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Passively Q-Switched Nd:YVO_4 Laser Using a Gold Nanotriangle Saturable Absorber *

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A passively Q-switched Nd:YVO_4 laser at 1064 nm is demonstrated based on a gold nanotriangle saturable absorber (GNT SA). Under a pump power of 3.82 W, the maximum average output power of 218 mW is achieved, corresponding to a slope efficiency of 12.9%. The minimum pulse width is 165 ns and the maximum pulse repetition rate is 300 kHz at the pump power of 3.48 W. Our results prove that the GNT SA is a promising saturable absorber for near-infrared lasers.

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Near-infrared pulsed lasers with high peak power and ultra-short pulse width are of potential interest in numerous applications such as ranging, microsurgery, geochemistry and precision laser machining.[1–3] The passive Q-switching technique is a commonly used method to achieve such lasers due to its simple and compact cavity design.[4,5] In recent years, novel two-dimensional (2D) materials, such as saturable absorbers (SAs) such as graphene, topological insulators (TIs) and transition metal dichalcogenides (TMDs),[6–10] have attracted researchers' attention because of their unique photonic and optoelectronic properties. Using these materials, hundreds of ns-level pulses have been achieved, which indicates the great potential of 2D materials for 1 μm pulsed lasers.[7–10]

As another important representative of 2D materials, metallic nanoparticles such as Au nanostructures have attracted more attention because of their large third-order nonlinearity and their fast recovery time,[11] broadband absorption[12] and ultrafast response time.[13] It is well known that the physical and chemical properties of nanostructures are closely related to their size and shape[14] and the nonlinear saturable absorption effect comes from ground state plasmon bleaching.[15–17] So far, it has been experimentally proved that three kinds of gold nanoparticles (GNPs), gold nanospheres (GNSs), gold nanorods (GNRs) and gold nanocones (GNCs), can be used as SAs for Q-switched lasers.[15,18–20] An all-fiberized Q-switched laser with a pulse width of 1.78 μs at 1.56 μm using a GNS SA was reported by Fan *et al.*[15] In 2016, Zhang *et al.* demonstrated an all-solid-state Q-switched laser using gold nanobipyramids (GNBPs) with a pulse width of 396 ns and Q-switched threshold of 7 W at 1.1 μm.[18] In 2017, based on GNRs, Song *et al.* reported a double-wavelength passively Q-switching Nd:YAG laser at 1064.3 and 1112 nm.[19] In addition to the above three GNPs, the GNTs and their compound are also particularly promising because of their sharp corners and edges, providing 'hot spots' that enhance surface-enhanced Raman spectroscopy (SERS) sensing abilities in near-infrared wavelengths. At present, the preparation techniques of the GNTs are simple and mature.[21–25] By accurately controlling the aspect ratios, the absorption peak of GNTs could be measured at 1092 nm (Fig. 1(a)). Furthermore, because of their unique electron–phonon and phonon–phonon interaction processes, the recovery time of GNTs is typically in a timescale of a few picoseconds. Additionally, Bai *et al.* have achieved an all-solid passively Q-switched Nd:YAG ceramic laser with a GNT SA at 1 μm.[26] Therefore, it is prospective to obtain a self-starting Q-switched laser operation in the near-infrared region.

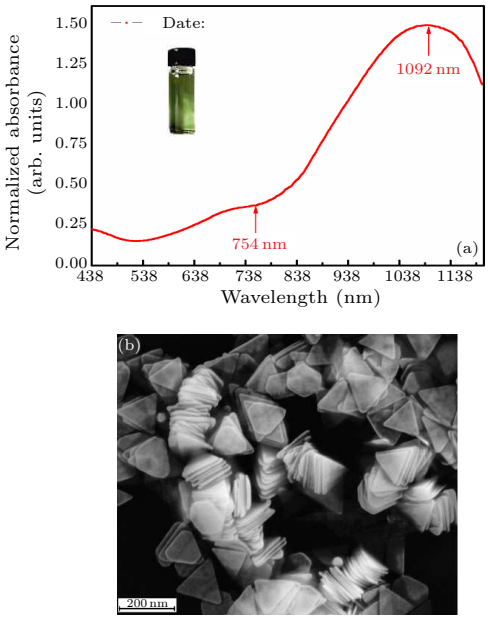

Fig. 1. (a) The absorption spectrum of the GNTs. Inset: image of the GNT solution. (b) TEM image of the GNTs.

