CHIN. PHYS. LETT. Vol. 34, No. 4 (2017) 044203

Passively Q-Switched Yb-Doped Fiber Laser Operating at 1.06 µm with Two-Dimensional Silver Nanoplate as Saturable Absorber *

Sheng-Gui Fu(付圣贵)**, Xue-Ying Ouyang(欧阳雪莹), Jin-Jian Li(李金健), Xiao-Juan Liu(刘晓娟)
School of Science, Shandong University of Technology, Zibo 255049

(Received 31 October 2016)

A two-dimensional silver nanoplate is prepared with the seed-mediated growth method and is used for achieving pulse fiber laser operation. By controlling the dimension parameters of the silver nanoplate, the surface plasmon resonance absorption peak of the material is successfully adjusted to 1068 nm. Based on the silver nanoplate as a saturable absorber, a passively Q-switched Yb-doped fiber laser operating at 1062 nm is demonstrated. The maximum average output power of 3.49 mW is obtained with a minimum pulse width of 1.84 µs at a pulse repetition rate of 65.7 kHz, and the corresponding pulse energy and peak power are 53.1 nJ and 28.8 mW, respectively.

PACS: *42.55.Wd*, *42.60.Gd*, *42.70.Hj* DOI: 10.1088/0256-307X/34/4/044203

Q-switched lasers have widely important applications in the fields of spectroscopy, remote sensing, telecommunications, and bio-medical diagnostics owing to their advantages of low cost, compactness, large pulse energy and so on.[1−8] The main technique of achieving passively Q-switched lasers is based on saturable absorbers (SAs). Typical SAs such as Cr^{4+}-doped crystals,[1] V^{3+}-doped crystals,[2] graphene and graphene-like two-dimensional materials[3−13] have been widely investigated and applied. As a result, based on Cr^{4+}-doped crystals, or V^{3+}-doped crystals as SAs, pulse lasers with high power, narrow width pulse can be obtained. However, the peak absorption of the crystals are always located at a narrow stationary area, which limits the widespread application of those kinds of SAs.

Graphene[3−7] and other graphene-like two-dimensional materials such as MoS_2,[8,10] WS_2[8,9] and $MoSe_2$,[8] black phosphorus,[11] and topological insulators (Bi_2Se_3,[12] Bi_2Ti_3[13]) have outstanding optical properties including ultra broad absorption, high third-order nonlinearity and ultrafast nonlinear response time.[6−14] Therefore, based on those SAs, pulsed laser operations within a wide spectral range can be obtained. The two-dimensional materials acting as SAs have promoted the progress of the pulsed lasers, while the absorption intensities of those materials are associated with the layers of the materials, which can only change gradiently rather than continuously.[6−13]

Recently, nanomaterials have received a great deal of attention due to their extraordinary electronic and optical properties dependent on their shape, size, and aspect ratio.[14−17] In comparison with the above-mentioned SAs, such as graphene and topological insulators, nanomaterial SAs have the most important advantage of a variable surface plasmon resonance (SPR) peak, which can be achieved by controlling the aspect of the materials.[16−19] Additionally, metal nanoparticles (NPs) exhibit a relatively fast response time of a few picoseconds,[18] and the SPR peak can range from the near-UV to the IR by changing the NP sizes and shapes. Recently, the theoretical potential of these SAs for Q-switching and mode-locking in the short-wavelength range has been studied.[14,20] In addition, several works have been demonstrated to investigate the potential of nanomaterials for pulsed lasers. Zhang *et al.* have demonstrated that gold nanobipyramids (Au-NBPs) can be used as SAs for ultrafast pulsed-laser applications.[17] Jiang *et al.* have proposed that spherical GNPs could be used to realize the passively Q-switched fiber laser.[15]

In this Letter, based on the silver nanoplate as a saturable absorber, a passively Q-switched Yb-doped fiber laser operated at 1062 nm is demonstrated. To our knowledge, no work has been reported before to focus on the applications of silver nanoplate in the pulse laser region. Based on the silver nanoplate as a saturable absorber, when the pump power is 345 mW, a 1062 nm Q-switched laser with the pulse width of 1.84 µs at the repetition rate of 65.7 kHz can be obtained. The results prove that silver nanoplates have a good performance as an SA in the field of pulse lasers. In our opinion, new SAs with wide absorption band and variable absorption peaks can be compounded by combining the silver nanoplate with graphene or other graphene-like two-dimensional materials, which will immensely promote the development of the passively Q-switched technology.

