Passively Mode-locking Operation Fiber Laser Generation using Black Phosphorus Saturable Absorber at 1-micron wavelength region

Ahmad Haziq Aiman Rosol, Husna Abdul Rahman, Zulzilawati Jusoh, Anas Abdul Latiff, Muhammad Farid Mohd Rusdi and Sulaiman Wadi Harun

***Abstract*— We demonstrate the generation of mode-locked ytterbium-doped fiber laser (YDFL) by using a black phosphorus (BP) as a passively saturable absorber (SA). The BP SA is exfoliated from the commercial bulk crystal BP by using a standard scotch tape. To realize the mode-locking operation, a piece of BP tape is adhered onto a fiber ferrule tip by an assistant of index matching gel before being sandwiched. Under 270 mW to 490 mW, the stable repetition rate of 14.85 MHz obtains at 1100 nm wavelength with maximum pulse energy of 0.94 nJ. Our findings may contribute to the pathway of graphene-like materials specifically for ultrafast fiber laser generation application.**

***Index Terms*— Mode-locking laser, double-clad ytterbium-doped fiber, saturable absorber.**

I. Introduction

Pulsed fiber lasers have gained so much interest in wide application areas such as micro-machining, medical surgery, and military system [1, 2]. Mode-locked is one of the technique to generate shorter pulse width of the pulsed laser by phase locking many longitudinal modes creates in the cavity. Mode-locked can be realized either passive or active technique. Compare to active technique, a passive technique is more reliable in generating pulse, uncomplex system, and not require an external electrical source. The passive mode-locked technique is more compact and simple in geometry and setup. However, the active mode-locked technique required an electronic switching such as acoustic optic modulator [3].

Up to date, various types of the saturable absorber (SAs) have been used for realizing passive mode-locked lasers, such as the ion-doped crystals [4], semiconductor saturable absorption mirror (SESAM) [5, 6] and carbon nanotubes [7, 8]. Among them, SESAMs are the most widely used due to their high flexibility and stability. However, SESAMs are expensive and have a limited range of optical response, which restricts their applications to a great extent. Developing low-cost SAs for a broadband operation has always been an objective for laser experts.

Since Geim and Novoselov won a noble prize in graphene work, the ultrafast laser community starts a progressive exploration of two-dimensional (2D) materials for the generation of ultrafast fiber laser [9-12]. The two-dimensional (2D) materials, including graphene, topological insulators (TIs) and transition metal dichalcogenides (TMDs) have been extensively studied in recent years due to their promising application in photonics. A weak intralayer atomic bonding of 2D materials by Van de Waals forces makes this material much easier to exfoliate. The presence of bandgap size in 2D materials make it has an ability to absorb a photon and saturate based on Pauli-blocking principle. Thus, this group of material has been used as an SA for generation of ultrashort pulse fiber laser [13]. Moreover, the limited bandwidth operation in SESAM can be solved by using a 2D material SA.

Recently, many researchers have focused on materials of black phosphorus (BP) [12, 14][10, 12]. The BP has a graphene-like structure which the layer are bound with weak Van de Waals forces [15]. Since BP consist of elemental phosphorus only, it can be easy to peel off using exfoliation technique. Compare to graphene and TMDs, energy bandgap of the BP is scalable with the number of layers. From monolayer to bulk BP, the bandgap size is changed from 1.5 eV to 0.3 eV [16]. BP is categorized as a hydrophilic material, which easily to damage once expose to air and oxygen. Therefore, extra precaution should be taken during the BP preparation process.

In this paper, we demonstrate a mode-locking operation fiber laser by using double-clad ytterbium doped fiber (YDF) as a gain medium and black phosphorus as a passive SA. The SA was obtained by mechanical exfoliation from the commercial bulk BP. The laser is capable of generating a mode-locking operation at 1100 nm wavelength with a repetition rate of 14.89 MHz.

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II. Preparation and Characterization of BP Tape

At first, we mechanically exfoliate the BP flakes from available commercial BP. The preparation of BP tape is shown in Figure 1. As shows in the figure, relatively thin flake was peeled off from a bulk BP crystal with a purity of 99.995% using a clear scotch tape. Then, we press the flakes repetitively on a tape until the flake homogeneously distributed and become thin, so it is enough to transmit light with higher efficiency. A small piece of BP tape was cut then attached to fiber ferrule end surface with index matching gel. This mechanical exfoliation method is promising and has been reported by other researchers [9, 12, 14, 17]. The advantageous of this technique is simplicity and reliability due free from the complex chemical process. Overall preparation process was done within 3 minutes due to hydrophilic characteristic owned by BP.

