Passively Q-Switched Yb-Doped All-Fiber Laser With a Black Phosphorus Saturable Absorber

Junli Wang, Yupeng Xing, Lei Chen, Sha Li, Haotian Jia, Jiangfeng Zhu, and Zhiyi Wei

***Abstract*—We report two kinds of Q-switched Yb-doped fiber lasers based on a black phosphorus saturable absorber (BP-SA). The BP-SAs are prepared by two different methods, one of which is the mechanical exfoliation method and the other is the liquid-phase exfoliation method. The BP-SAs are inserted into the all-fiber Yb-doped oscillation cavity in different forms. We have experimentally shown that the passively Q-switched pulse trains could be obtained by the two methods. First, we achieve the Q-switched pulse in 1029.63 nm by using a few-layer black phosphorus sheet. The fiber laser was capable of generating pulses with a maximum average output power of 13.12 mW and a repetition rate of 79.46 kHz, corresponding to the maximum single-pulse energy of 165.11 nJ and the shortest single-pulse width of 1.55 μs. In addition, we obtain narrower pulsewidth by dropping the black phosphorus solution onto the tapered fiber. The maximum single pulse energy of 114.72 nJ and the minimum pulsewidth of 1.09 μs were obtained. The repetition rate ranges from 49.13 to 101.3 kHz.**

***Index Terms*—Black phosphorus, Q-switched fiber lasers, tapered fiber, ytterbium.**

I. Introduction

Saturable absorbers (SAs) are widely used in the passively Q-switched or mode-locked fiber lasers because of their advantages such as flexibility in design, simplicity, compactness and low cost [1]. So, various types of SAs have been extensively studied and developed in the past few decades, which include the semiconductor saturable absorber mirrors (SESAMs) [2]–[4], single-wall carbon nanotubes (SWCNTs) [5], [6] and graphene [7]–[10]. Graphene is the most attractive among these saturable absorbers due to its unique optoelectronic characteristics and broadband saturable absorption effect, but lacking of the band gap limits to applications of graphene [9], [10]. In recent years, the new two-dimensional (2D) nanomaterials have emerged such as topological insulators (TIs) [11] and transition metal dichalcogenides (TMDs) [12]–[14]. They have the advantages of ultra-fast recovery time and broadband saturable absorption, but have the disadvantage of complicated preparation process. Recently, black phosphorus (BP) has joined in the family of 2D materials.

Black phosphorus (BP) has gained wide attention recently because of its unique properties. BP is synthesized from red phosphorus under high temperature and high pressure. The structure of black phosphorus is similar to the graphene. But, BPs have significant advantages over graphene because they have a direct band gas which varies with nanosheet thickness from $\sim$2.0 eV (single layer) to $\sim$0.3 eV (bulk) [15], [16]. This indicates that BP has promising applications in photonic and optoelectronic field. BP have the advantages of broadband saturable absorption and a third-order optical nonlinearity. So BP could serve as a broadband saturable absorber to generated short pulse in passively Q-switching and mode-locking laser. Because BP comprises only the elemental "phosphorus", it could be easily peeled off by mechanical exfoliation [17]. Simultaneously, it could be made into black phosphorus solution.

In 2015, Yu Chen *et al.* [17] firstly demonstrated a stable passive Q-switched Er-doped fiber laser based on mechanically exfoliated BP-SAs, which generated pulses with a maximum average output power of 1.49 mW. The pulse repetition rate was tuned from 6.893 kHz to 15.47 kHz by the increases of pump power, the pulse width ranging from 39.84 μs to 10.32 μs. The passive mode–locked pulse train also have been obtained at 1.5-μm and 2-μm waveband by using mechanically exfoliated BP-SAs. At 1.5-μm region, 946 fs [17] and 272 fs [18] mode-locked pulses have been reported, corresponding to the repetition rate of 5.96 MHz and 28.2 MHz, respectively. In 2016, F A A Rashid *et al.* [19] reported the dual-wavelength passively Q-switched ytterbium-doped fiber laser used a few-layer black phosphorus (BP) thin film The maximum pulse energy of 2.09 nJ and the shortest pulse width of 1.16 μs are achieved. The repetition rate was increased from 52.52 to 58.73 kHz. Furthermore, Yazhou Wang *et al.* [20] have obtained a stable passively Q-switched Tm-doped fiber laser with a micro-fiber at 2-μm waveband, with the repetition rate of 28 kHz, the maximum pulse energy of 154.2 nJ and the shortest pulse width of 5.6 μs. The passively Q-switched Yb-doped fiber lasers based on BP-SA with tapered fiber have few reported.

