# 1.5-MHz repetition rate passively Q-switched Nd:$YVO_4$ laser based on $WS_2$ saturable absorber*

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A transmission-type tungsten disulfide ($WS_2$)-based saturable absorber (SA) is fabricated and applied to passively Q-switched Nd:$YVO_4$ laser. The $WS_2$ nanosheets are deposited on a quartz substrate by the vertical evaporation method. By inserting the $WS_2$ SA into the plano-concave laser cavity, we achieve 153-ns pulses with an average output power of 1.19 W at 1064 nm. To the best of our knowledge, both of them are the best results among those obtained by the Q-switched solid-state lasers with $WS_2$-based absorbers. The repetition rate ranges from 1.176 MHz to 1.578 MHz. As far as we know, it is the first time that MHz level Q-switched pulses have been generated in all solid state lasers based on low-dimensional materials so far.

**Keywords:** Q-switched lasers, solid-state lasers, nonlinear optical materials

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## 1. Introduction

Q-switching is advantageous in the production of giant pulses with extremely high pulse energy.[1] Higher output power is possible in Q-switched solid state lasers (SSLs)[2] than that in Q-switched fiber lasers. Therefore, Q-switched SSLs, especially at 1 μm wavelength, have extensive applications in the fine processing, military and medical fields, etc.[3–5] In recent years, many military applications, such as optoelectronic countermeasure and precision laser radar, require high power lasers that emit sub-microsecond pulses with a high repetition rate.[6,7] With the power and pulse width fixed, the higher the repetition rate of laser pulse, the better the interference effect is and the wider the expanded scope of its military applications.[7] Consequently, high repetition rate Q-switching has obviously become a crucial technology in the military field.

Compared with active Q-switching,[4] passively Q-switching does not necessarily rely on the high power consumption of external modulating components such as electro-optic or acousto–optic modulators, so that it can completely satisfy the requirements for low cost and equipment miniaturization.[8] The generation of passively Q-switched pulse is due to the energy mutation caused by the nonlinear saturable absorption of intracavity saturable absorber (SA), such as the semiconductor saturable absorber mirror (SESAM)[9,10] or $Cr^{4+}$:YAG.[11–13] Considering the expensive cost, complex fabrication, narrow wavelength sensibility from the above SA, carbon nanotubes (CNTs),[14–16] graphene,[17–19] and some new low-cost two-dimensional (2D) graphene-like materials like topological isolators (TIs),[20–24] transition metal dichalcogenides (TMDs) including $WS_2$, molybdenum disulfide ($MoS_2$), etc.,[25–33] black phosphorus (BP)[34–38] are made into the effective SAs through a simple fabrication process and used for Q-switching technology in SSLs of various wavelength bands.[14–38] As shown in Table 1, these emerging SAs are (SWCNT, single-walled carbon nanotube; DWCNT, multi-walled carbon nanotude; SAM, saturable absorption mirror; PVA, polyvinyl alcohol; PMMA, polymethyl methacrylate) mostly made by growing nanomaterials through chemical vapor deposition and depositing them on a quartz substrate or a mirror by the spin-coating method. Meanwhile, these materials possess excellent nonlinear optical responses[39] and ultrafast relaxation times,[40] which are appropriate to the generation of a high repetition rate and short pulse duration lasers. Based on the relatively mature CNTs and graphene SAs, the repetition rate and the pulse width of passively Q-switching SSLs reported have been respectively optimized to super-500 kHz and sub-100 ns, and the average output power has reached the watt-level. However, even if numerous research results have proved that graphene-like 2D materials are the excellent SAs in Q-switched SSLs, the repetition rate and the average output power of reported pulsed lasers are very low. The maximum repetition rate of 333 kHz and the shortest pulse width of 182 ns are obtained in a Yb:LGGG laser Q-switched by $MoS_2$ SAM, and the corresponding average output power is only 600 mW.[29]

