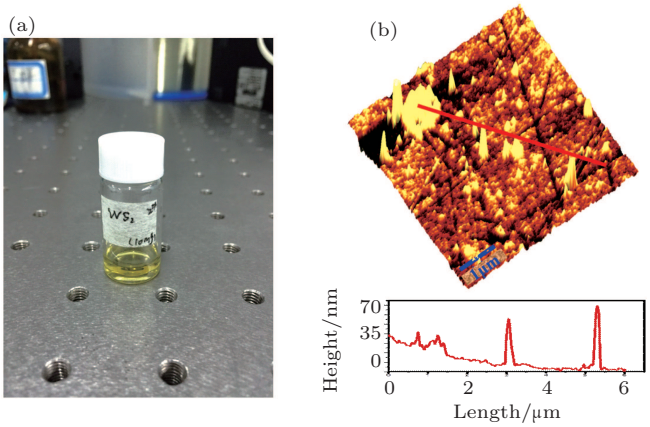


Fig. 1. (color online) (a) WS_2 dispersion after ultrasonication and centrifuging. (b) The AFM scan image of WS_2 NPs and thickness of the WS_2 film.

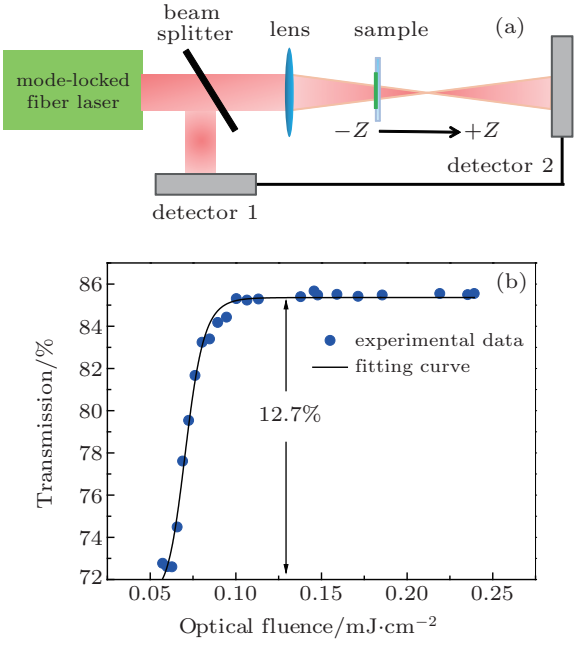


Fig. 2. (color online) (a) The schematic of z-scan system. (b) The nonlinear transmission curve of WS_2 film.

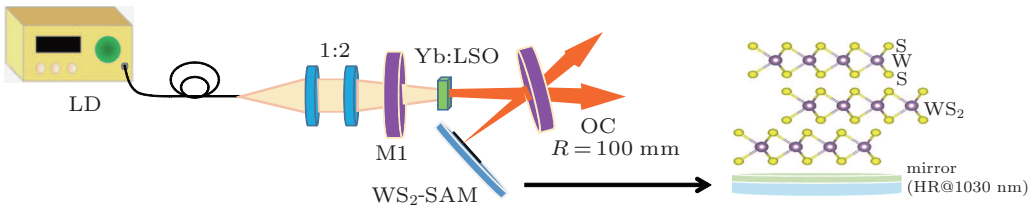


Fig. 3. (color online) Schematic of Yb:LSO laser with a WS_2-SAM.

3. Results and discussion

The average output power of Yb:LSO laser with and without WS_2-SA was plotted in Fig. 4(a). Initially, we investigate the performance of continuous wave (CW) Yb:LSO laser by replacing the WS_2-SAM with a high reflective mirror. The pump threshold was measured to be 2.8 W. With the pump power increasing to 9 W, the average output power increases to 2.77 W, corresponding to an optical-to-optical efficiency of 30.8%. When the WS_2-SAM was used as the end mirror, the laser threshold was up to 6 W. Q-switching began at the pump power of 6.8 W, and the maximum output power was measured to be 250 mW. Note that the output power of Q-switched laser is much less than that of CW laser, which is primarily attributed to the large loss introduced by both of WS_2/PVA and BK7 substrate.

