

# The generation of Q-switched erbium-doped fiber laser using black phosphorus saturable absorber with 8% modulation depth

C. M. Fauziah<sup>1,2\*</sup>, A. H. A. Rosol<sup>3</sup>, A. A. Latiff<sup>4,5</sup> and S. W. Harun<sup>2</sup>

<sup>1</sup>Politeknik Sultan Azlan Shah, 35950 Behrang, Perak, Malaysia

<sup>2</sup>Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

<sup>3</sup>Faculty of Electrical Engineering, Universiti Teknologi Mara, 40450, Shah Alam, Selangor

<sup>4</sup>Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia

<sup>5</sup>Faculty of Electronic and Computer Engineering (FKEKK), Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

E-mail: \*cmfauziah@gmail.com

**Abstract.** We report a generation of the Q-switched laser operating in 1.55-micron region by using black phosphorus (BP) as a saturable absorber (SA). A 980-nm laser diode was pumped into Erbium-doped fiber (EDF) gain medium in ring cavity configuration. The BP-based SA was prepared by mechanically exfoliating the BP crystal using scotch tape. The obtained BP-tape SA has a modulation depth of 8 %. To realize a Q-switching operation, a small piece of the tape is then integrated into between two fiber ferrule tips. A stable Q-switching operation started at 40 mW. The maximum repetition rate obtainable at 28.57 kHz, with pulse width of 5.35  $\mu$ s. This finding shows the BP is one of the promising material to work as an SA for pulsed laser generation.

## 1. Introduction

Pulse fiber lasers have undergone tremendous development in the past few decades since they have quite different characteristics compared with continuous wave lasers. High peak power, controllable repetition rate, and pulse width enable the pulse fiber laser to contribute significantly to laser development for practical applications, including material processing, LIDAR, laser communications, environmental detection, medical care, nonlinear frequency conversion, and laser acceleration [1-4]. Q-switching is one type of pulse fiber lasers, which is of great interest in recent years for the above-mentioned applications. Also, Q-switched all-fiber lasers have advantages in term of their flexibility, large accumulated one-trip gain, high beam quality and intense power confined in mode field diameters of only a few micrometers. Q-switching in all-fiber lasers has been achieved by applying a mechanical force on highly dispersive fiber Bragg gratings (FBG). The mechanical force or vibration could be provided by piezoelectric actuators [5], magnetostrictive transducers [6], or acoustooptics modulators [7]. Modulation of the Q-factor can also be realized in passive approaches using semiconductor saturable-absorber mirrors [8] and solid-state saturable-absorber fibers [9]. Recently, the search for new saturable absorber (SA) materials, essential for passive Q-switching, has intensified, as the alternative to the traditional SAs. For instance, single wall carbon nanotubes (SWNTs) and two-dimensional (2D)



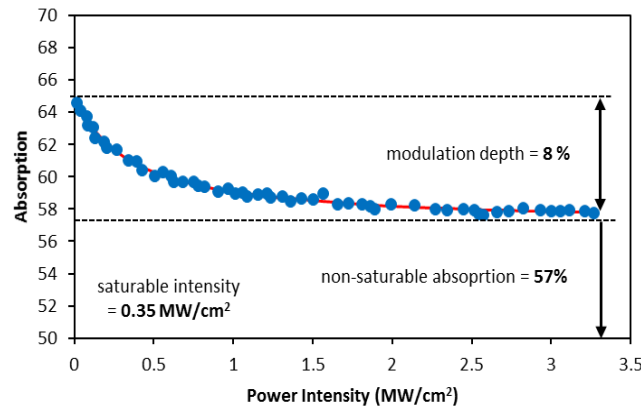
materials such as graphene and transition metal di-chalcogenides (TMDs) have emerged as new SA material with superior performance, such as wide-band operation, mechanical and environmental robustness [10].