The silver nanoplates used in our experiment were

*Supported by the Foundation of Shandong Province under Grant No J13LN28, and the National Natural Science Foundation of China under Grant No 11304184.
**Corresponding author. Email: shengguifu_sdt@163.com

synthesized through a seed-mediated growth method. For the preparation of seed solution, 220 µL of 1% sodium citrate, 20 µL of 0.1 M silver nitrate, 48 µL of 30% hydrogen peroxide and 120 µL of 0.1 M sodium boron hydride were added into 20 mL pure water, and the solution was vigorously stirred for 5 min. Then, 1.67 mL acetonitrile were added into 3.3 mL pure water, and the solution was placed in ice water for 15 min. After that, 50 µL of 0.1 M ascorbic acid, 61 µL of 1% citrate, 2 mL seed solution which has been concentrated 2.5 times and 40 µL of 0.1 M $AgNO_3$ were sequentially added into the solution. Next, the solution was placed into the ice water for 30 min and centrifuged at 3000 rpm for 10 min.

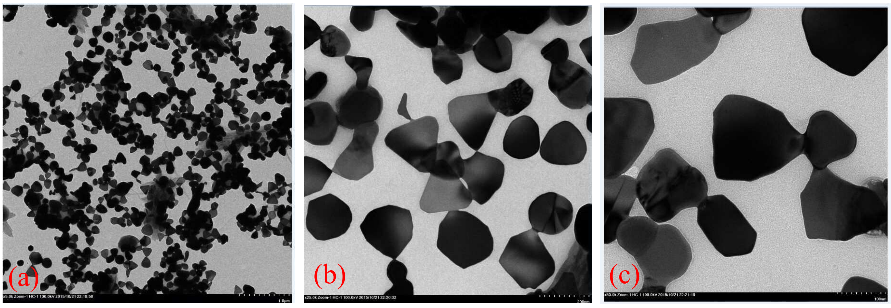

Fig. 1. TEM images of the silver nanoplate: (a) scale bar of 1000 nm, (b) scale bar of 200 nm, and (c) scale bar of 100 nm.

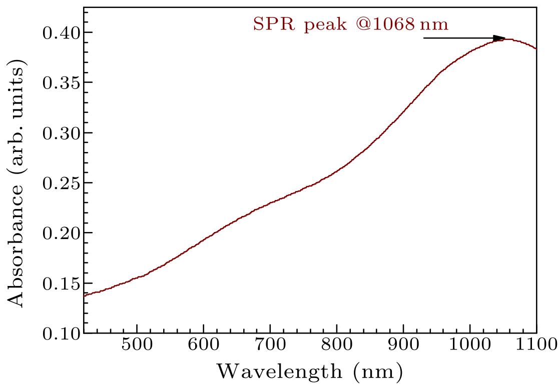

Fig. 2. The absorption spectrum of the silver nanoplate.

Figures 1(a)–1(c) show the transmission electron microscopy (TEM) image of the silver nanoplate SA film with scale bars of 1000, 200 and 100 nm, respectively. Additionally, the corresponding absorption spectrum in the range from 400 nm to 1100 of the silver nanoplate is shown in Fig. 2. It is obvious that the absorption peak locates at 1068 nm, which corresponds to the longitudinal SPR.

The experimental setup of the silver nanoplate-based passively Q-switched Yb-doped fiber laser is shown in Fig. 3. A 20-cm-long Yb-doped fiber (Liekki Yb 1200-4/125) with the peak absorption of 1200 dB/m at 976 nm was employed as the laser gain medium with a total absorption of 240 dB. A 974 nm laser diode with a maximum output power of 600 mW was used as the pump source. Additionally, two fiber Bragg gratings (FBGs), FBG1 with a high reflection ($R > 99\%$) at 1062 nm and FBG2 with a transmission of 10% at 1062 nm, were used to compose the laser cavity for the 1062 nm laser operation. The total cavity length was about 35 cm. The laser pulse and repetition rate of the laser pulses were recorded by a Tektronix TDS4054B digital oscilloscope (500 MHz bandwidth, 2.5 G samples/s) and a fast PIN photodiode. The average output power was measured by a power meter (MolectronPM3). The emission spectrum was measured with an optical spectrum analyzer (AQ6370B).

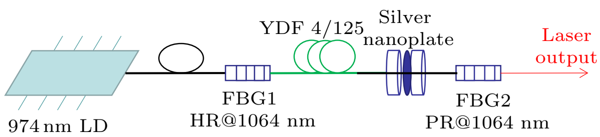

Fig. 3. Experimental setup of the silver nanoplate saturable absorber-based passively Q-switched Yb-doped fiber laser.