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**Table 1.** Passively Q-switching SSLs based on new materials.

| SA | Gain medium | Wavelength/nm | Repetition rate/kHz | Pulse width/ns | Output power/W | Reference |
|---|---|---|---|---|---|---|
| SWCNT-SA | Nd:LuYGdVO$_4$ | 1060 | 450 | 52 | 1.56 | 14 |
| | Nd:LuVO$_4$ | | 630 | 95 | 1.8 | |
| DWCNT | Nd:YAG | 1064 | 316 | 90 | 0.64 | 15 |
| Graphene SAM | Nd:GdVO$_4$ | 1063 | 704 | 105 | 2.3 | 17 |
| Graphene K9 glass substrate | Nd:LYSO | 1079 | 159 | 96 | 1.8 | 18 |
| Graphene oxide/PVA | Nd:GdVO$_4$ | 1063 | 600 | 104 | 1.22 | 19 |
| $Bi_2Se_3$ | Nd:YVO$_4$ | 1064 | 135 | 250 | 0.074 | 20 |
| $Bi_2Se_3$ quartz plate | Nd:GdVO$_4$ | 1063 | 547 | 666 | 0.032 | 21 |
| $Bi_2Te_3$ quartz substrate | Yb:GAB | 1043 | 110 | 370 | 0.04 | 22 |
| $Bi_2Se_3$ film | Yb:KGW | 1030 | 174 | 1500 | 0.82 | 23 |
| $MoS_2$-BK7 | Nd:YAlO$_3$ | 1079 | 232.5 | 227 | 0.26 | 25 |
| $MoS_2$ mica | Tm:GdVO$_4$ | 1902 | 48 | 800 | 0.1 | 26 |
| PMMA/$MoS_2$ | Yb:Ca$_3$Y$_2$(BO$_3$)$_4$ | 1030–1050 | 140.4 | 420 | 0.105 | 27 |
| $WS_2$-BK7 | Pr:LiYF$_4$ | 640 | 88 | 630 | 0.022 | 28 |
| $MoS_2$ substrate | Yb:LGGG | 1025–1028 | 333 | 182 | 0.6 | 29 |
| $MoS_2$ quartz glass | Pr:GdLiF$_4$ | 605 | 69.1 | 278 | 0.017 | 30 |
| | | 639 | 140.3 | 403 | 0.009 | |
| | | 721 | 74 | 382 | 0.008 | |
| $MoS_2$ golden mirror | Tm:CLNGG | 1979 | 112 | 4840 | 0.062 | 31 |
| $MoS_2$ quartz glass | Nd:GdVO$_4$ | 1060 | 732 | 970 | 0.227 | 32 |
| | Nd:YGG | 1420 | 77 | 729 | 0.052 | |
| | Tm:Ho:YGG | 2100 | 149 | 410 | 0.206 | |
| BP quartz glass | Yb:ScBO$_3$ | 1063 | 30 | 495 | 0.167 | 34 |
| BP SAM | Cr:ZnSe | 2400 | 176 | 189 | 0.036 | 35 |
| BP quartz glass | Pr:GdLiF$_4$ | 639 | 172 | 189 | 0.018 | 36 |
| | Nd:GdVO$_4$ | 1064 | 312 | 495 | 0.022 | |
| | Tm:Ho:YGG | 2100 | 122 | 636 | 0.027 | |
| | Yb:LuYAG | 1030 | 63.9 | 1730 | 0.006 | |
| BP gold-film mirror | Tm:CaYAlO4 | 1930 | 17.7 | 3100 | 0.012 | 37 |
| | Er:Y$_2$O$_3$ | 2720 | 12.6 | 4470 | 0.006 | |
| BP SAM | Yb:CYA | 1046 | 113.6 | 620 | 0.037 | 38 |

In this paper, we demonstrate $WS_2$ as SA for the Q-switched Nd:YVO$_4$ laser. The $WS_2$-based SA is fabricated by the vertical evaporation method. To achieve a higher repetition rate and shorter pulse width, an only 40-mm length plano-concave laser cavity is designed. Eventually, the 153-ns pulses with a repetition rate of 1.578 MHz and an average output power of 1.19 W are obtained in the 1064-nm Q-switching operation. The results are much better than previous ones from the SSLs Q-switched by TMDs-based absorbers.

