ABSTRACT

This paper reports a few-layer black phosphorus (BP) as a saturable absorber (SA) or phase-locker in generating mode-locked pulses from a double-clad ytterbium-doped fiber laser (YDFL). We mechanically exfoliated the BP flakes from BP crystal through a scotch tape, and repeatedly press until the flakes thin and spread homogenously. Then, a piece of BP tape was inserted in the cavity between two fiber connectors end facet. Under 810 mW to 1320 mW pump power, stable mode-locked operation at 1085 nm with a repetition rate of 13.4 MHz is successfully achieved in normal dispersion regime. Before mode-locked operation disappears above maximum pump, the output power and pulse energy is about 80 mW and 6 nJ, respectively. This mode-locked laser produces peak power of 0.74 kW. Our work may validates BP SA as a phase-locker related to two-dimensional nanomaterials and pulsed generation in normal dispersion regime.

Keywords: Mode-locked laser, fiber laser, saturable absorber, ytterbium doped fiber

1. INTRODUCTION

Towards 20s century, mode-locked fiber lasers have attracted considerable interest as they can be useful in many applications such as micromachining, metrology and defence system [1-3]. Mode-locked laser source offers more precise cutting in micromachining. Better than active mode-locking techniques, passive mode-locking techniques are implemented in this research to generate pulse lasers since they are more compact in geometry and simpler in setup. Additional switching electronics such as acousto-optic modulators and generates limited pulse duration become a drawback for active techniques [4]. Up to the present time, various types of saturable absorber (SAs) have been used for realizing passive mode-locked lasers [5-8]. SESAMs are the most commonly used SA due to their high flexibility, and stability [9, 10]. 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.

Recently, two-dimensional (2D) materials such as graphene and transition-metal dichalcogenides (TMDs) have been considered as promising building blocks for the next-generation photonics technology, owing to its unique planar advantages [11]. Particularly, the existence of quantum confinements, the absence of inter-layer interactions and the strong intra-layer covalent or ionic bonding, allow researchers to fabricate compact, flexible and efficient photonic devices. For graphene, strong light-matter interaction is required due to zero bandgap and low absorption co-efficiency (2.3%/layer) [12-14]. Consequently it restrains the graphene application. For TMDs materials such as molybdenum disulfide (MoS2) [15, 16] and tungsten disulfide (WSe2) [17, 18], the fabrication process of SAs using these materials is more complicated.

Another interesting 2D material is black phosphorus (BP) which is regarded as the most thermo-dynamically stable allotrope [19]. Many interesting findings on its unique electronic properties have been discovered and reported [20, 21]. However, its optical properties are much less explored, except for its polarization dependent optical response as dictated by the anisotropic feature of BPs [22, 23]. The broadband nonlinear optical response in BP is promising for infrared and mid-infrared optoelectronics [24]. Stimulated by the similarity between graphene and BP in terms of single elemental component and direct band-gap, it is natural to find out whether BP could be used as an SA for Q-switching and mode-locking applications. In 2015, Chen et al. demonstrated the use of mechanically exfoliated BP as an SA successfully by generating Q-switching and mode-locking operation in the C-band region [25]. In this paper, we demonstrate the fabrication of BP 2D-material by mechanical exfoliation method and its application as a new type...
of effective SA for ultra-fast photonics. Through mechanical exfoliation using scotch tape, bulk BPs could be peeled to form 2D thin layers. A small piece of the tape could be attached onto the end-facet of a fiber ferrule, turning it into an SA device. By placing the SA device inside an Ytterbium-doped fiber laser cavity, passive mode locking operation of the fiber laser could be initiated, which suggests that 2D BP material could be developed as an effective SA for ultra-fast photonics.