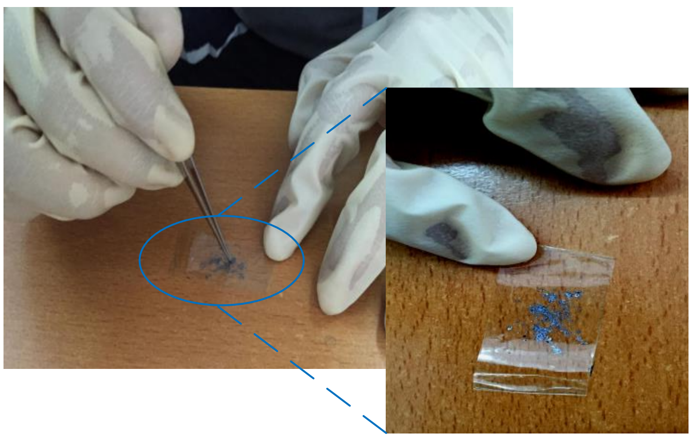


Figure 1. Actual image of BP tape preparation.

The obtained BP tape has undergone standard characterization machine such as field emission scanning electron microscopy (FESEM), and energy dispersive spectroscopy (EDS). Also, modulation depth measurement for measuring the SA ability of BP tape. The FESEM image of the BP tape is shown in Figure 2(a). As shown in the figure, a uniform BP layers with nonappearance of >1 µm voids presence on the surface tape. Figure 2(b) shows the EDS data from the captured FESEM image. The figure shows only phosphorus element peak observes at an energy of 2 keV which verify the existence of BP element on the tape surface. The most important parameter for a material can be determined as an SA is by investigating the nonlinear absorption profile of the material. The investigation can be done through a balance twin-detector measurement technique. A mode-locked laser source is launched into the SA sample in unidirectional of linear configuration. The pulse power is gradually increased as a function of incident intensity onto the BP tape SA. We record the incident power to a sample and also its transmitted power for measured the nonlinear absorption properties of SA. Figure 2(c) shows the nonlinear absorption properties of BP tape as the absorption of the material decreases with the increment of power intensity. The saturable absorption and non-saturable absorption was 8 % and 57 %, respectively. As shown in the figure, about 0.35 MW/cm2 power intensity is used to saturate the BP tape.

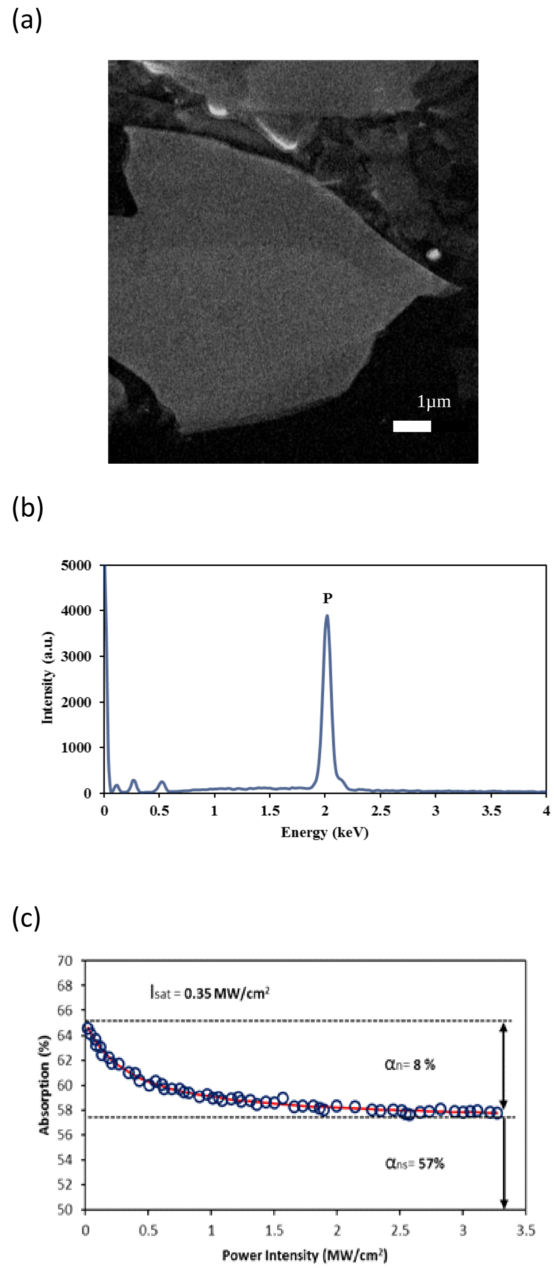


Figure 2. The properties of BP tape. (a) FESEM image. (b) EDS data. (c) Optical nonlinearity properties.