## 2. Preparation and characterization of $WS_2$

Firstly, the few-layer $WS_2$ is prepared by using a liquid phase exfoliation method.[41] The proper quantity of bulk $WS_2$ powders is added into a water solution. After a 5-hour high-power sonication, the bulk $WS_2$ is exfoliated into few-layer nanosheets which are dispersed in the water solution. Following the synthesis of the few-layer $WS_2$ suspension, the $WS_2$ nanosheets are transferred onto uncoated quartz substrate by the vertical evaporation method.[42] We pour the $WS_2$ suspension in a square box. Then a hydrophilic quartz plate (1-mm thick) is inserted vertically into the box. Exposing them to air until all the solvent has evaporated, the $WS_2$ nanosheets are deposited on the surface of the quartz substrate. Finally, the quartz coated with $WS_2$ nanosheets acts as a transmission-type absorber of the high repetition rate Q-switched operation. Unlike the previous method, the vertical evaporation method not only controls the transmission rate of $WS_2$ SA, but also is a low-cost fabrication method.

The Raman spectrum of the $WS_2$ SA excited by a 532-nm laser source is measured by a Raman spectrometer. As displayed in Fig. 1(a), two characteristic vibration modes $E^1_{2g}$ (in-plane) and $A_{1g}$ (out-of-plane) are located at 352.2 cm$^{-1}$ and 415.9 cm$^{-1}$, respectively. It should be noted that the frequency difference between two modes is in agreement with the case of few-layer $WS_2$.[43,44] The linear absorption of the $WS_2$ SA is investigated in a wavelength range from 300 nm to 1100 nm by using an optical spectrometer scanning as depicted in Fig. 1(b). Considering the interference from the absorptions of quartz substrate, we prepare the pure quartz substrate as a reference. In comparison with a very flat profile at a level of 93%±0.5% of pure quartz plate (red line), the transmission of $WS_2$ quartz plate (blue dotted line) varies nonlin-

early with wavelength and shows a transmission of 72.7% at our laser wavelength of 1064 nm. Ruling out the interference from the substrate, $WS_2$ SA shows an absorption of 20.7% at 1064 nm.