Recently, black phosphorus (BP), a newly emerged 2D material, has also gained wide attention in recent years for potential application in developing the next-generation optoelectronics devices such as a sensor, field-effect transistors and solar cells [11-13]. Multi-layer BP has a similar structure with bulk graphite. In a single layer, each phosphorus atom is covalently bonded to three adjacent phosphorus atoms to form a stable honeycomb structure, and different layers are stacked together by van der Waals interaction [14]. A multi-layer BP has a direct energy bandgap structure, with bandgap from 0.3 eV to 2 eV depending on the number of layer [15]. Naturally, BP has the common properties of 2D materials such as wideband absorption, ultrafast carrier dynamics and planar characteristic [16]. Note that BP comprises only the elemental “phosphorus”. Hence it could be easily peeled off by using scotch tape. Stimulated by the similarity between graphene and BP regarding single elemental component and direct band-gap, it is natural to find out whether BP could be used as an SA for the Q-switching and mode-locking applications. The Q-switched of BP SA has been reported by [17, 18] with repetition rate from 31 kHz to 82.85 kHz at the wavelength of 1550 nm and also by using Ytterbium dope fiber for the mode-locked laser.

In this paper, we demonstrate a Q-switched Erbium-doped fiber laser (EDFL) using a mechanically exfoliated BP as SA. The BP-based SA tape was prepared by peeling bulk-structured BP 2D thin layer using a scotch tape. By inserting a small piece of the BP -SA tape into the EDFL cavity, Q-switched pulses with maximum pulse energy of 28.3 nJ is achieved, the shortest pulse width is 5.35  $\mu$ s. To the best of our knowledge, this is the first report on BP -SA tape based passively Q-switched fiber lasers.

## 2. Preparation and characterization of the BP based SA

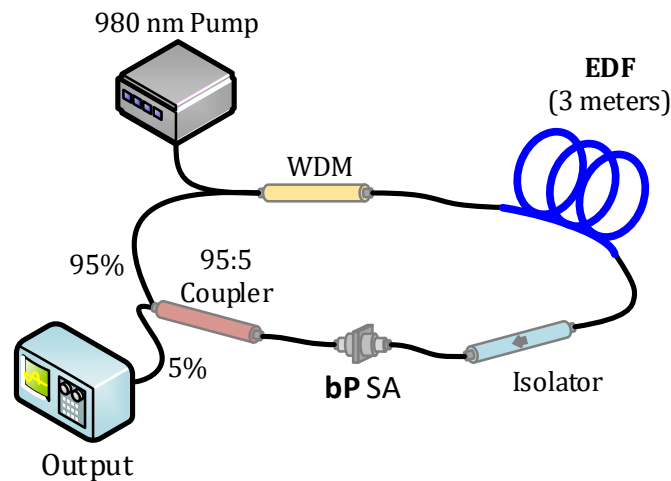
In this work, the BP based SA was prepared by mechanical exfoliation method, which has been widely used in graphene-based ultra-fast fiber laser applications [19, 20]. The nonlinear optical response property for the multilayer BP on the scotch tape is then investigated to confirm its saturable absorption by using the balance twin-detector measurement technique. A self-constructed mode-locked fiber laser (1562 nm wavelength, 1.05 ps pulse width, 16.3 MHz repetition rate, 3.2 MW/cm<sup>2</sup> maximum intensity before sample) is used as the input pulse source. The transmitted power and also a reference power for normalization are recorded as a function of incident intensity on the tape by varying the input laser power. With increasing peak intensity, the material absorption decreases as shown in Figure 1, confirming saturable absorption. The experimental data for absorption are fitted according to  $\alpha(I) = \alpha_s / (1 + I/I_{sat}) + \alpha_{ns}$ , where  $\alpha(I)$  is the absorption,  $\alpha_s$  is the modulation depth,  $I$  is the input intensity,  $I_{sat}$  is the saturation intensity, and  $\alpha_{ns}$  is the non-saturable absorption. As shown in the figure, a modulation depth, non-saturable intensity, and saturation intensity were obtained to be 8 %, 57 % and 0.35 MW/cm<sup>2</sup>, respectively. Taking into account its nonlinear optical response leading to absorption saturation at relatively low fluence, the mechanically exfoliated BP meets basic criteria of a passive SA for fiber lasers.