III. YDFL Cavity Configuration

The experimental setup for our passively mode-locked YDFL is schematically shown in Figure 3. It uses a 10 m long double-clad ytterbium doped fiber (YDF) as a gain medium. The YDF has a core diameter of 4.0 µm, NA of 0.20 and cutoff wavelength of around 980 nm. It has a cladding absorption coefficient and group velocity dispersion (GVD) of 3.95 dBm (at 975 nm) and -18 ps2/km, respectively. The YDF was pumped by a 980-nm multimode laser diode (LD) via a multimode combiner (MMC). The mode-locking operation can be realized by inserting a piece of BP tape in between two fiber ferrules. A 10-dB coupler is used to close the loop of ring cavity configuration by splicing a 90 % coupler port to the MMC feedback port. Another 10 % coupler port is used to investigate the generated laser performances. The temporal performance of mode-locked laser was monitored by using a 350-MHz oscilloscope (OSC) and a 7.8 GHz RF spectrum analyzer (RFSA) via a 2-GHz photodetector (PD). An optical spectrum analyzer (OSA) with 0.002 nm resolution was used to observe the spectral performance of the mode-locked laser.

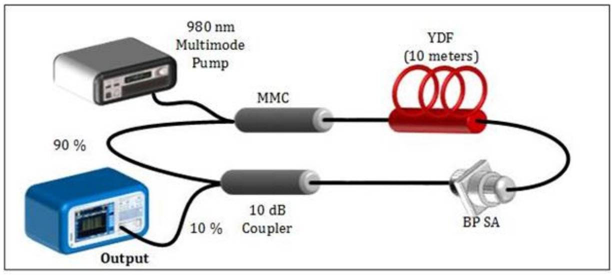
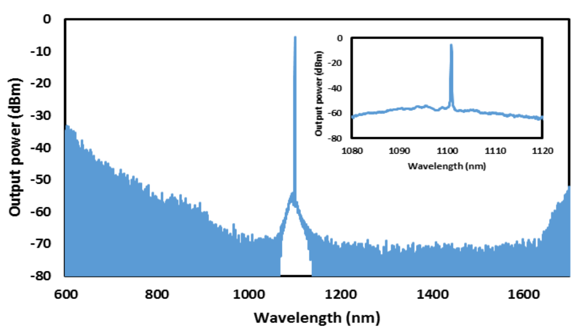


Figure 3. Schematic illustration of mode-locked YDFL configuration.

IV. Result and Discussion

The self-started mode-locking operation achieves at 270 mW pump power, and uninterruptedly stable up to 490 mW pump level. Figure 4(a) shows the output spectrum of mode-locked YDFL with peak lasing at 1100 nm and pumping wavelength of 980 nm is fully absorbed. The inset image shows the enlarged spectrum of peak lasing at 1100 nm wavelength with a 3-dB spectral bandwidth of 0.07 nm (17.34 GHz). The output power and pulse energy of mode-locked YDFL have been observed within 270 mW to 490 mW pump power. Figure 4(b) shows the output power obtained linearly from 4 mW to 14 mW with an optical-to-optical efficiency of 4.19 %. From the output power over repetition rate value, the pulse energy is relatively determined. Maximum pulse energy is recorded about 0.944 at maximum pump power level.