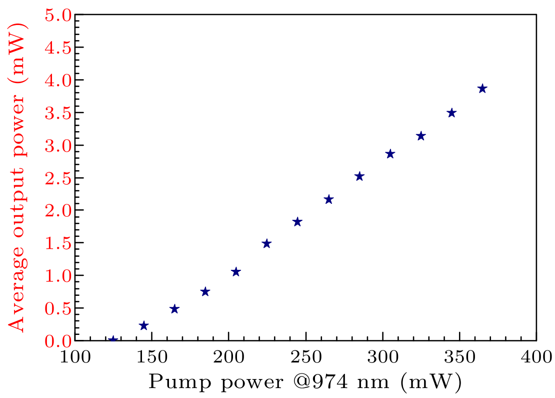

Fig. 4. Output powers versus pump powers for the cw and Q-switched operation.

In the experiment, stable passively Q-switched operation was observed at the pump power of 145 mW, and the pump threshold was higher than that of the graphene or graphene-like two-dimensional-material-based Q-switched Yb-doped fiber lasers, which were mainly due to a higher saturation intensity of the silver nanoplate. Figure 4 shows the relationship between the average output power and the pump power. As is shown, the output power was linearly dependent on the pumped power. The maximum output power of 3.49 mW was obtained when the pumped power was 345 mW, corresponding to an optical-to-optical efficiency of 1% and a slope efficiency of 1.6%. The emission spectrum of the fiber laser is shown in Fig. 5, the spectrum was measured with an optical spectrum analyzer with a resolution of 0.05 nm. It is obvious that the laser operates at 1062 nm, as shown in Fig. 2, and 1062 nm was within the high absorption region of the silver nanoplate SA. Therefore, the demonstration of the Yb-doped fiber laser operating at 1062 nm is suitable for verifying the absorption properties of the silver nanoplate.

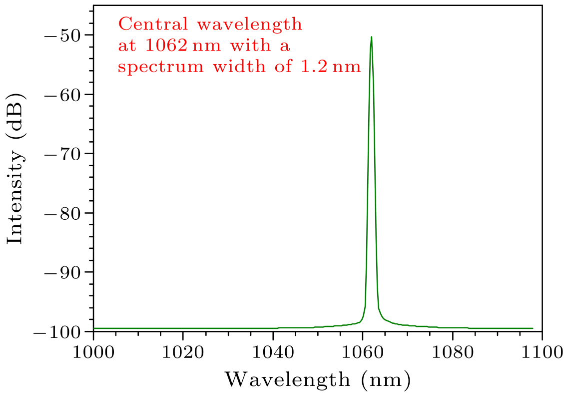

Fig. 5. The laser emission spectrum of the Yb-doped fiber laser at 1062 nm.

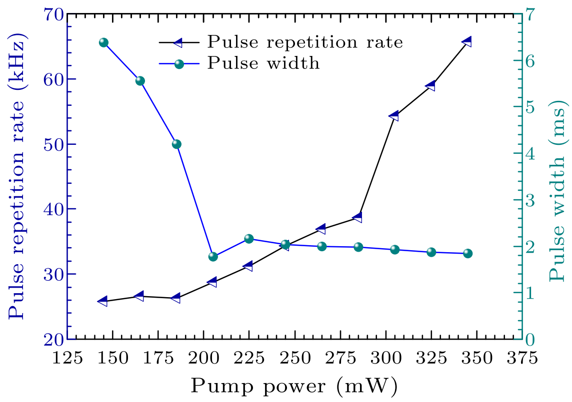

Fig. 6. The pulse repetition rate and pulse width versus the pump power.

In addition, the performance of the pulse widths and repetition rates at different pump powers have also been investigated. As shown in Fig. 6, the pulse widths have descendant tendency with the increase of the pump power, and the minimum pulse width of 1.84 µs was obtained under a pump power of 345 mW. Meanwhile, the repetition rate increased from 25.8 kHz to 65.7 kHz when the pump power changed from 145 mW to 345 mW.

Figure 7 shows the pulse train (measured by an Tektronix TDS4054B digital oscilloscope (500 MHz bandwidth, 2.5 G samples/s)) of the passively Q-switched fiber laser. The repetition rate was about 65.7 kHz. The duration of a single pulse was 1.84 µs (shown in Fig. 8), corresponding to a pulse energy of 53.1 nJ and a peak power of 28.8 mW. Additionally, in the experiment, when the pump power was higher than 345 mW, the passively Q-switched operation became unstable, as described in some passively Q-switched fiber lasers reported previously.[6,7,14] The reason for the unstable Q-switched operation is the over-saturation of the SA at high incident intensity.

