

Q-switched Erbium-doped Fiber Laser with a Black Phosphorus Saturable Absorber

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Received May 24, 2017; accepted June 28, 2017; published June 30, 2017

Abstract—A passively Q-switched Erbium-doped fiber laser (EDFL) is demonstrated using a black phosphorus saturable absorber as the Q-switcher. The laser generates a stable pulse operating at a wavelength of 1562.35 nm within a pump power region from 7.2 mW to 42.3 mW. At a 980 nm pump power of 42.3 mW, the EDFL generates an optical pulse train with a repetition rate of 44.72 kHz and pulse width of 9.8 μ s. The maximum pulse energy of 81.5 nJ is obtained at a pump power of 35.2 mW. A higher performance Q-switched EDFL is expected to be achieved with the optimization of the saturable absorber and laser cavity.

Two-dimensional (2D) layered nanomaterials such as transition-metal dichalcogenides (TMDs) and graphene possess unique planar properties, strong intra-layer covalent bonding and high quantum confinements [1]. These features enable the construction of smaller, efficient and flexible optical devices. For example, graphene has been discovered to have advantages in broad saturable absorption and ultra-fast recovery time [2]. However, this material has its drawbacks such as low absorption efficiency (2.3%/layer) and absence of a band-gap. TMD materials such as molybdenum disulphide (MoS₂) and tungsten disulfide (WS₂) were discovered to be able to overcome the weaknesses of graphene by having unique absorption properties and a layer thickness dependent bandgap. However, these materials are difficult to fabricate since they require a complicated process, thus limiting their potential to become a perfect SA.

The emergence of a new SA material, black phosphorus (BP) has shifted the attention of current research once again as it is found to have the most thermodynamically stable allotrope. Its characteristics are quite similar with those of graphene, having a direct band-gap and being composed of a single element. Despite having an anisotropic structure that requires controlled polarization, BP has many unique electronic properties that may unlock considerable potential of electronic device development [3]. Another important feature is the broad nonlinear optical response, which is the key attribute for infrared optoelectronics application. Therefore, BP is a promising material that may find its importance in Q-switched and mode-locked pulse applications [4]. In 2015, Chen *et al.* demonstrated the generation of Q-

switched and mode-locked pulse operation employing mechanically exfoliated BP in the C-Band region [5]. Subsequently, in 2016, Mohamad *et al.* demonstrated a similar usage of BP in the ytterbium fiber laser to generate a mode-locked laser [6].

In this paper, we describe the fabrication of BP as SA by a mechanical exfoliation method. The process was done by peeling raw BPs into a thin layer that may fix onto the end-facet of a fiber ferrule. The BP SA usage was demonstrated by placing it inside the EDFL cavity to generate a Q-switching pulse, which indicates the potential of a BP 2D nanomaterial in the field of laser physics.

The mechanical exfoliation method is free from complicated chemical procedures and expensive instruments, and thus its advantages are simplicity and reliability compared to other techniques. In this work, relatively thin flakes were peeled off from a big block of commercially available BP crystal using a clear scotch tape. Then, we repeatedly pressed the flakes stuck on the scotch tape so that the BP flakes become thin enough to transmit light with high efficiency. Later, a small piece of the tape was cut off and attached to a standard FC/PC fiber ferrule end surface with the help of index matching gel. After connecting the ferrule with another FC/PC fiber ferrule using a standard flange adapter, the all-fiber BP based SA was finally realized.

We verified the quality of the BP tape by taking field emission scanning electron microscopy (FESEM) image. The composition of the transferred layers was then confirmed by energy dispersive x-ray spectroscopy (EDS) on the FESEM image. The presence of a BP material was confirmed by the occurrence of higher peak phosphorus at an energy of 2keV as shown in Fig. 1a. The inset of Fig. 1a shows the FESEM images, which indicates the existence of uniform layers and confirms the absence of >1 μ m aggregates or voids in the composite SA. We also performed Raman spectroscopy measurement on the fabricated BP SA tape sample, and the spectrum is shown in Fig. 1b. The spectrum indicates that the BP sample exhibits three distinct Raman peaks at 360cm⁻¹, 438cm⁻¹, and 465cm⁻¹, corresponding to A_g¹, B_{2g} and A_g² vibration modes of layered BP [7]. While the B_{2g} and A_g²

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correspond to the in-plane oscillation of phosphorus atoms in BP layer, the A_g^1 mode corresponds to the out-of-plane vibration. The ratio between A_g^1 peak and silicon (Si) level at 520cm^{-1} estimates the thickness of BP flake as $\sim 200\text{ nm}$. The thickness for a single-layer BP is about 0.8 nm [8], thus the prepared BP based SA is expected to consist of about 250 layers.