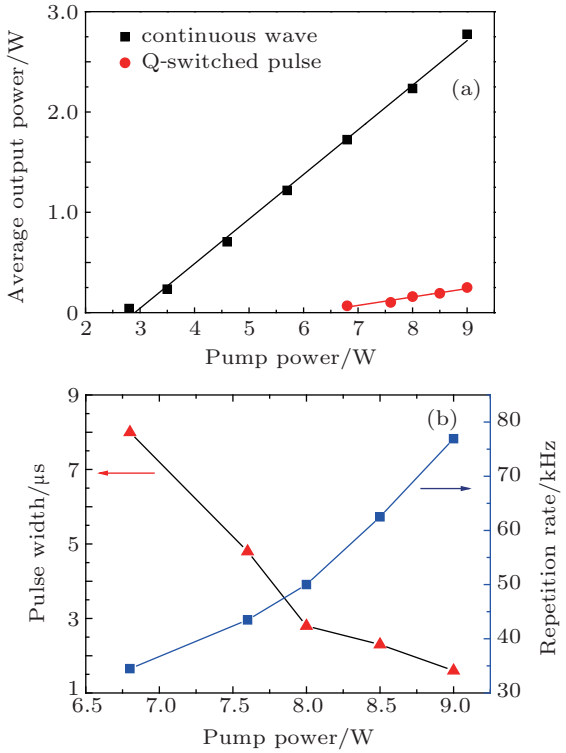


Fig. 4. (color online) (a) Average output power versus incident pump power for continuous wave and Q-switched operation. (b) Pulse width and repetition rate versus incident pump power for Q-switched operation.

The laser performance was observed using a 1 GHz digital oscilloscope (Agilent, 54833A). Figure 4(b) shows the pulse width and repetition rate versus incident pump powers. The pulse width decreases from 8 μs to 1.6 μs, while the pump power increases from 6.8 W to 9 W, and the pulse repetition rate increases from 34.5 kHz to 76.9 kHz. The low repetition rate of Q-switched solid-state laser should be attributed to the higher saturable optical intensity of the WS_2-SA. Higher saturable energy led to shorter buildup time for the pulse generation,[28] so the Q-switched solid-state laser could sustain with a low repetition rate. Note that the repetition rate and the pulse width are not completely linearly dependent on pump power. This is attributed to the gain competition between two wavelengths of 1034 nm and 1056 nm. The gain competition would affect the inversion population. As a result, the non-saturable inversion population changes the output characteristics of Q-switched pulses. Figure 5(a) shows the shorted pulse width of 1.6 μs obtained in our Q-switched Yb:LSO laser based on WS_2 saturable absorber, which is similar to the reported passively Q-switched fiber lasers with WS_2-SAs.[23] The pulse width could be reduced by reducing cavity length and optimizing the WS_2-SA. The energy of Q-switched pulses as a function of incident pump power is shown in Fig. 5(b). When increasing the pump power to 9 W, the maximum pulse energy of 3.25 μJ could be obtained. However, from the evolution of the pulse energy, larger pulse energy could be expected since the pulse energy of Q-switched pulses is not saturated.

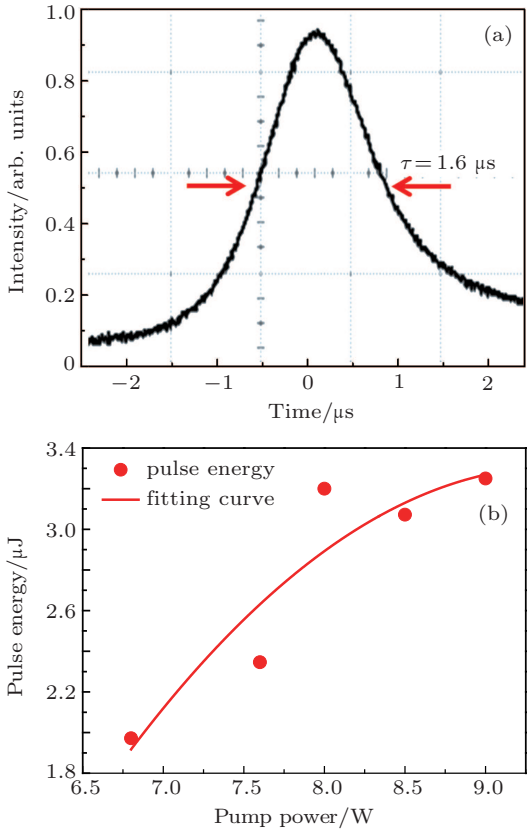


Fig. 5. (color online) (a) Temporal profile of the shortest pulse under pump power of 9 W. (b) Pulse energy as a function of incident pump power.