In our work, two kinds of passively Q-switched Yb-doped fiber lasers (YDFL) based on BP-SAs are presented. The BP-SAs were fabricated by the mechanical exfoliation method and the liquid phase exfoliation (LPE) method. We have experimentally shown that the passively Q-switched pulse train was generated in the 1029.63 nm based on the BP-SA flakes. The

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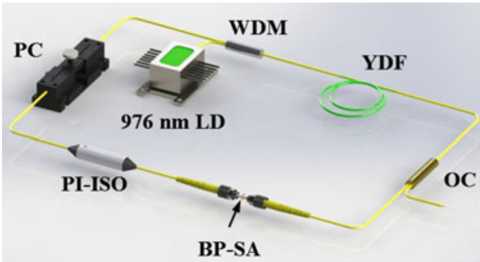

Fig. 1. The experimental setup of Q-switched Yb-doped fiber laser based on a mechanically exfoliated BP-SA.

YDFL was capable of generating pulses with a maximum average output power and repetition rate of 13.12 mW and 79.46 KHz, corresponding to the maximum single pulse energy of 165.11 nJ and pulse width as narrow as 1.55 μs. We also did another experiment that the passively Q-switched Yb-doped fiber laser was realized by the optical deposition method, which deposits a BP nanosheets isopropanol solution onto a tapered fiber. Compared with the mechanical exfoliated method, the one had the advantages of effective interaction between the laser and the BP material and a high damage threshold. The stable Q-switched pulse are achieved with the maximum single pulse energy of 114.72 nJ, the minimum pulse duration of 1.09 μs, and the repetition rate range from 49.13 kHz to 101.3 kHz. The experiment results show that the method of depositing BP nanosheets on the tapered fiber is a convenient and reliable way to achieve both short and high energy Q-switched pulse.

II. Experimental Setup

Fig. 1 shows the experimental setup of the passively Q-switched Yb-doped fiber laser. The Q-switched fiber laser is based on BP-SAs which was peeled from the high-purity (99.998%) bulk BP crystal with the use of scotch tape. The bulk BP crystal is provided by Nanjing XFNANO Materials Tech Co., Ltd. The ring laser oscillator cavity is comprised of a wavelength division multiplexer (WDM), a gain fiber, a polarization independent isolator (PI-ISO), a polarization controller (PC), a BP-SA and an optical coupler (OC). A 16 cm long Yb-doped fiber with absorption coefficient of 1200 dB/m at 976 nm was used as the gain medium. The fiber laser is pumped by a 976 nm laser diode (LD). The PI-ISO was used to force the unidirectional operation in the fiber ring cavity. The PC was employed in the cavity to optimize the Q-switched operation. The 50% port of an optical coupler is used to output laser. The BP-SA was fabricated by mechanical exfoliation method with the high purity argon protection. The thickness of BP flakes is measured by an atomic force microscope (AFM), as shown in Fig. 2(a). The typical thickness is ~17 nm, corresponding to the layer number of 28 [21].Then, the obtained relatively thin BP flakes was transferred onto the standard FC/APC fiber end face. The fiber core was entirely covered by the thin BP flakes. The standard FCAPC fiber with deposited BP-SA was connected with the other clean one by a standard flange adapter, which forms all-fiber structure. To obtain BP-SA, the mechanical exfoliation method is simple, reliable and low cost. An optical spectrum analyzer and a sampling oscilloscope (Tektronix DOP 3052) are employed to simultaneously monitor the optical spectrum and the temporal evolution of the output pulse train.