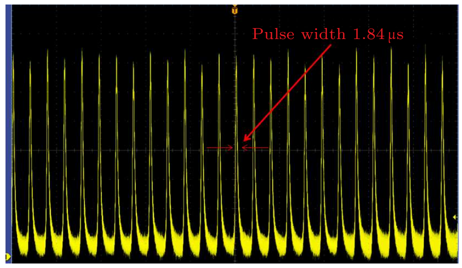

Fig. 7. A typical Q-switched laser pulse of 1.84 µs and a pulse train of the Q-switched laser at the pulse repetition rate of 65.7 kHz.

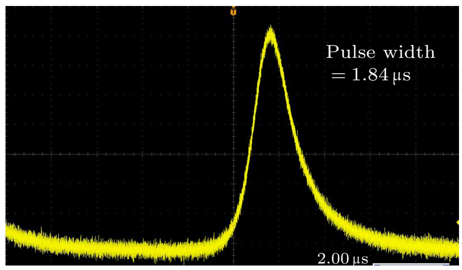

Fig. 8. A typical Q-switched laser pulse of 1.84 µs.

In summary, the silver nanoplate has been successfully prepared and employed as a saturable absorber for generating pulse laser operation. Under a pump power of 345 mW, stable Q-switched pulses with a maximum output power of 3.49 mW and a minimum pulse width of 1.84 µs are achieved. The experimental results show that silver nanoplate performs well in the field of pulsed laser.

References

[1] Zhang L, Li C Y, Feng B H, Wei Z Y, Li D H, Fu P M and Zhang Z G 2005 *Chin. Phys. Lett.* **22** 1420
[2] Xue Q H, Zheng Q, Bu Y K and Qian L S 2004 *Chin. Opt. Lett.* **2** 708
[3] Paschotta R, Häring R, Gini E, Melchior H, Keller U, Offerhaus H L and Richardson D J 1999 *Opt. Lett.* **24** 388
[4] Popa D, Sun Z, Hasan T, Torrisi F, Wang F and Ferrari A C 2011 *Appl. Phys. Lett.* **98** 073106
[5] Sobon G, Sotor J, Jagiello J, Kozinski R, Librant K, Zdrojek M, Lipinska L and Abramski K M 2012 *Appl. Phys. Lett.* **101** 241106
[6] Liu J, Wu S, Yang Q H and Wang P 2011 *Opt. Lett.* **36**

4008
[7] Kassani S H, Khazaeizhad R, Jeong Nazari T, Yeom D I and Oh K 2015 *Opt. Mater. Express* **5** 373
[8] Chen B H, Zhang X Y, Wu K, Wang H, Wang J and Chen J P 2015 *Opt. Express* **23** 26723
[9] Zhang M, Howe R C, Woodward R I, Edmund K J, Felice T, Hu G H, Popov V and Taylor J R 2015 *Nano Res.* **8** 1522
[10] Mao D, Wang Y D, Ma C J, Han L, Jiang B Q, Gan X T, Hua S J, Zhang W D, Mei T and Zhao J L 2015 *Sci. Rep.* **5** 7965
[11] Chen Y, Jiang G B, Chen S Q, Guo Z N, Yu X F, Zhao C J, Zhang H, Bao Q L, Wen S C, Tang D Y and Fan D Y 2015 *Opt. Express* **23** 12823
[12] Yu Z H, Song Y R, Tian J R, Dou Z Y, Guoyu H Y, Li K X, Li H W and Zhang X P 2014 *Opt. Express* **22** 11508
[13] Tang P, Zhang X, Zhao C J, Wang Y, Zhang H, Shen D Y, Wen S C, Tang D Y and Fan D Y 2013 *IEEE Photon. J.* **5** 1500707
[14] Kang Z, Xu Y, Zhang L, Jia Z, Liu L, Zhao D and Qin W 2013 *Appl. Phys. Lett.* **103** 041105
[15] Jiang T, Xu Y, Tian Q, Liu L, Kang Z, Yang R, Qin W 2012 *Appl. Phys. Lett.* **101** 151122
[16] Fan D F, Mou C B, Bai X K, Wang S F, Chen N and Zeng X L 2014 *Opt. Express* **22** 18537
[17] Zhang H N and Liu J 2016 *Opt. Lett.* **41** 1150
[18] Kim K H, Griebner U and Herrmann J 2012 *Opt. Lett.* **37** 1490
[19] Link S, Burda C, Mohamed M B, Nikoobakht B and El-Sayed M A 2000 *Phys. Rev.* B **61** 6086
[20] Rao W, Li Q, Wang Y, Li T and Wu L 2015 *ACS Nano* **9** 2783
[21] Li Q, Zhuo X, Li S, Ruan Q, Xu Q H and Wang J 2015 *Adv. Opt. Mater.* **3** 801