**Figure 1.** Nonlinear absorption profile.

### 3. Experimental setup

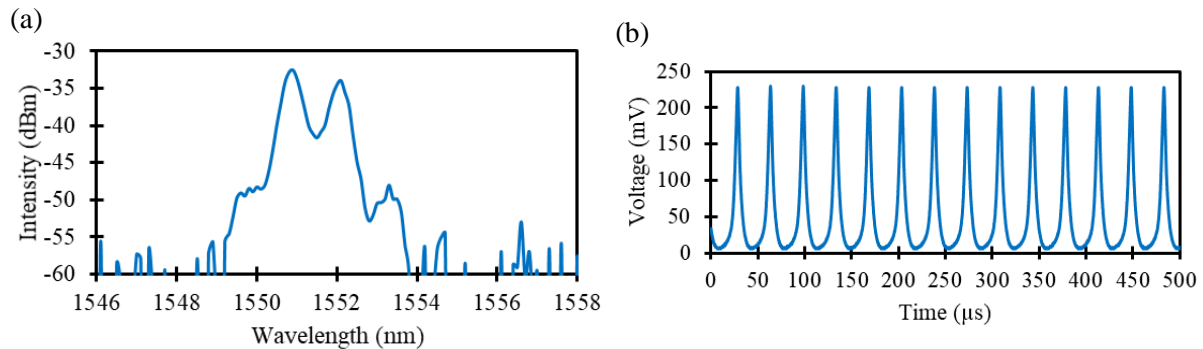
The setup of the Q-switched fiber laser is depicted in Figure 2. A 3 m long piece of erbium-doped fiber (EDF) was used as an active fiber. The EDF has core and cladding diameters of 4  $\mu\text{m}$  and 125  $\mu\text{m}$  respectively, a numerical aperture of 0.16 and Erbium ion absorption of 23 dB/m at 980 nm. It was co-directionally pumped via a fused 980/1550 nm wavelength division multiplexer (WDM) by a 980-nm laser diode. The signal was coupled out using 95/5 output couplers (OC) which channeled out 5 % of the light oscillating in the ring cavity for both spectral and temporal diagnostics. The fiber isolator forced a unidirectional signal propagation. As mentioned above, we chose a BP based SA to obtain the Q-switched pulse. The prepared multi-layered BP on the scotch tape was integrated into the fiber laser cavity by sandwiching a  $\sim 1 \text{ mm} \times 1 \text{ mm}$  piece of the composite tape between two fiber connectors. The SA was adhered to the ferrule using index matching gel. The cavity length was measured to be approximately 12 meter. The optical spectrum analyzer (OSA) with a spectral resolution of 0.07 nm was used for the spectral analysis while an oscilloscope (OSC) was used to analyze the output pulse train of the Q-switching operation via a photo-detector.