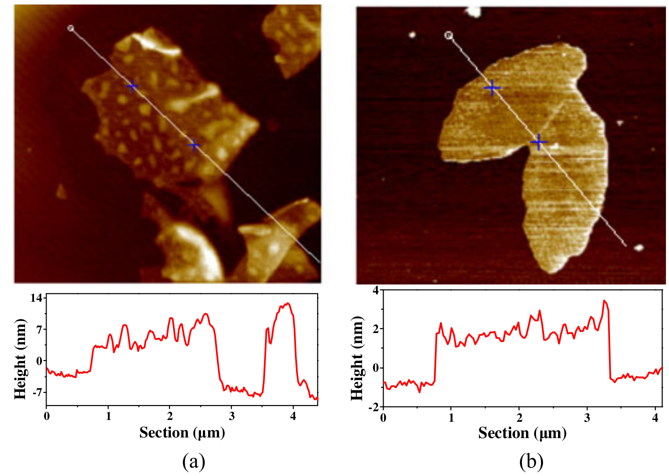

Fig. 2. (a) AFM micrograph (top) of the BP fabricated by the mechanical exfoliation method and its height profile (bottom). (b) AFM micrograph (top) of the BP fabricated by the liquid-phase exfoliation method and its height profile (bottom).

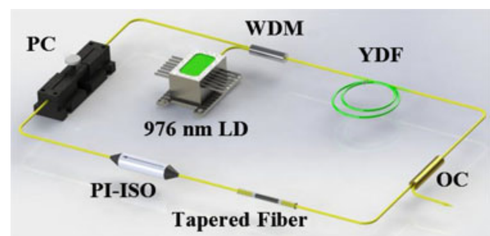

Fig. 3. The experimental setup of the passively Q-switched Yb-doped fiber laser with a tapered fiber.

Fig. 3 shows the experimental schematic of the passively Q-switched Yb-doped fiber laser with a tapered fiber. The devices are almost identical to those in Fig. 1(a), such as the wavelength division multiplexer (WDM), the polarization independent isolator (PI-ISO), the polarization controller (PC), the optical coupler (OC), the Yb-doped fiber, and the 976 nm laser diode (LD). The only difference is that we uses a tapered fiber instead of a flange. Then we use the black phosphorus solution instead of black phosphorus sheets as a saturable absorber. The black phosphorus solution is fabricated by liquid phase exfoliation method with isopropanol solvent. The AFM image of the BP nanosheets with LPE method is shown in Fig. 2(b), the BP nanosheets have a thickness of 3.2 nm, corresponding to the layer number of 5. In our experiments, the laser based on tapered fiber SA has a comparable pulse energy and relatively narrow pulse width, suggesting that the interaction between the evanescent field and the black phosphorus solution is an efficient method for the pulse laser generation.

The tapered fiber in the experiment is shown in Fig. 4(a). The device consists of the U type groove, the quartz capillary and the tapered optical fiber. As shown in Fig. 4(b), first of all, the tapered fiber is fabricated by the flame brushing technique. Then, the optical fiber is fixed on the U type groove with UV

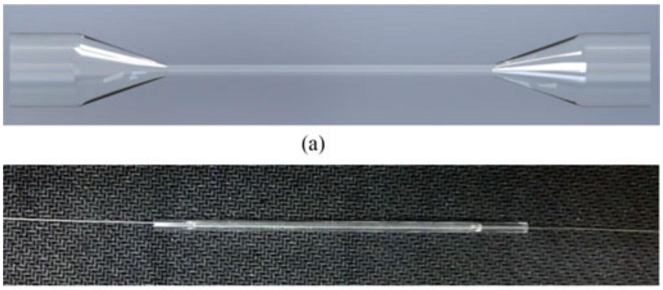

Fig. 4. (a) The sketch of the tapered fiber. (b) The photograph of the packaged tapered fiber.

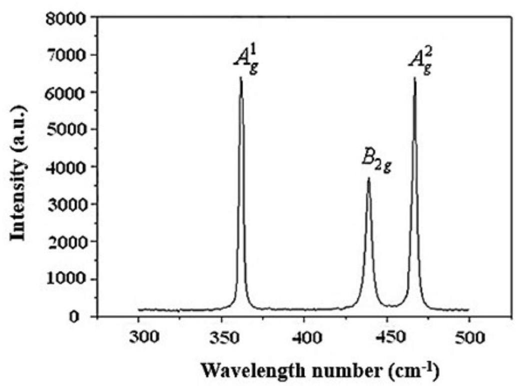

Fig. 5. Raman spectra of black phosphorus.

curable adhesive. Finally, the U groove is inserted into the quartz capillary. In this way, the dust can be prevented from falling in the cone area, and the volatilization rate of the black phosphorus solution can be reduced. When we conducted the experiment of the tapered fiber, we used the syringe to inhale the appropriate amount of black phosphorus solution. Then we injected the black phosphorus solution into the quartz tube.

