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Tungsten disulfide - graphene oxide as saturable absorber for passively Q-switched mode-locked Nd: $GdTaO_4$ laser at 1066 nm

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ABSTRACT

tungsten disulfide (WS_2) & Graphene oxide (GO) based saturable absorber (SA) was demonstrated and studies for passively Q-switched mode-locked Nd: $GdTaO_4$ laser. The fabrication process of mixed SA was described. Passively Q-switched mode-locked operation with sub-600ps pulses was obtained by using this SA. Taking into account the simpler manufacturing progress, larger single pulse energy and better modulation depth, the mixed WS_2-GO saturable absorber seems to be good way as suitable saturable absorber for solid state lasers.

1. Introduction

Diode-pumped passively mode-locked solid-state lasers with simple resonant cavity structure, proper average power and rather high peak power have been applied in many fields such as: industry, scientific research and medical practice [1,2]. Primary attention was paid to saturable absorbers with low cost, fast recovery time and good modulation depth. As single carbon atomic layer and zero-gap semiconductor, graphene with high electron mobility and wide modulation wavelength range shows better applications as SAs in solid state lasers especially for multi-wavelength lasers [3,4]. For its simple production process and same saturable absorption properties as graphene, graphene oxide (GO) seems more suitable as SAs for passively Q-switched and mode-locked lasers [5]. However, with modulation depth, neither graphene nor graphene oxide could be used as saturable absorbers to generate larger pulse energies [6,7].

Research on graphene and GO usher a door to graphene analogues with good photoelectric properties. Two-dimensional (2D) nano system was formed in graphene-like materials (such as MoS_2 or WS_2 etc.) owing to the weak van der Waals interaction between layers and strong covalent bonds in layers [8,28,29]. Most recently, MoS_2 nanosheets have shown stronger nonlinear optical response than graphene determined by the unique symmetry lattice structure and electronic band structure [9–11]. Many reports of MoS_2 SA used in fiber lasers [12–15]. Some researches also demonstrated MoS_2 SA in solid state lasers [16,17]. In addition, few layers of tungsten disulfide nanosheets were proved to be a promising saturable absorber for ultrafast lasers. Compared with many reports of WS_2 SA in fiber lasers [18–20,30], there are few reports can be found in solid state lasers [21]. Many 2D material (WS_2 or MoS_2) nanosheets on saturable absorber will cause larger absorption loss. Many researches have shown that graphene and GO exhibit widest modulation wavelength range among all 2D materials [22]. Mixed SA devices shows improved nonlinear optical properties than that of graphene, such as modulation depth and saturation intensity [3]. Owing to the wider absorption at around 808 nm, lower symmetry and higher photo luminescence efficiency, Nd:$GdTaO_4$ single crystal can be employed as an appropriate solid-state laser materials in high-power lasers [23]. In addition, shorter fluorescence lifetime of excited-state (178.4 μs) made this crystal easily to produce mode-locked pulses [23].

In this paper, we experimentally showed passively Q-switched mode-locked Nd:$GdTaO_4$ laser at 1066 nm with mixed WS_2-GO SA. The transmissivity and absorption coefficient of the WS_2-GO SA are measured to be 88.1% and 0.268 at 1066 nm, respectively. The repetition rate of 83 MHz and the minimum pulse width of 586 ps were achieved. The results clearly indicates the few-layers WS_2-GO film can employed as suitable SA for ultrafast lasers.

2. Preparation and characterization of WS_2-GO saturable absorber

Graphene oxide (GO) was prepared by a modified Hummers

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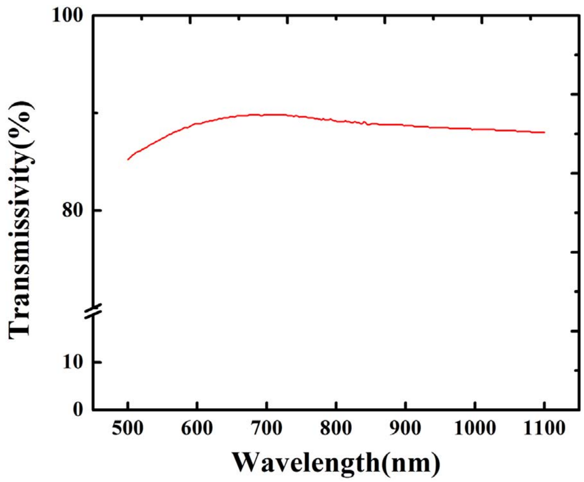