In this work, we successfully fabricate a GNT SA grown by the seed-mediated growth method,[27,28]

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and demonstrate a diode-end-pumped passively Q-switched Nd:YVO_4 laser with GNTs as an SA operating at 1064 nm for the first time. The maximum average output power of 218 mW is obtained under a pump power of 3.82 W, and the pulse width and pulse repetition rate are 165 ns and 300 kHz, respectively, corresponding to an optical conversion efficiency of 5.71% and a slope efficiency of 12.9%.

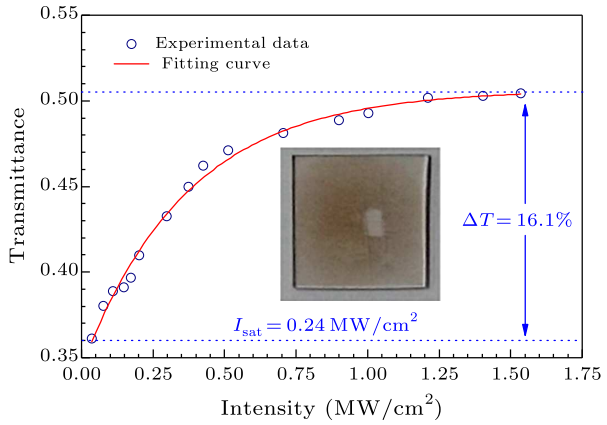

Fig. 2. The relationship between nonlinear transmission and incident peak intensity of the GNT SA at 1.0 μm. Inset: image of the GNT/PVA SA.

The GNTs in our experiment were synthesized by the seed-mediated growth method. The details of the preparation process for the GNT solution (the inset of Fig. 1(a)) can be seen in Bai's previous work.[21] Figure 1(b) shows a transmission electron microscopy (TEM) image of the GNTs with a scale bar of 200 nm, which clearly shows triangular morphology. The corresponding absorption spectrum of the GNTs is shown in Fig. 1(a) including two absorption peaks. One is the transverse surface plasmon resonance (SPR) absorption peak located at approximately 754 nm and the other is the longitudinal SPR absorption peak at 1092 nm. The fabrication of our GNT SA is different from that in previous works, and the solution was not just simply shifted onto a K9 glass sheet. In this work, the GNTs/polyvinyl alcohol (PVA) film used in our work was synthesized via a solution-phase exfoliation/spin-coating method, which can be used to obtain film of several tens of nanometers in thickness.[29] Firstly, 4.0 g PVA is dissolved in 100 ml of double-distilled water and continuously stirred over a magnetic stirrer at a constant temperature of 80℃ for 2 h to obtain the homogeneous PVA solution at ∼4 wt.%. Next, 50 ml of the GNT solution and 100 ml of the PVA solution as-prepared beforehand was pipetted by a pipette into a beaker and vigorously stirred for another 2 h. The mixture was then sonicated for 24 h using an ultrasonic homogenizer to produce well-dispersed colloidal solution. The solution was left for 24 h to observe whether there was precipitate. Finally, 0.1 ml of the suspension was sprayed onto a glass substrate by the spin-coating method and evaporated in an oven by maintaining it at 30℃ for 4 h to obtain the GNTs/PVA-SA (the inset of Fig. 2). The nonlinear optical absorption of the GNT SA was characterized using an open-aperture Z-scan technique. For this, a picosecond fiber source operating at 1064 nm was used as the pump light (15 ps pulse duration, 41 MHz pulse repetition rate). Continuously adjusting the distance between GNT SA and the beam splitter further varied the intensity. As described in Fig. 2, it turned out that the modulation depth and saturation intensity were 16.1% and 0.24 MW/cm^2, respectively, further indicating that the GNT SA can be used to induce Q-switching.