Fig. 4(a) shows the diameter of the taper waist available is 5 μm, which is the thinnest part of the tapered fiber. We package the tapered fiber with a capillary which is convenient for the protection of the tapered fiber from dust and the BP-SA from oxidation. Fig. 5 shows that the Raman spectra of black phosphorus. We can find out three conspicuous Raman peaks are exhibited by the sample at 360 cm^{-1}, 438 cm^{-1}, and 465 cm^{-1}.

III. Experimental Results and Discussion

In our first experiment, the Q-switched pulse trains were generated based on BP-SA. Without the BP-SA4, the ring cavity started the continuous wave (CW) at the pump power of 30 mW. As pump power increasing, the Q-switched phenomenon didn't be observed by carefully adjusting PC. Then, under the same condition of experiment, thin BP-SA that was peeled repeatedly from bulk BP by using scotch tape was added into the ring cavity. The CW occurred at the pump power of 38 mW. For the ring cavity, the output CW threshold becomes higher because the BP-SA introduced more loss. When the pump power increased to 50 mW, the stable Q-switched pulse trains were obtained.

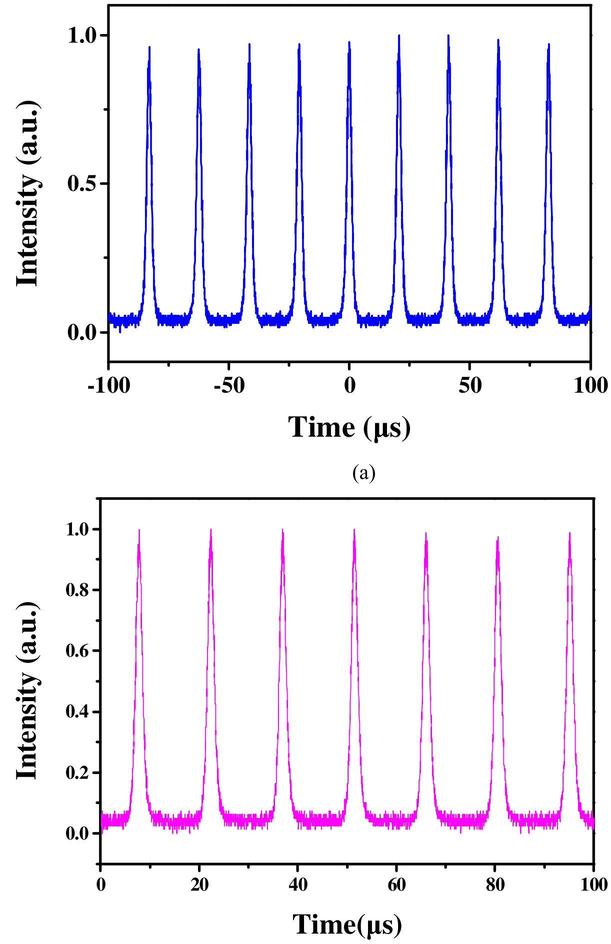

Fig. 6. (a) The pulse trains of the Q-switched Yb-fiber laser based on BP-SA flake at the pump power of 94 mW. (b) The pulse trains of the Q-switched Yb-fiber laser based on the BP solution at the pump power of 95 mW.