Fig. 1. UV–vis–NIR transmitted spectrum of WS_2-GO saturable absorber.

method [24]. The preparation process of WS_2-GO SA is depicted as follows. First of all, 0.1 ml of the alcohol dispersed GO solution was added into 10 ml of alcohol. Secondly, 0.005 g of WS_2 powder (purity of 99.99%) was added into the alcohol dispersed GO solution. And then, the mixture was stirred by ultrasound for 20 min. Next, a quartz sheet was completely submerged into the mixture. After that, the quartz substrate was left at room temperature for 18 h. Finally, the WS_2-GO based saturable absorber was obtained.

UV–vis–NIR transmitted spectrum and absorption spectrum were shown in Fig. 1 and Fig. 2. As shown in Fig. 1 and Fig. 2, The transmissivity and absorption coefficient of the WS_2-GO SA are measured to be 88.1% and 0.268 at 1066 nm, respectively. Fig. 3 shows the nonlinear transmission curve of the WS_2-GO SA, which was measured by a 52-fs Yb-PCF amplifier at 1040 nm with a repetition rate of 42 MHz, The modulation depth and saturation power intensity were about 8.6% and 1.16 MW/cm^2, respectively.

3. Experimental setup

Fig. 4 shows the schematic of the Nd: $GdTaO_4$ laser. A standard Z-folded cavity with the length of 1.8 m was used. The pump source was a fiber-coupled diode laser with center wavelength of 808 nm. The Nd:$GdTaO_4$ crystal was employed as gain media in the experiment with the dimensions of 2×2×5 mm^3. Laser crystal was mounted in a water-cooled copper block and the circulating water temperature was kept less than 20 °C. Flat mirror M_1 was highly reflectively coated at

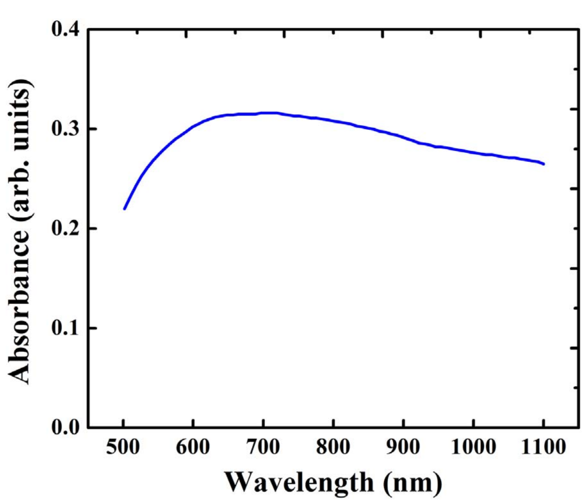

Fig. 2. Linear absorption coefficient of WS_2-GO saturable absorber.

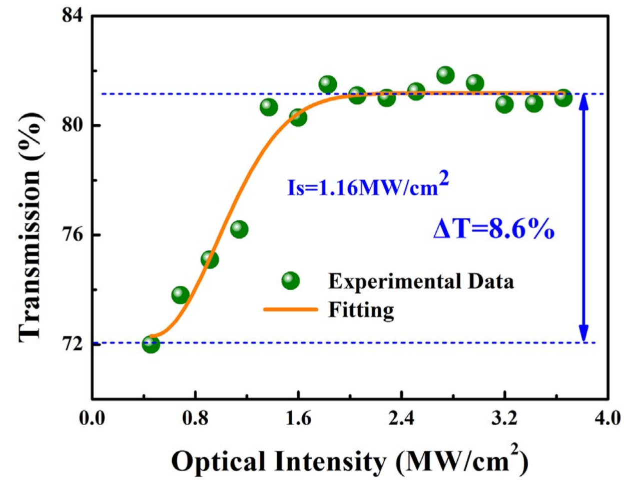

Fig. 3. Measured saturable absorption with a modulation depth of 8.6%.