2. EXPERIMENTAL WORK OF MODE-LOCKED YDFL

2.1 BP-SA preparation and characterization

The fabrication of the BP samples through mechanical exfoliation approach is similar approach to the preparation of graphene based saturable absorbers for ultra-short pulse laser applications [26, 27]. This technique is advantageous mainly because of its simplicity and reliability, where the entire fabrication process is free from complicated chemical procedures and costly instruments. The relatively thin flakes were peeled off from a big block of commercially available BP crystal (purity of 99.995 %). A small piece of the BP tape was attached between two fiber ferrules end surface. BP material is easily damaged with the exposure to oxygen and water molecules. To solve, the whole preparation process was done in less than 2 minutes.

The characterization of the BP tape, which was fabricated via mechanical exfoliation approach are summarized in Figure 1. The composition of the transferred layers is confirmed by the energy dispersive x-ray (EDX) on the BP tape. The presence of BP material on the scotch tape adhesive surface is verified by the presence of the Raman spectrum as shown in Figure 1(a). The Raman spectrum, which is recorded by a spectrometer when a 514 nm beam of a Argon laser is radiated on the flakes for 10 ms with an exposure power of 50 mW. As shown in the figure, the sample exhibits three distinct Raman peaks at 360 cm$^{-1}$, 438 cm$^{-1}$ and 465 cm$^{-1}$, corresponding to the $A_{1g}$, $B_{2g}$ and $A_{2g}$ vibration modes of layered BP. While the $B_{2g}$ and $A_{2g}$ modes correspond to the in-plane oscillation of phosphorus atoms in BP layer, the $A_{1g}$ mode corresponds to the out-of-plane vibration. The ratio between $A_{1g}$ peak and silicon (Si) level at 520 cm$^{-1}$ provides a rough estimate of the thickness of BP flake at ~ 4.5 nm [28]. The thickness for single-layer BP is about 0.6-0.8 nm [22, 29], so the prepared BP based SA is estimated to contain of 5~8 layers.

Next, we investigate the nonlinear optical characteristic for the multi-layer BP on the scotch tape by applying the balance twin-detector measurement technique. This is to confirm the obtained BP tape saturable absorption ability. In the experiment, the polarization state was controlled by a polarization controller (PC). A mode-locked fiber laser was used as the input pulse source. The transmitted power and also a reference power for normalization were recorded as a function of incident intensity on the BP tape by varying the input laser power. With increasing peak intensity, the material absorption decreases as shown in Figure 1(b), confirming saturable absorption. As shown in Figure 1(b), the modulation depth ($\alpha_J$), non-saturable absorption ($\alpha_{na}$), and saturation intensity ($I_{sat}$) are obtained to be 8 %, 57 % and 0.35 MW/cm$^2$, respectively. The experimental data for absorption are fitted according to a simple two-level SA model [30]. Taking into account that the nonlinear optical response leading to absorption saturation was obtained at relatively low fluence, the mechanically exfoliated BP meets basic criteria of a passive SA for fiber lasers. From material perspective, BP is an anisotropic crystal, its linear absorption is sensitive to light polarization state. Further investigation was done by varying the polarization state to various angles using a PC. It is found that the output intensity of the laser indicates only two states; one with output power trend similar to Fig 1(b) or low output power (almost near to zero reading). This proves that the BP based SA is polarization-dependent due to anisotropic layered material characteristic [22]. Thus a PC is employed in the proposed laser cavity to adjust the polarization of oscillating light so that it matches the SA transmission axis.
2.2 Laser configuration