Therefore, the generation of Q-switched pulse is due to the saturable absorption effect of BP-SA sheet. Fig. 6(a) shows the pulse trains of the passively Q-switched Yb-doped fiber laser based on BP flakes at the pump power of 50 mW. It has a repetition rate of 48.56 kHz, corresponding to a pulse interval of 20.59 μs. The single pulse width of 2.27 μs is shown in Fig. 7(a), which is a symmetric Gaussian-like shape. In our second experiment, the Q-switched pulse trains were also generated based on BP solution. We obtained the stable Q-switching pulse trains when the pump power reached 95 mW as showed in Fig. 6(b). The repetition rate is 65.79 kHz. The single pulse width of 1.56 μs is shown in Fig. 7(b). The Q-switching pulse trains phenomenon is caused by the interaction of evanescent wave and the black phosphorus nanosheets deposited taper fiber. However the Q-switching threshold with tapered fiber is higher than our first experiment. The reason may be that the interaction between the laser and the BP-SA is too weak due to the evanescent field. In addition, the BP-SA fabricated with mechanical exfoliated method shows excellent performance. As shown in Fig. 8, the modulation depth is 15.75% and the saturation intensity is 10.57 MW/cm^2.

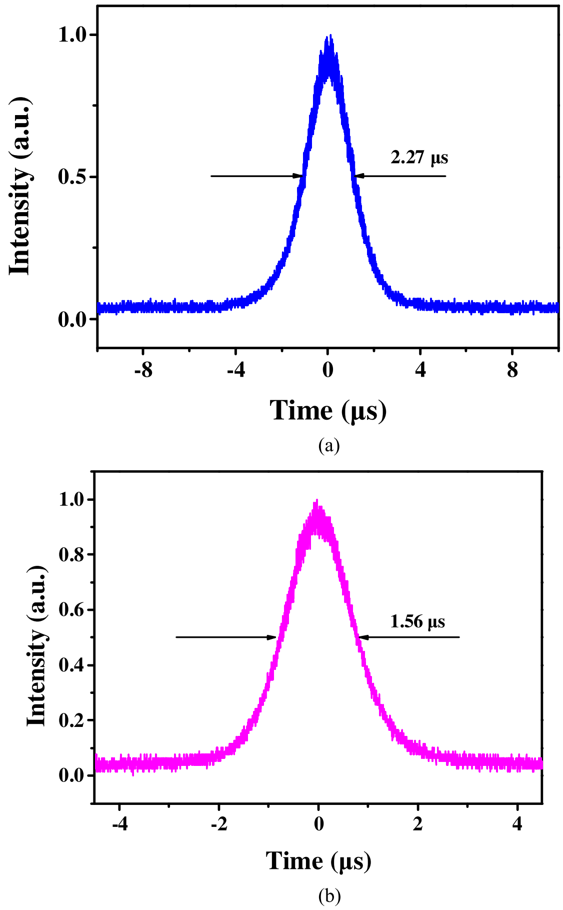

Fig. 7. (a) The single pulse profile of the Q-switched Yb-fiber laser based on BP-SA flake at the pump power of 94 mW. (b) The single pulse profile of the Q-switched Yb-fiber laser based on the BP solution at the pump power of 95 mW.

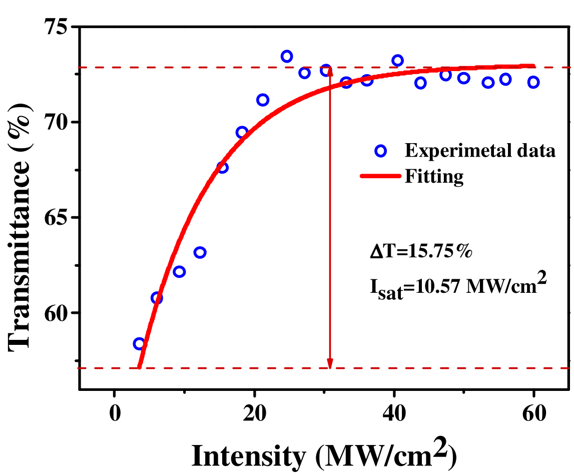

Fig. 8. Nonlinear saturable absorption of the BP-SA fabricated by the mechanical exfoliation method.