The experimental arrangement is schematically shown in Fig. 3. A narrow line-width 808 nm fiber-coupled laser diode (NA=0.22) was used as the pumping source. After a 1:1 coupling lens system, the pump laser was coupled into the laser crystal and the waist diameter was about 300 μm. A linear plane-concave cavity with the length of 30 mm was designed for the 1064-nm operation. The concave mirror was used as an input mirror with a curvature radius of 300 mm, which was anti-reflection (AR) coated for 808 nm and high reflection (HR) for 1064 nm. The output coupler M2 is a flat mirror with a transmission of 4% for 1064 nm. A 1.0 at.% doped Nd:YVO_4 crystal with $3 \times 3 \times 15$ mm^3 dimensions was used as the laser gain medium wrapped in indium foil and tightly mounted in a copper block water-cooled to 19℃. Both sides of the laser crystal were AR coated for 1064 nm and 808 nm (<0.2%). The power meters were a Molectron PM10 type probe and a Molectron EPM2000 meter. The laser pulse was detected by a 1 GHz InGaAs detector produced by New Focus with a rising time of 400 ps. The pulse width and repetition rate were recorded by an Infiniium DSO90804A digital storage oscilloscope (8 GHz bandwidth, 40 G samples/s).

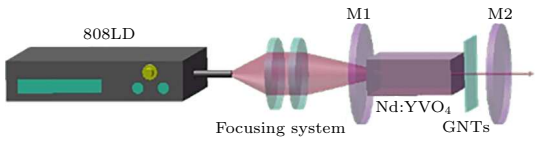

Fig. 3. Schematic illustration of the Q-switched Nd:YVO_4 laser based on GNTs.

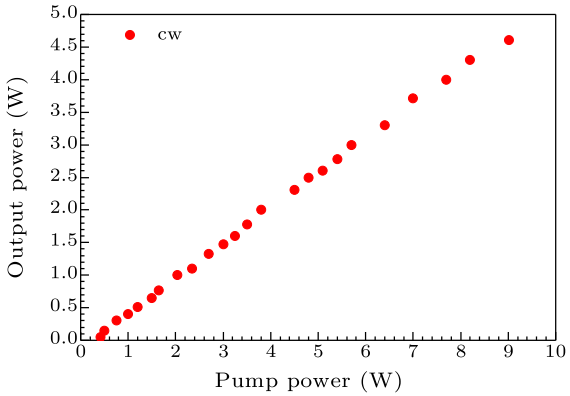

Fig. 4. The output power of the cw laser versus the pump power.

Firstly, the continuous-wave (cw) performance of the laser was investigated. The linear relationship between the cw output power versus the pump power is shown in Fig. 4. The maximum output power of 4.61 W was obtained at the pumped power of 9.01 W, corresponding to an optical-to-optical efficiency of

51.2% and a slope efficiency of 53.7%.

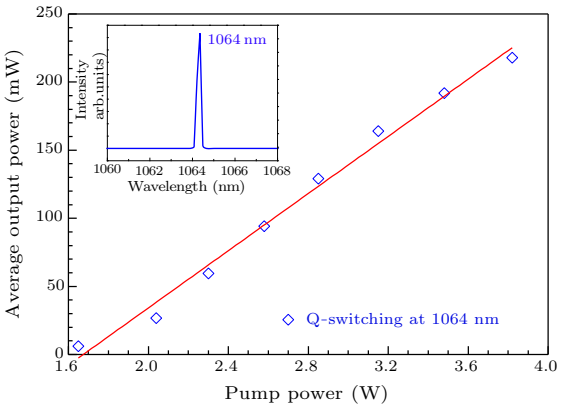

Fig. 5. The output power of the Q-switched laser versus the pump power. Inset: laser emission spectrum.