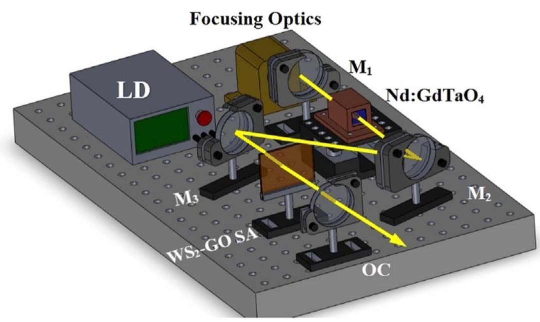

Fig. 4. Schematic setup of the QML Nd: $GdTaO_4$ laser.

1.06 μm and anti-reflectively coated at 808 nm. The two concave mirrors M_1 and M_2 have the same radius of curvature of −400 mm. The flat mirror OC was employed as output coupler with the transmissions of 1.5% at 1.06 μm laser wavelength. Mixed WS_2-GO films deposited on the quartz sheet was employed as the saturable absorber. The laser spot radius on the mixed saturable absorber was 0.12 mm.

4. Experimental results and discussions

Firstly, continuous wave operation was obtained with the optical conversion efficiency and the slope efficiency of 6.2% and 12% respectively. The threshold pump power of continuous wave operation was 0.9 W. Then WS_2-GO saturable absorber was inserted into the laser cavity before the output coupler. When the pump power increases to 1.5 W, Q-switched operation can be obtained. The Q-switched mode-locked operation was obtained with the pump power increases to 2 W. In order to protect the crystal and quartz substrate of WS_2-GO saturable absorber,the maximum pump power is 4 W. Also, the mode-locked operation with this laser can be obtained with the higher pump power.

Fig. 5 shows the relationship of the output power versus pump power. Under the pump power of 4 W, the maximum average output power of 0.197 W was obtained with the optical conversion efficiency of 4.9%.

An oscilloscope (Agilent DSO54832b) and a fast photo-detector (ET-3000) were employed to record the Q-switched mode-locked laser pulse during this experiment. Fig. 6 and Fig. 7 shows the temporal shape of a Q-switched pulse envelope and the pulse train of the QML Nd:$GdTaO_4$. laser. The repetition rate of the mode-locked pulse inside the Q-switched envelope is 83 MHz. The mode-locked pulse width can be estimated according to the following formula [25,26]:

$$t_{real}^2 = t_{measure}^2 - t_{probe}^2 - t_{oscilloscope}^2$$

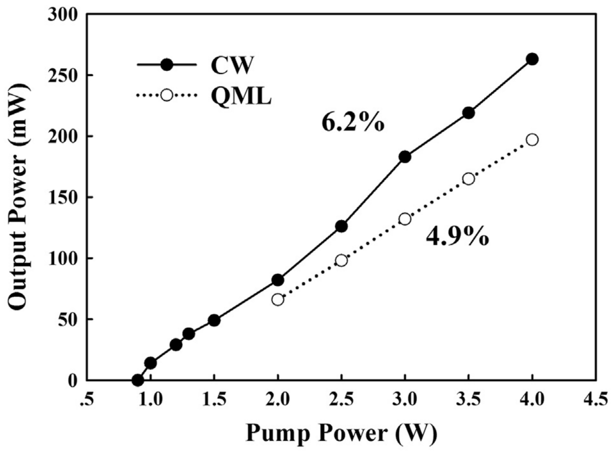

Fig. 5. The output power versus the incident pump power of the continuous wave (CW) and Q-switched mode-locking (QML).