Under different pump powers, the optical spectrum of two experiments keeps unchanged as shown in Fig. 9. The Fig. 9(a) shows the optical spectrum of the first experiment is centered at 1029.63 nm and the 3-dB spectral width is 0.6 nm. As for Fig. 9(b), the central wavelength is located at two different posi-

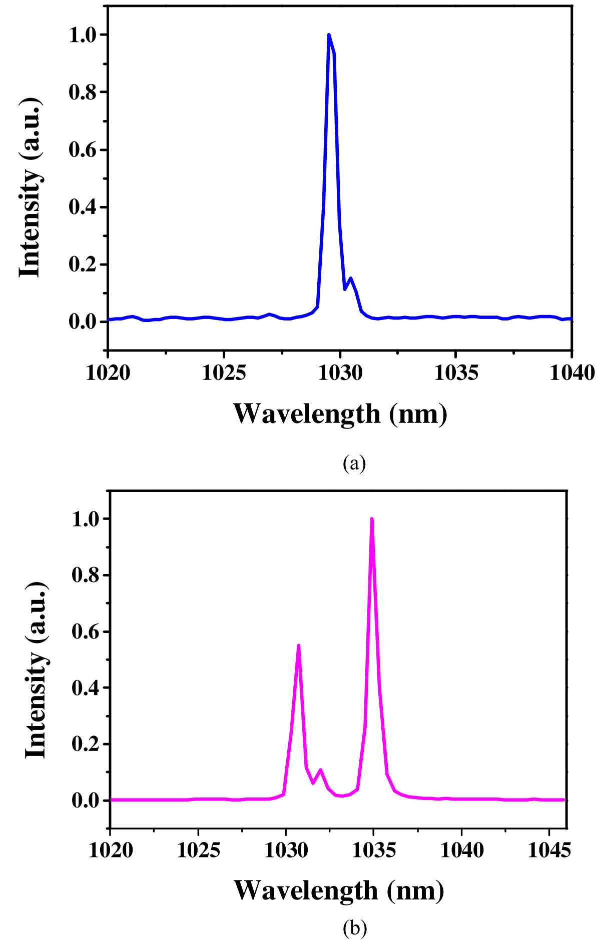

Fig. 9. (a) The optical spectrum of the passively Q-switched Yb-fiber laser based on the BP-SA. (b) The optical spectrum of the dual-wavelength Q-switched phenomenon from the Q-switched Yb-fiber laser based on the BP solution.

tions of 1030.72 nm and 1034.42 nm, respectively. We can obviously see the typical dual wavelength Q-switched phenomenon. In the experiment, it was observed that the length and the absorption coefficient of the fiber influence the center position of wavelength.

In our second experiment, as the pump power was increased to 95 mW, the typical Q-switched pulse trains were monitored by a photodetector/sampling oscilloscope (Tektronix DOP 3052) as shown in Fig. 10, which displays the evolution of the Q-switching pulse trains. Fig. 10(a) shows the pulse trains with the repetition rate of 65.79 kHz at the pump power of 95 mW. Fig. 10(b) displays that with the repetition rate of 69.44 kHz at the pump power of 105 mW. Fig. 10(c) presents that with the repetition rate of 72.90 kHz at the pump power of 115 mW. Fig. 10(d) shows the pulse trains with the repetition rate of 79.15 kHz at the pump power of 125 mW.

In our previous experiment, when the pump power ranges from 50 mW to 84 mW, the repetition rates increased from 48.56 kHz to 79.46 kHz. The corresponding single pulse width was decreased from 2.27 μs to 1.59 μs with minimum pulse width of 1.55 μs at 74 mW pump power. In our second experiment. When the pump power ranges from 95 mW to