We constructed a fiber laser cavity schematically at 1 µm wavelength in order to evaluate its mode-locking ability. Figure 2 shows the proposed laser configuration where the fabricated BP based SA is used as a mode locker. The SA is integrated into the fiber laser cavity by sandwiching a ~1 mm × 1 mm piece of the multi-layer BP tape between two FC/PC fiber ferrules via a fiber connector. Insert image shows clearly a position of BP tape. A 10 m long double-clad Ytterbium doped fiber (YDF) was used to provide amplification at 1-micron region. It has a cladding absorption coefficient of 3.95 dBm at 975 nm and the group velocity dispersion (GVD) of -18 ps²/km. The fiber was pumped with a 980 nm multimode laser diode (LD) via a multimode combiner (MMC). The addition of a PC enables adjustment of the polarization state within the cavity for the mode-locking action. A 10 dB fused optical fiber coupler was used to collect 10% power from the cavity and retains 90% of the light in the ring cavity to oscillate. Other fibers in the cavity is a standard SMF (with a GVD of 44.2 ps²/km), which constitutes the rest of the ring. The total ring cavity length is around 14.8 m and the net cavity dispersion is estimated in normal dispersion condition as ~ 0.39 ps². The laser performance was monitored and measured using an optical spectrum analyser (OSA), 500 MHz oscilloscope (OSC), and 7.8 GHz RF spectrum analyser (RFSA) coupled with a 1.2 GHz InGaAs photodetector (PD). OSA is used for the spectral analysis of the mode locked laser, while OSC and RFSA are used to analyse the output pulse train of the mode locking operation via PD.

3. PERFORMANCE OF MODE-LOCKED

The mode-locking operation self-starts at the input multimode pump power of 816 mW provided that the intra-cavity PC is suitably adjusted. The self-starting mode-locking is maintained up to the pump power of 1322 mW and operates at the fundamental repetition frequency of the cavity of 13.4 MHz. The output spectrum of the mode-locked YDFL, which is obtained after the 10 dB coupler at the threshold pump power of 816 mW is shown in Figure 3(a).
spectrum operates at center wavelength of 1085 nm with a 3 dB spectral bandwidth of 0.23 nm without Kelly sideband. This confirms the mode-locked pulse operates in normal dispersion. The relation between the input pump power and output power is shown in Figure 3(b), which depicts that the output power increases from 10 mW to 80 mW with the corresponding pump power rise from 816 mW to 1322 mW. The optical-to-optical efficiency is relatively high (13.12 %) because of the low insertion loss from the SA. Fig. 4(d) also presents the relation between the input signal power and the calculated pulse energy. It is observed that the pulse energy increases linearly with the pump power with the maximum pulse energy of 5.93 nJ. Due to over-saturation of the BP-SA, the mode-locked YDFL output become unstable and suddenly disappeared once the pump power exceeded 1322 mW. The BP-SA remain undamaged as we tuned pump power up to 1322 mW for more than a day. By keeping in an air tight container, less expose to oxygen or water molecules helps to protect BP-SA from damage easily.

Figure 3(c) shows a stable mode-locked pulse train with a peak to peak spacing of 74 ns, which matches with the cavity length of 14.8 m. The oscilloscope trace shows a pulse width of 26 ns, which is much broader than the actual pulse width. This is due to the resolution limitation of the oscilloscope. Thus, the pulse width can be measured using an auto-correlator or mathematically calculated based on the time bandwidth product (TBP). By assuming the TBP is 0.441 for Gaussian pulse profile, the minimum possible pulse width was estimated mathematically about 7.54 ps. The corresponding radio frequency spectrum as shown in Figure 3(d) indicates that our laser cavity operates at the stable regime, given that the fundamental frequency (13.4 MHz) has a high signal-to-noise ratio (SNR) (up to 45 dB). The peak of fundamental frequency decreased moderately until 7th harmonic, so this identifies the mode-locked has a narrow pulse width. At all pump power level, no presence of fundamental frequency observed when the BP-SA is removed. The experimental results verify the mode locking ability of the newly developed multi-layered BP-SA. This shows that the BP could be used to develop promising optoelectronic devices with high power tolerance, offering inroads for more practical applications, such as large energy laser mode-locking, nonlinear optical modulation and signal processing etc.
4. CONCLUSION

We fabricated an SA device from a multi-layers of BP and used it to mode-lock an YDFL. Self-starting and stable mode-locked pulses were obtained at the threshold pump power of 816 mW, up to 1322 mW with a consistent pulse repetition rate of 13.4 MHz. The maximum pulse energy calculated was 6 nJ at pump power of 1322 mW, with high peak power of 0.74 kW. Our results contribute to a growing body of works that studies nonlinear optical properties of BP which might pave the way for ultrafast photonics applications.

REFERENCE