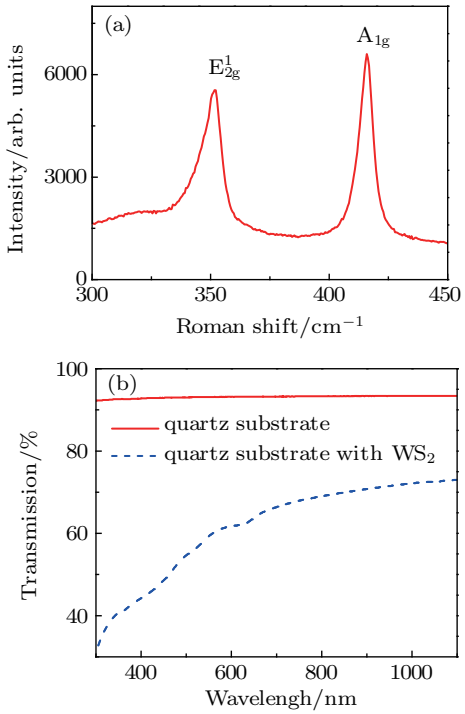



**Fig. 1.** (color online) (a) Raman spectrum; (b) Transmission spectra.

## 3. Experimental setup

Figure 2 shows the schematic of passively Q-switched Nd:$YVO_4$ laser with our $WS_2$ SA. The pump source is a 30-W fiber-coupled laser diode (LD) with emission centered at 808 nm. The core diameter is 200 μm and the numerical aperture is 0.22. Through a 1:2 optical focusing system, the pump laser is focused onto the gain crystal with a spot radius of about 200 μm. A 3×3×15 mm a-cut Nd:$YVO_4$ crystal with an $Nd^{3+}$ concentration of 0.7 at.% is employed as the gain medium, and both light-passing faces of the crystal are coated for 808-nm and 1064-nm anti-reflection (AR) films. In order to ensure excellent heat dissipation, the Nd:$YVO_4$ crystal is wrapped with indium foil and mounted in a water-cooled copper block maintained at 20 °C by a cool-water machine. The Q-switched laser is based on a standard plano-concave cavity with a length of about 40 mm. $M_1$ is a dichroic mirror, which is coated for 808-nm AR and 1064-nm high-reflection (HR) films. The concave mirror $M_2$ with a radius of curvature of 100 mm acts as an output coupler (OC), which has a transmittance of 15% at a laser wavelength of 1064 nm. During Q-switching operation, the as-fabricated $WS_2$ SA is inserted into the laser cavity and located as close to the gain crystal as possible. A fast photodetector (DET10A/M, Thorlabs, Inc., USA) with a specified rise time of 1 ns and a digital oscilloscope (TDS5000B, Tektronix, Inc., USA) with 1-GHz bandwidth are employed to detect and record the laser pulse in the experiment.

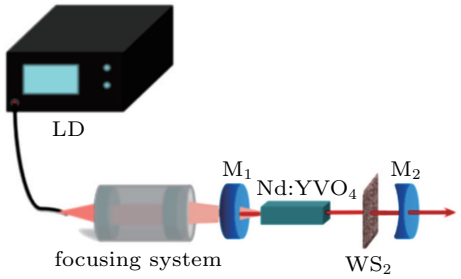



**Fig. 2.** (color online) Schematic diagram of the experimental setup.

## 4. Experimental results and discussion

Initially, in order to confirm the function of the $WS_2$ SA we investigate the performance of continuous wave (CW) Nd:$YVO_4$ laser without SA as a reference. The CW laser operation is realized at a threshold pump power of 2.2 W. The relationship between the CW output power and the pump power is plotted in Fig. 3(a). The blue dots and the red line represent output power and its fitting line, respectively. An average output power of 4.7 W is obtained under a pump power of 11 W, resulting in an optical-to-optical efficiency of 42.7% and a high slope efficiency of 56%. Any self Q-switching has not been observed during the CW laser experiment. When $WS_2$ SA is inserted into the laser resonator, the pulsed laser oscillation is achieved by finely tuning the position of SA in the laser cavity and adjusting the pump power. As soon as the pump power exceeds the threshold of 8.5 W, the stable passively Q-switched operation (QS) is observed. Such a QS can be maintained until the pump power rises up to 10.5 W. However, the absorber would be damaged by high power laser irradiation if we continue to increase pump power. The average output power of QS mode with respect to pump power is demonstrated by blue pentagram notations and the purple fitting line of Fig. 3(a). Under the restriction of thermal damage, the maximum average output power can reach 1.19 W under a pump power of 10.5 W, corresponding to the slope efficiency of 30% and optical-to-optical efficiency of 11.3%. Such a high output power and slope efficiency are attributed to two factors. One is the sufficient spatial mode-matching between the volume of the pump and laser beams in the Nd:$YVO_4$ gain crystal exploited in our experiment. The other one is the improved performance that will be realized with a good balance between suitable transmissions of $WS_2$ SA and OC. However, it can be found that the slope efficiency of the QS laser has a relative drop compared with that of the CW laser and the QS pump threshold is higher, which mainly is caused by the insertion loss of the $WS_2$ SA.