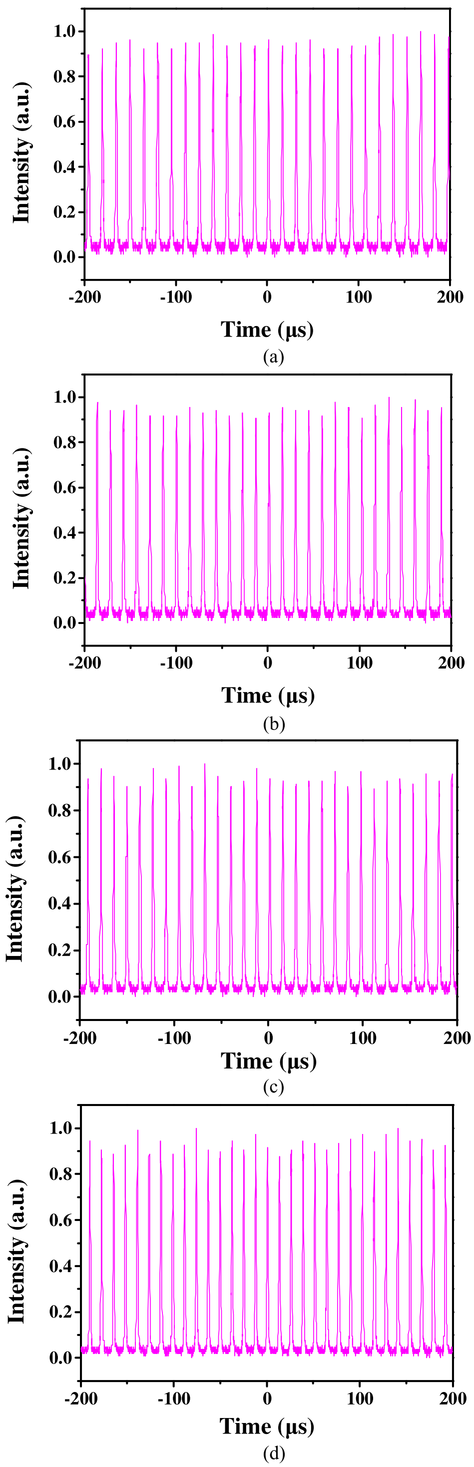

Fig. 10. The typical stable pulse train of the Q-switched lasers at the pump power of (a) 95 mW, (b) 105 mW, (c) 115 mW, and (d) 125 mW corresponding the repetition rate of 65.79, 69.44, 72.9, and 79.15 kHz, respectively.

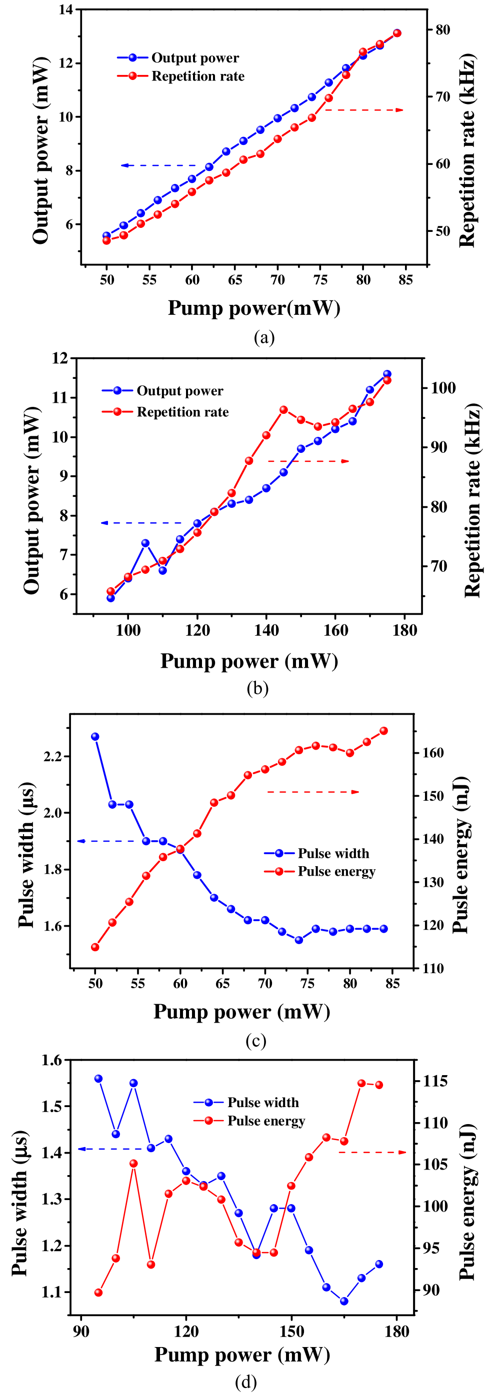

Fig. 11. (a) The output power and the repetition rate versus the pump power of the first experiment. (b) The output power and the repetition rate versus the pump power of the second experiment. (c) The pulsewidth and the pulse energy versus the pump power of the first experiment. (d) The pulsewidth and the pulse energy versus the pump power of the second experiment.