(a)



(b)

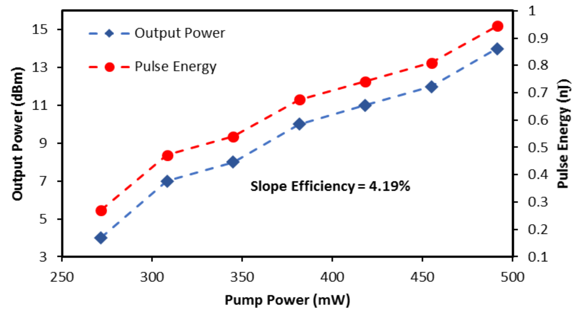
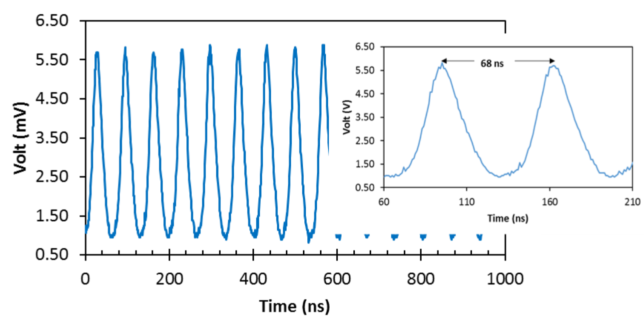


Figure 4. Mode-locked YDFL spectral performances. (a) Lasing spectrum at 271 mW pump power. Inset is enlarged image of peak lasing at 1095 nm. (b) Output power and pulse energy.

In this experiment, the temporal performance of the mode-locking operation is observed in time-domain and frequency-domain via OSC and RFSA, respectively. Figure 5 shows the pulse train of mode-locked YDFL at threshold (270 mW) and maximum (490 mW) pump power. As shows in the figure, the enlarging pulse train visibly confirms the consistency of pulse period is obtained within 68 ns to 69 ns, which corresponding to the repetition rate of 14.81 MHz to 14.85 MHz. Direct from OSC, the pulse width is observed about 22.92 ns to 27.68 ns. Due to the OSC resolution limitation, the actual pulse width can be determined through a time-bandwidth product (TBP). The minimum possible pulse width is relatively about 25.43ps, using Gaussian pulse profile. The stability of the pulse can be confirmed by using the RFSA. Figure 6 shows the RF spectrum of mode-locked YDFL with 80 MHz spans. The fundamental repetition rate stands at 14.81 MHz with a signal-to-noise ratio (SNR) obtained is 28 dB. Only two harmonics observe due to a few number of longitudinal modes exist in our cavity. Moreover, it is corresponding to the narrow spectral bandwidth of output spectrum and the broader pulse width size.

(a)



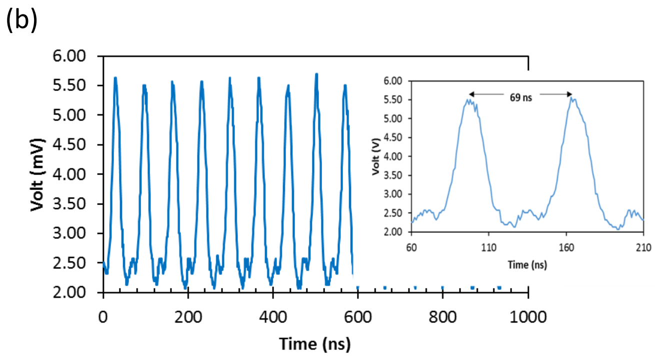


Figure 5. Typical pulse train at 271mW and 491 mW pump power.

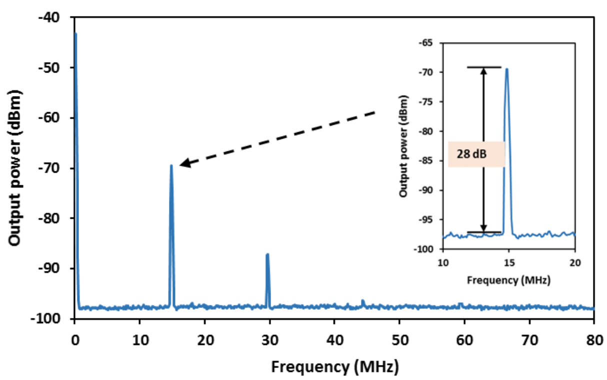


Figure 6. RF spectrum with 80 MHz spans.

V. Conclusion

We fabricated BP tape as a passive SA in YDFL ring cavity for mode-locking operation at a centered wavelength of 1100 nm. Stable mode-locked pulse trains were recorded with the increase of pump power from 270 to 490 mW. Maximum pulse repetition rate of 14.85 MHz and maximum pulse energy of 0.944 nJ were obtained at 490 mW pump power. The possibility of tracing pulse laser in 1-micron wavelength region and the ability of BP as an SA to generate mode-locked pulse trains in YDFL could have many advantages in the photonics studies and its applications.

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