The pulse repetition rate and the pulse width under different incident pump powers are recorded in Fig. 3(b). From the figure we can see that the pulse width has a rapid drop

from 283 ns to the shortest 153 ns as the pump power increases from 8.5 W to 10.5 W, while the repetition rate increases continuously from 1.176 MHz to 1.578 MHz. Our maximum repetition rate of 1.578 MHz is nearly twice as high as that reported in Q-switched SSLs based on low-dimensional nanomaterials,[17] even at least five times as high as that of the previous TMD Q-switched SSLs.[29] The higher repetition rate of passively Q-switched SSLs may be attributed to the ultrafast relaxation time of $WS_2$ ($\sim$ 30 fs),[43] relatively large stimulated emission cross section of Nd:$YVO_4$[44] and an appropriate short cavity.

The pulse duration of 153 ns with a pulse repetition rate of 1.578 MHz is obtained under an output power of 1.19 W. The pulse trains and single pulse profile are displayed in Fig. 3(c). The shortest pulse width of 153 ns is slightly shorter than 182 ns of the previous passively Q-switched SSLs with TMDs SA.[29]

According to the recorded average output power, pulse repetition rate and pulse width, we can approximately calculate the pulse peak power and pulse energy (Fig. 3(d)). The maximum single pulse energy is estimated to be 0.75 μJ and corresponding peak power is 4.9 W. As shown in Fig. 4(a), the optical spectrum of QS laser is centered at 1064.383 nm and the full width at half maximum (FWHM) is measured to be 0.107 nm. Finally, the beam quality of the Q-switched Nd:$YVO_4$ laser at a pump power of 10.5 W is measured by the 90/10 knife-edge method and shown in Fig. 4(b). The $M^2$ factors are calculated to be $M_x^2 = 1.90$ and $M_y^2 = 1.97$.

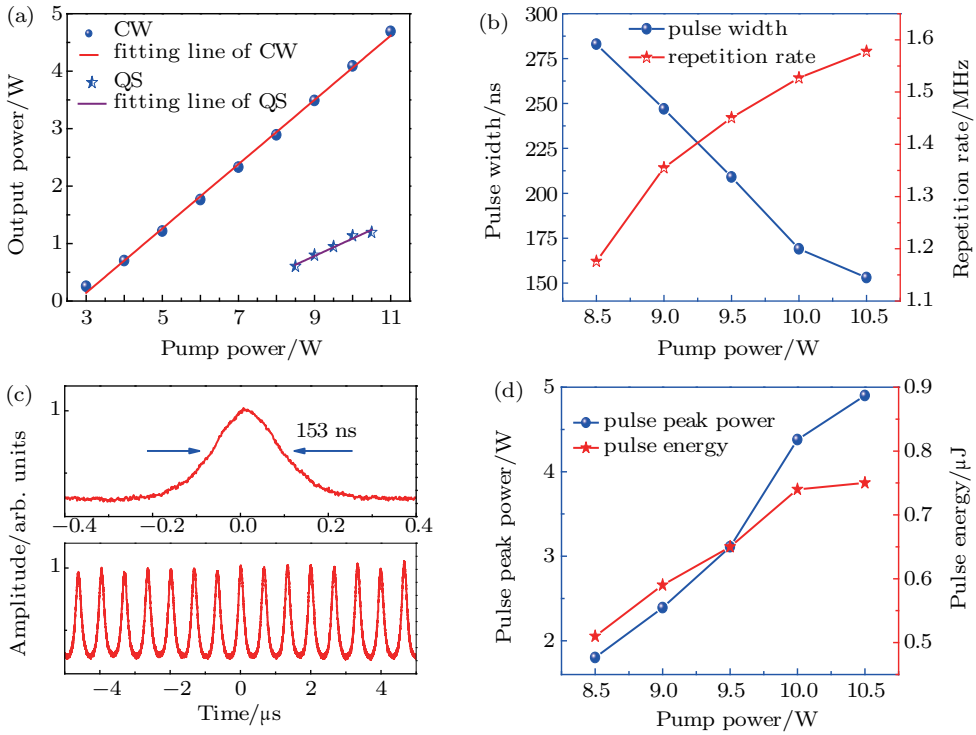



**Fig. 3.** (color online) (a) Output power versus the pump power. (b) Evolutions of the pulse repetition rate and the pulse width with the pump power. (c) The pulse trains and single pulse profile of the shortest pulse. (d) Evolutions of the pulse peak power and the pulse energy with pump power.