Finally, we observed the spectra for the CW and Q-switching operation. The results are shown in Figs. 6(a) and 6(b). It could be seen in continuous wave state, the center wavelength is 1056.6 nm. However in Q-switching state, it turns out to be dual-wavelength operation, and the center wavelengths are about 1034.3 nm and 1056.8 nm. The output power at 1056.8 nm is larger than at 1034.3 nm for a larger gain cross section. In experiments, the surface of gain medium was deliberately tuned with a slight deviation angle to M1,

thus the Fabry–Perot effect between mirror M1 and Yb:LSO crystal could be excluded. One reason for dual-wavelength Q-switching is that the laser crystal Yb:LSO has a large emission area. The emission bandwidth of Yb:LSO is as broad as 73 nm[29] and it could be tuned from 1016 nm to 1086 nm,[30] which underlay the dual-wavelength operation. Another reason is the shift of spectrum peak caused by non-stability. It is noteworthy that the output spectra of the Q-switched laser (1034.3 nm and 1056.8 nm) correspond to two of five peaks of the emission spectrum for Yb:LSO crystal (1032 nm and 1055 nm).[31] At last, the non-saturable loss introduced by WS_2 film contributes to a significant decrease of output power, and the tungsten disulphide saturable absorber film also has a great influence on the emission spectrum of the laser.

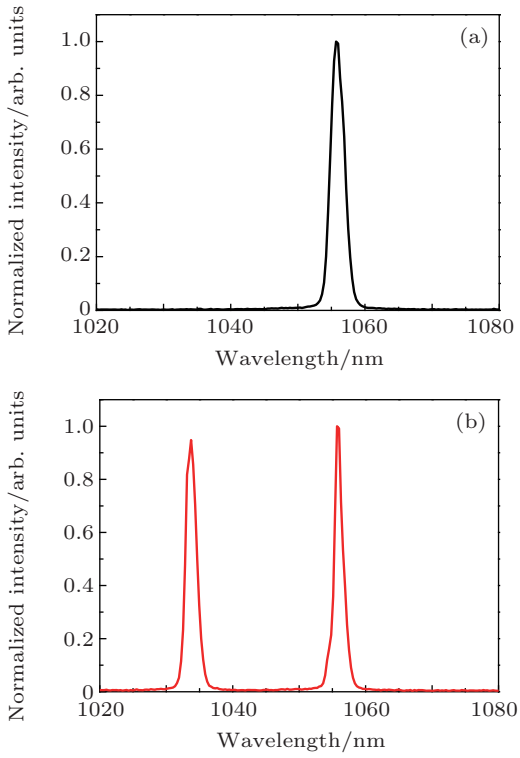


Fig. 6. (color online) (a) The spectrum of CW operation. (b) The spectrum of Q-switching operation.

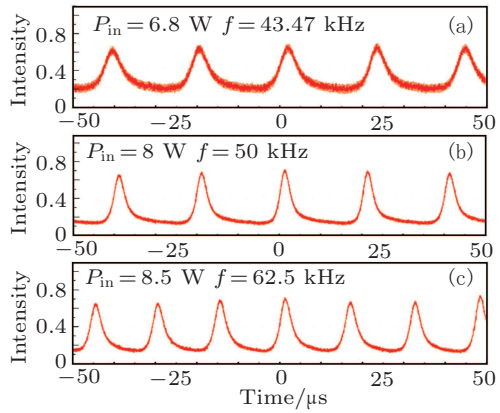


Fig. 7. (color online) Q-switched pulse trains under incident pump powers of (a) 6.8 W, (b) 8 W, and (c) 8.5 W.

Figure 7 shows pulse trains of Q-switched Yb:LSO laser under different pump powers, in which no satellite pulse as reported in Refs. [11], [32], and [33] is observed, which indicates that the dual-wavelength is time-overlapped under Q-switching regime.

4. Conclusions

A passively Q-switched dual-wavelength solid-state laser based on WS_2 saturable absorber was demonstrated. Q-switching operated simultaneously at the center wavelengths of 1034.3 nm and 1056.8 nm. The pulse width and repetition rate were measured from 8 μs to 1.6 μs, and 34.5 kHz to 76.9 kHz, respectively. The maximum output power was 250 mW, corresponding to a single pulse energy of 3.25 μJ. To the best of our knowledge, it is the first time to obtain dual-wavelength Q-switching operation based on WS_2-SA in solid-laser lasers.

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