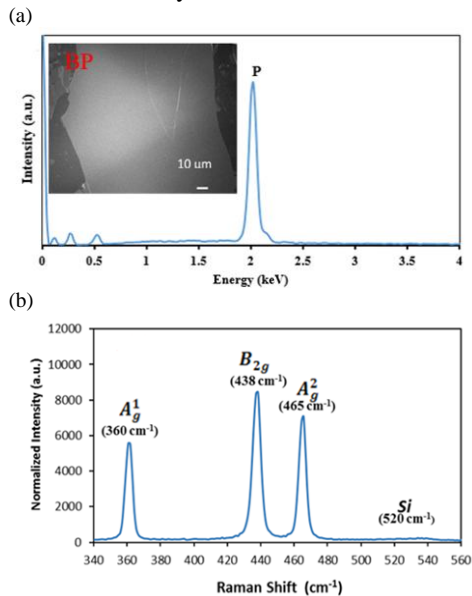


Fig. 1. Characterization of the exfoliated BP layers, transferred onto the tape: (a) EDS data, Inset: FESEM image for BP, (b) Raman spectrum of the BP-SA tape.

Figure 2 shows the experimental setup for the proposed BP based Q-switched EDFL. It uses a 2.8m long Erbium-doped fiber (EDF) as the gain medium. The EDF was pumped by a 980nm laser diode via a 980/1550nm wavelength division multiplexer (WDM). An isolator was spliced after gain medium to prevent backward light operation in the cavity. The BP SA was inserted into a fiber ring laser cavity to produce a passively Q-switched Erbium-doped fiber laser (EDFL). The output from the laser was taken out from the cavity via an optical coupler of 80/20, with the output from 80% port oscillating inside the cavity while another 20% port was used to measure the power, spectrum and pulse duration. The results were monitored and analyzed by an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm , 1.2 GHz InGaAs photodetector combined with 350 MHz oscilloscope and a 7.8 GHz radio frequency spectrum analyzer (RFS), respectively.

Stable and self-starting Q-switching operation is obtained just by adjusting the pump power over the threshold of 7.2 mW . The Q-switching operation was maintained up to the pump power of 42.3 mW . Low threshold pump obtained from this cavity indicates our proposed cavity has a low intra-cavity loss which contributes towards high optical-to-optical laser efficiency and low power device consumption in future development of a handheld laser.

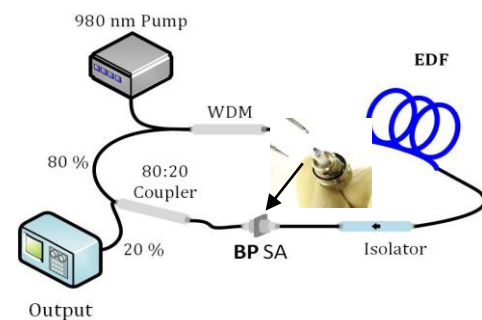


Fig. 2. The schematic setup of the Q-switched EDFL employing the fabricated BP based SA.

Without SA, the continuous-wave lasing started at 6 mW pump level. Figure 3 shows the output spectrum of the Q-switched laser at a pump power of 35.2 mW . As seen, the laser operates at a wavelength of 1562.35 nm with a peak of -7.5 dBm and a 3 dB spectral bandwidth of 2.4 nm . The pulse broadening is most probably due to the self-phase modulation effect in the ring cavity. Figure 4 shows the oscilloscope traces of a Q-switched pulse train at a pump power of 35.2 mW . It has a pulse-to-pulse separation of $28.5\mu\text{ s}$, corresponding to a pulse repetition rate of 35 kHz . As can be seen in the inset image of Fig. 4, a single pulse envelope of the obtained pulse train has a full-wave half-maximum of $12.8\mu\text{ s}$. There is no distinct amplitude modulation in each envelope of the Q-switched spectrum, which means that the self-mode locking effect on the Q-switching is weak. An additional length of nonlinear fiber in this cavity is expected to induce mode-locking operation. However, more loss was generated and no lasing obtained at the output.

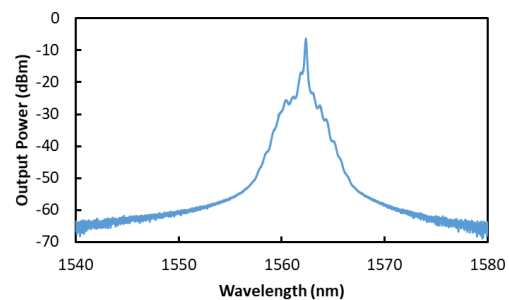


Fig. 3. Output spectrum of the Q-switched EDFL.