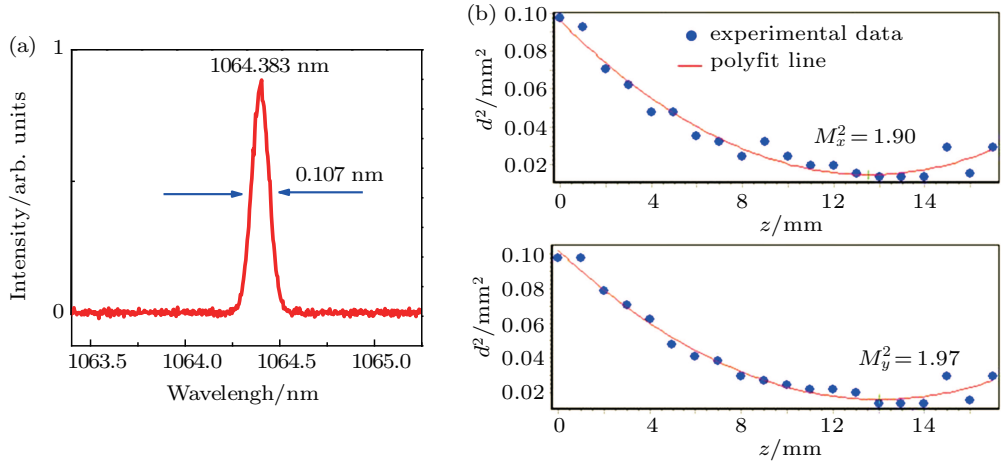



**Fig. 4.** (color online) (a) Optical spectrum. (b) Laser beam quality.

Comparing with the results previously reported on passively QS laser based on TMDs SA, we obtain here short pulses with significantly large output power and higher than the 1-MHz repetition rate. Even, a maximum repetition rate of 1.578 MHz can be considered as being superior among the QS lasers based on other nanomaterials like CNTs, graphene, and TIs (see Table 1). However, compared with the results obtained with the QS laser by SESAMs or $Cr^{4+}$:YAG,[8–13] our Q-switched laser results, the pulse width and output power lag behind. It is mainly due to the immature fabrication technology of 2D materials-based SAs. Thus future design of new emerging SAs for the generation of high energy ultrashort Q-switched pulses should focus on the optimization of the modulation depth and the SA transmittivity. Besides, the present results can still be certainly improved by shorting the laser cavity, by optimizing mode-matching between pump and laser beams and by removing the generated heat in $WS_2$ SA.

## 5. Conclusions

In this article, the efficient performance of a transmission-type $WS_2$ SA on the high repetition rate Q-switched Nd:$YVO_4$ laser is demonstrated. The minimal duration of output pulses is 153 ns at pulse repetition rate 1.578 MHz, average output power 1.19 W, and wavelength of $\sim$ 1064.4 nm. The results are the best among the results obtained by Q-switched solid-state lasers with TMDs-based absorbers. Nevertheless, it is the first time that the repetition rate has been above 1 MHz for Q-switched solid state laser based on one-dimensional or 2D materials. The maximum single pulse energy is 0.75 μJ and the highest peak power is 4.9 W. The results indicate that the $WS_2$ SA made by the vertical evaporation method can be used to generate high-output-power hundreds of nanosecond laser pulses at a repetition rate at an MHz-level.

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