175 mW, the repetition rate increased from 65.79 kHz to 101.3 kHz. The corresponding single pulse width was changed between 1.59 μs and 1.09 μs. These are typical features of Q-switched pulse as shown in Fig. 11. Fig. 11(a) and (b) show the output powers and the repetition rates versus the pump power simultaneously. Fig. 11(a) shows the average output power of 13.12 mW and repetition rate of 79.46 kHz were obtained at the maximum pump power of 84 mW in our first experiment. Fig. 11(b) shows the average output power of 11.6 mW and repetition rate of 101.3 kHz were obtained at the maximum pump power of 175 mW in our second experiment. Fig. 11(c) and (d) present the single pulse

TABLE I
TYPICAL Q-SWITCHED RESULT BASED ON THE BP-SA IN YB-DOPED FIBER LASERS

Ref.	Incorporation method	Wavelength/nm	Min. pulse width/μs	Repetition rate/kHz	Max. pulse energy/nJ
[19]	Deposited on fiber end	1038.68~1042.0	1.16	52.52~58.73	2.09
[25]	Deposited on fiber end	1056.6~1083.3	4	6.0~44.8	7.1
[26]	Deposited on fiber end	1069.4	10.8	8.2~32.9	328
[27]	Deposited on tapered fiber	1064.7	2.0	26~76	17.8
This work	Deposited on fiber end	1029.63	1.55	48.56~79.46	165.11
This work	Deposited on tapered fiber	1030.72~1034.4	1.09	65.79~101.3	114.72

width and the single pulse energy are varied by increasing the pump power. In our first experiment, the shortest single pulse width of 1.55 μs and the maximum single pulse energy of 165.11 nJ are displayed in Fig. 11(c). Comparing with the results of the first experiment, the single pulse width was reached the minimum value of 1.09 μs when pump power is 165 mW and the maximum single pulse energy of 114.72 nJ are obtained at the pump power of 170 mW in our second experiment as shown in Fig. 11(d).

In the first experiment, the pulse width can be further narrowed by shortening the ring laser cavity and increasing the modulation depth of the BP-SA [22]–[24]. We believe that the pulse energy could be further improved by optimizing the BP-SA parameters and Cavity design.

In our second experiment, the single pulse energy of the Q-switching pulse has been greatly improved. When the pump power exceeded 175 mW, the Q-switching state becomes unstable. If the pump power was increased further, the Q-switching state disappeared. The unstable Q-switching phenomenon may be attributed to over-saturation of the BP-SA rather than to thermal damage, as typically observed in some other passively Q-switched fiber laser [17], [22], [23]. At the same time, the Q-switching state can exist in the range of pump light from 95 to 175 mW, which has a wider range than our first experiment. The results show that the damage threshold of black phosphorus solution is higher than BP-SA flake when the evanescent wave interacts with the black phosphorus solution. The Q-switching or the mode-locking operation are related to the modulation depth of the saturable absorber in fiber laser.

We compared the Q-switching output performance of the BP-SA with the other team's work. Although with the same Yb-doped fiber, this paper still make tremendous sense. From Table I, we can see that the output-parameters of these Q-switching lasers are different from our work. Our work possesses the narrowest pulse width of 1.09 μs and the highest repetition rate of 101.3 kHz. The single pulse energy is also higher than most of them. The reason is that we use a tapered fiber with black phosphorus solution but other reports use BP flakes as saturable absorber. The small waist of taped fiber enhances the interaction of the evanescent light field and the BP-SA.

IV. CONCLUSION

In conclusion, two kinds of Q-switched Yb-doped Fiber Lasers was presented. The Q-switching operation with BP flakes fabricated by mechanical exfoliation method obtained the maximum single pulse energy of 165.11 nJ and the narrowest pulse width of 1.55 μs. For the Q-switched Yb-doped fiber laser with a tapered fiber, the BP-SA solution were fabricated by the liquid phase exfoliation method. In the laser experiment, the maximum repetition rate of 101.3 kHz and the shortest single pulse width of 1.09 μs were obtained at the pump power of 165 mW. In addition, the maximum single pulse energy was 114.72 nJ and the optical spectrum of the pulse is centered at 1030.72 nm and 1034.42 nm. The laser performance can be further improved by optimizing the diameter of tapered fiber and the size of black phosphorus granules. We will try to achieve better results.

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