Figure 5 shows the repetition rate and the pulse width versus the pump power. The repetition rate of the BP based Q-switched YDFL has a monotonically increasing, near-linear relationship with the pump power level, which is consistent with another Q-switched fiber laser [9, 10]. When the pump power is tuned from 7.2 to 42.3 mW , the pulse train repetition rate varies from 9.61 to 44.72 kHz .

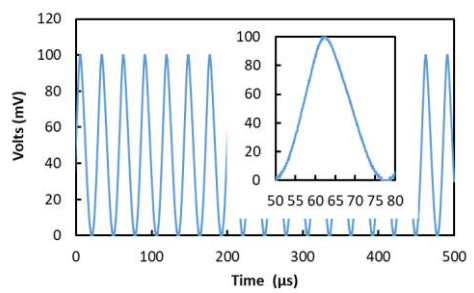


Fig. 4. Typical pulse train for the Q-switched EDFL at a pump power of 35.2 mW. Inset image is a single pulse envelope.

On the other hand, the pulse width is inversely proportional to the pump power, where the pulse duration becomes shorter as the pump power increases. The pulse width monotonically reduces from 40.1 to 9.8 μs as the pump power increases from the threshold value to the maximum pump power of 42.3 mW. Figure 6 depicts the average output power and single pulse energy against the pump power. As seen, both output power and pulse energy show an increasing trend with the increase of the pump power. For instance, the output power is linearly increased with a rate of 9.64% with the pump power. However, we noticed that the pulse energy starts to saturate as the pump power is increased above 35.2 mW. The maximum pulse energy of 81.5 nJ was obtained at a pump power of 35.2 mW. From the summary of pulsed lasers generated by BP SA, our obtained pulse energy is comparable, and moreover, it has a high repetition rate [11]. The pulse energy could be improved by reducing the insertion loss of the SA and optimizing the laser cavity.

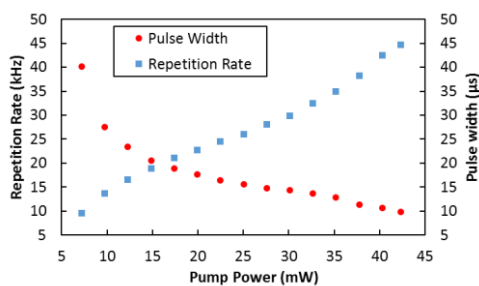


Fig. 5. Repetition rate and pulse width as a function of pump power.

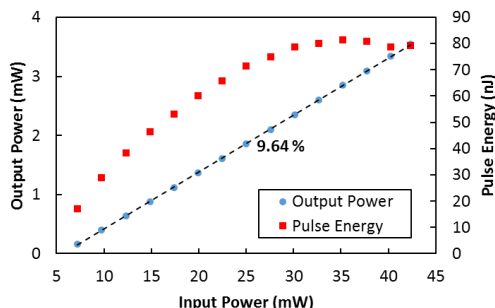


Fig. 6. The output power and calculated pulse energy against the input pump power.

The RF spectrum of the Q-switched pulses is also measured at a pump power of 35.2 mW, and the result is shown in Fig. 7. Its fundamental mode peak locates at the frequency of 35 kHz and has a signal-to-noise ratio (SNR) of 67 dB, which confirms the stability of the pulse. So far, the SA function in BP tape has remained robust after we increased pump power to a maximum limit of 150 mW.

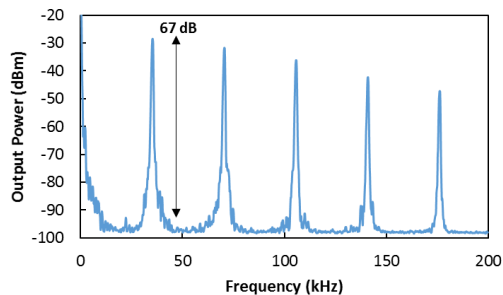


Fig. 7. RF spectrum of the Q-switched pulse train at a pump power of 35.2 mW.

In conclusion, a Q-switched EDFL operating at 1562.35 nm is successfully demonstrated based on a mechanically exfoliated BP as a Q-switcher. When the pump power is tuned from the threshold pump power of 7.2 to 42.3 mW, the pulse train repetition rate varies from 9.61 to 44.72 kHz. On the other hand, the pulse width reduces from 40.1 μs to 9.8 μs as the pump power increases from the threshold value to the maximum pump power of 42.3 mW. The maximum pulse energy of 81.5 nJ is obtained at a pump power of 35.2 mW. This result shows the great potential of a BP nanomaterial for application in Q-switching pulse generation.

N. N. Razak wishes to thank Ministry of Higher Education, Malaysia for awarding MyPhD Scholarship for her PhD.

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