**Figure 2.** Experimental setup of the proposed Q-switched EDFL employing a mechanically exfoliated BP.

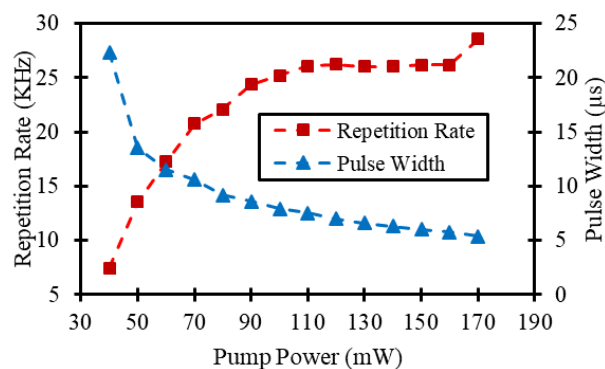
#### 4. Experimental results

Continuous wave operation begins at a pump power of 25 mW, and stable Q-switched pulses were achieved when the pump power was increased to 40 mW. The Q-switching operation was maintained up to the maximum pump power of 170 mW. Typical characteristics of the Q-switched pulses emitted from the fiber laser at a pump power of 170 mW are presented in Figure 3. The optical spectrum of the Q-switched pulses is centered at 1550.9 nm, and the 3-dB spectral width is approximately 0.4 nm, as shown in Figure 3 (a). Figure 3(b) displays a typical oscilloscope trace of the Q-switched pulse train, which shows a pulse period and pulse width of 35.0  $\mu$ s and 5.35  $\mu$ s, respectively. There is no distinct amplitude modulation in the entire Q-switched envelope in the spectrum, which leads to knowledge that the self-mode locking effect on the Q-switching is weak.



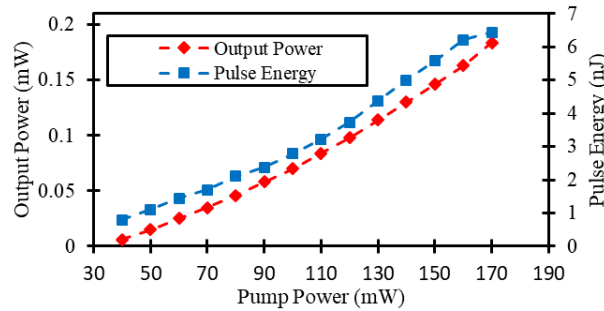
**Figure 3.** Typical characteristics of the Q-switched pulses emitted from the fiber laser at a pump power of 170 mW, where (a) Optical spectrum and (b) oscilloscope trace.

To verify that the passive Q-switching was attributed to the BP based SA, the FC fiber ferrule filled with BP tape was replaced with a common clean ferrule. In this case, no Q-switched pulses were observed on the oscilloscope even when the pump power was adjusted over a wide range. This finding has confirmed that the BP-based SA was responsible for the passively Q-switched operation of the laser. Unlike the fixed repetition rate of a mode-locked fiber laser the pulse repetition rate in our laser increased with the pump power, which is a typical feature of passive Q-switching operation. Figure 4 shows the pulse repetition rate and pulse width of the Q-switched fiber laser as functions of the incident pump power. By increasing the pump power from 40 to 170 mW, the pulse repetition rate could be varied over a wide range of frequencies, from 7.46 to 28.57 kHz. On the other hand, the pulse width decreased from 22.34  $\mu$ s near the pump threshold of 40 mW to 5.35  $\mu$ s at a pump power of 170 mW. The minimum pulse width obtained in our experiment could be narrowed by shortening the cavity length and improving the modulation depth of the few-layer BP.



**Figure 4.** Pulse repetition rate and pulse width at different pump powers.

Figure 5 shows the dependence of the average output power and pulse energy of the Q-switched fiber laser versus the pump power. The pulse energy was calculated based on the measured average output power and the repetition rate. When the pump power exceeded the threshold, both average output power and pulse energy increased almost linearly with the pump power. The maximum average output power was 0.18 mW at a pump power of 170 mW, corresponding to a pulse energy of 6.4 nJ. We believe that the performance of Q-switched pulses produced by the laser could be further improved by optimizing the SA parameters of BP tape and the cavity design.



**Figure 5.** Average output power and pulse energy versus incident pump power.

## 5. Conclusion

We experimentally demonstrated a passively Q-switched ring EDFL using a few-layer bP flakes onto a scotch tape as a SA. The BP tape was prepared by the mechanical exfoliation method and sandwiched between two fiber connectors with a fiber adapter to form a fiber-compatible BP -based SA. Stable Q-switched pulses at 1550.9 nm were successfully obtained. The laser showed a pump threshold of 40 mW and a minimum pulse duration of 5.35  $\mu$ s. The pulse repetition rate could be varied over a wide range of frequencies, from 7.46 to 28.57 kHz, by adjusting the pump power. Our experimental results suggest that few-layer BP is a promising material for pulsed laser applications.

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