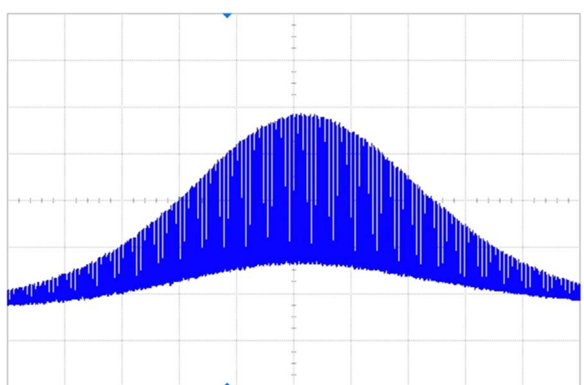

Fig. 6. Temporal shape of a Q-switched pulse envelope (500 ns/div).

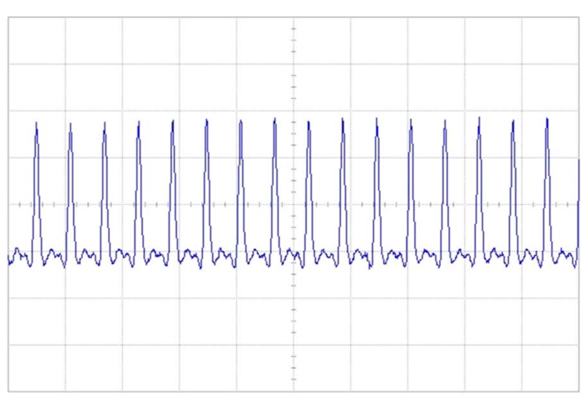

Fig. 7. Pulse train of the Q-switched mode-locked Nd: $GdTaO_4$ laser (20 ns/div).

In this formula, t_{real} is the real rise time of the pulse, $t_{measure}$ is the measured rise time, t_{probe} is the rise time of the probe and $t_{oscilloscope}$ is the rise time of the oscilloscope.

In our case, the rise time of mode-locked pulses, oscilloscope and probe are 0.6 ns, 0.35 ns and 0.175 ns respectively. In addition, the pulse width is approximately 1.25 times more than the rise time. Therefore, the mode-locked pulse width can be estimated as 568 ps.

The output spectrum of the Q-switched mode-locked Nd:$GdTaO_4$ laser with WS_2-GO SA is shown in Fig. 8. The resolution of the spectrum analyzer is about 1 nm (FWHM). Laser wavelength centered at 1066 nm with the full width at half maximum (FWHM) of 1.93 nm has been demonstrated. The output spectrum is exactly consistent with the peak fluorescence wavelength of the Nd:$GdTaO_4$ crystal [27].

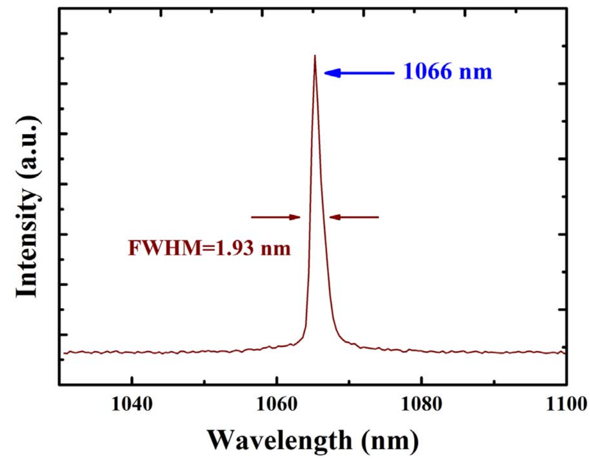

Fig. 8. Spectrum of the QML Nd: $GdTaO_4$ laser by WS_2-GO SA.

5. Conclusions

In summary, we have experimentally demonstrated a passively Q-switched mode locked Nd: $GdTaO_4$ laser using mixed WS_2-GO as SA. Under the pump power of 4 W, the maximum average output power of 0.197 W was obtained with the optical conversion efficiency of 4.9%. The shortest mode-locked pulse width can be estimated as 568 ps. The preparation process of WS_2-GO SA was also depicted. Moreover, Nd:$GdTaO_4$ with wide absorption bandwidth is suitable for laser diode-pumped.

Acknowledgments

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