Then, the passively Q-switched operation was realized by inserting the SA into the cavity near M2. The relationship between the average output power and pump power is shown in Fig. 5. A maximum average output power of 218 mW was obtained at a pump power of 3.82 W, corresponding to an optical conversion efficiency of 5.71% and a slope efficiency of 12.9%, respectively. When the pump power was higher than 3.82 W, the passively Q-switched operation was unstable, thus the incident power did not exceed that. Because of the large insert loss of the SA, the threshold of 1.62 W was much higher than that of the cw operation. The dependences of the pulse width and the pulse repetition rates on the pump power are depicted in Fig. 6. It could be found that with increasing the pump power, the pulse width varied from 910 to 165 ns. Meanwhile, the repetition rate changed from 65 to 300 kHz, which presents a typical feature of passively Q-switched lasers. At a pump power of 3.48 W, the minimum pulse width of 165 ns and the maximum repetition rate of 300 kHz were obtained with the 4% output coupler. Then we calculated the corresponding single pulse energy and peak power estimated to be 0.63 μ J and 3.80 W. As shown in the inset of Fig. 5, the emission spectrum of the passively Q-switched laser is located in 1064 nm, which was detected by an optical spectrum analyzer (Yokogawa AQ6315 A) of a spectra range from 350 to 1750 nm.

A typical oscilloscope trace with the pulse repetition rate of 300 kHz and a temporal pulse shape with the width of 165 ns are shown in Fig. 7. To better contrast with our work, some representative Q-switched lasers using various 2D SAs in near-infrared wavelengths are summarized in Table 1. It can be seen that we obtained the best results in the GNP-based Q-switched lasers in both the pulse width and the repetition rate. Noting that our work is also competitive compared with another nanosheet-based Q-switched laser at about 1 μm.

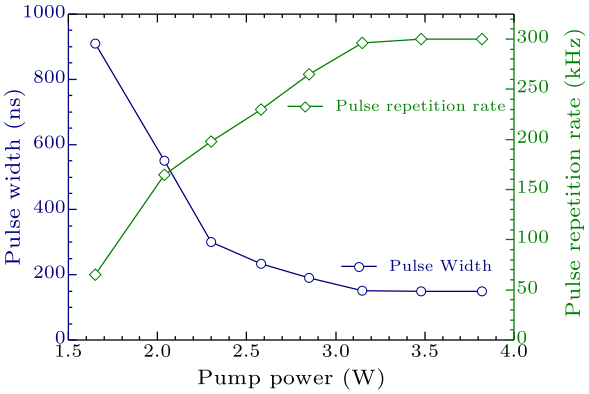

Fig. 6. Evolution of pulse repetition rate and pulse width varying with pump power.

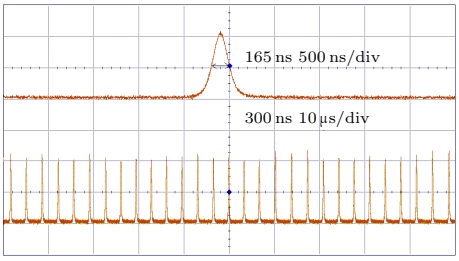

Fig. 7. Temporal traces of the Q-switched pulse train.

Table 1. Summaries of the passively Q-switched solid-state laser at near-infrared wavelength based on 2D SAs.

Gain medium	Wavelength (nm)	Type of SA	Pulse width (ns)	Repetition rate (kHz)	Ref.
GNP-based Q-switched laser					
Nd:YVO_4	1064	GNBPs	396	91	Ref. [18]
Nd:GAGG	1061	GNRs	250	220	Ref. [20]
Nd:YAG	1064	GNRs	223	300	Ref. [19]
Nd:YVO_4	1064	GNTs	165	300	Our work
Other nanosheets-based Q-switched laser					
Nd:$GdVO_4$	1340	graphene	450	22–52	Ref. [6]
Nd:Lu_2O_3	1077, 1081	TIs	720	44–95	Ref. [7]
Yb:CYA	1046	BP	620	87–113	Ref. [8]
Nd:$YAlO_3$	1079	MoS_2	227	32–232	Ref. [9]
Yb:GAB	1061	WS_2	440	37–107	Ref. [10]

In conclusion, a diode-pumped passively Q-switched Nd:YVO_4 laser operating at 1064 nm with a GNT SA has been demonstrated for the first time to the best of our knowledge. The maximum average output power of 218 mW is obtained under a pump power of 3.82 W, corresponding to an optical conversion efficiency of 5.71% and a slope efficiency of 12.9%. The pulse repetition presents the variations of 65–300 kHz with the pump power increasing from 1.65 to 3.82 W. The minimum pulse width of 165 ns with the pulse rep-

etition rate of 300 kHz is obtained at the pump power of 3.48 W.

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