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Mode-locked ytterbium-doped all-fiber lasers based on few-layer black phosphorus saturable absorbers

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ABSTRACT

In this paper, we demonstrated ytterbium-doped mode-locked fiber lasers based on saturable absorbers (SAs) made of few-layer black phosphorus (BP) with all normal dispersion. The few-layer BP was prepared with the liquid phase exfoliation method and was deposited onto fiber facets by an optically driven process. By incorporating the BP-SA into an ytterbium-doped fiber cavity, stable mode-locking laser operation in all-normal dispersion region was achieved with a repetition rate of 46.3 MHz. The laser spectrum was centered at 1030.6 nm with a 3 dB bandwidth of 0.11 nm. Maximum output power of 32.5 mW was achieved and showing no signs of saturation.

1. Introduction

Passively mode-locked fiber lasers have attracted widespread interests in recent years for their advantages of compactness and low cost [1,2]. Many techniques have been developed to realize passively mode-locking scheme for fiber laser including nonlinear loop mirror, nonlinear polarization rotation, and various types of saturable absorbers (SAs) [3–5]. The semiconductor SA approach has been a relatively mature technique for mode locking, nevertheless, its application is limited by its complex fabrication process, expensiveness and a narrow operating bandwidth [6]. Alternative SAs made by novel materials have been drawing research attentions in recent years such as single wall carbon nanotubes (CNTs) and two-dimensional (2D) materials including graphene, transition metal dichalcogenides (TMDCs), topological insulators (TIs). These materials have all been explored as potential candidates for the next-generation optoelectronic devices [7–13]. However, the strong light scattering caused by the tubular structure of CNTs leads to a high loss of incident light; the relatively weak optical absorption (2.3% per layer) of graphene limits its applications in nonlinear processes if strong light-matter interaction is needed; TMDCs possess a large bandgap that is more suitable for visible band [12,14]; and TIs also limit themselves by the complex fabrication processes [15].

Very recently, a novel 2D material, few-layer BP, has been found to own outstanding nonlinear optical characteristics and considered suitable for infrared and mid-infrared light bands. The nonlinear absorption of BP at 400, 800, 1562 and 1930 nm has been investigated using open-aperture Z-scan technique [16], and BP is the most thermodynamically stable allotrope of phosphorus. Few-layer BP is a 2D layered anisotropy crystal with a direct bandgap and its band gap energy is determined by the number of layers (from 0.3 eV for bulk BP to 2 eV for monolayer BP) that could extend into the breach of zero-gap graphene and large-gap TMDCs [17]. The controllable band energy combined with a relatively large bandgap span makes BP a promising and more suitable prospect for infrared and mid-infrared laser applications comparing with early pioneering 2D materials [13–15], which was first demonstrated with pulsed fibers laser at 1571 nm based on mechanically exfoliated BP-SAs [18].

In this paper, we report a passively-mode-locked ytterbium-doped fiber laser (YDFL) utilizing a few-layer BP-SA that was fabricated by the liquid phase exfoliation (LPE) method. The fiber-based BP-SA was prepared with an optically driven (OD) processing, which possessed the advantages of pronounced repeatability and reliability comparing with the mechanical exfoliation method. Dissipative soliton operation in an all normal dispersion region was achieved and stable passively mode-locked dissipative soliton laser was observed at around 1030 nm. The repetition rate of the output laser pulses were measured at 46.3 MHz and the maximum output power was 32.5 mW. To the best of our knowledge, this is the first time to incorporate fiber-based few-layer BP-SAs that is fabricated by an optically driven process into the 1030 nm mode-locked fiber laser systems, which holds the benefits to substantially improve the repeatability and reliability comparing with the previous tape processing method for the fiber lasers [18,19].

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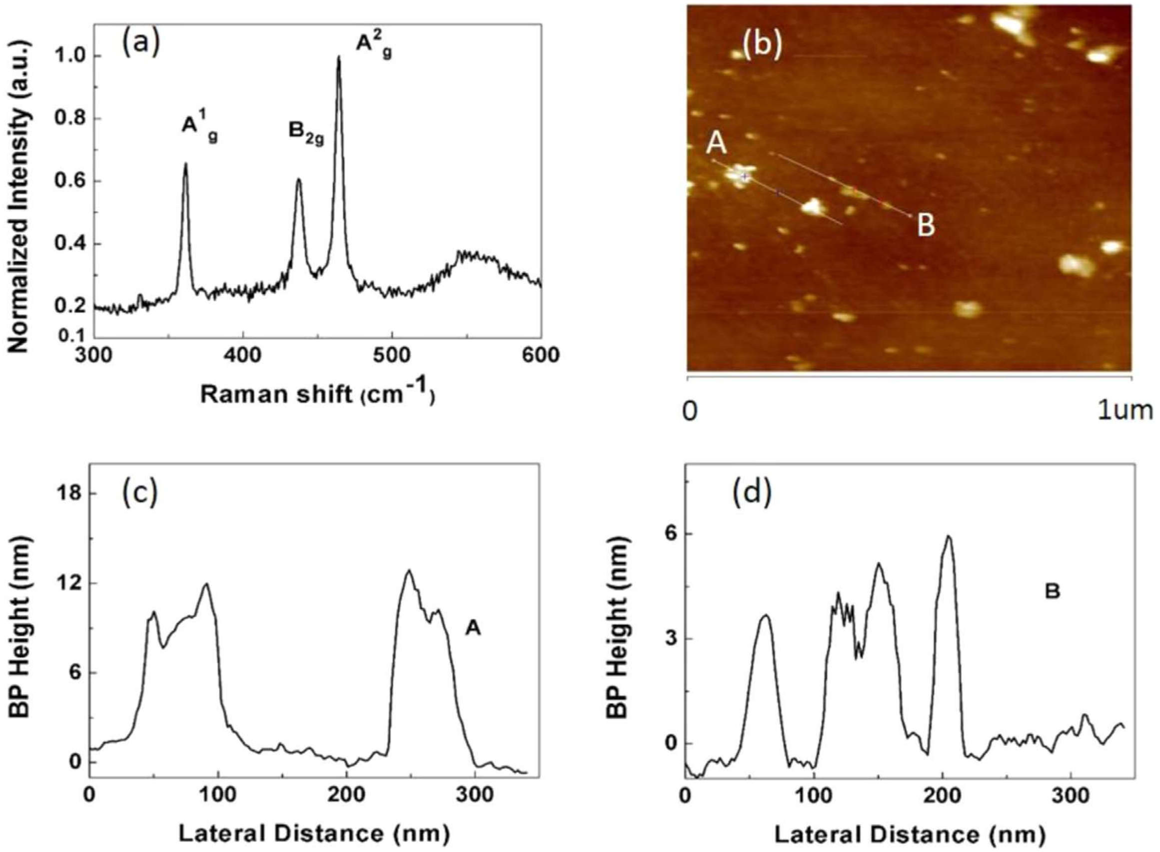

Fig. 1. (a) Raman shift of BP powder; (b) AFM photo of the prepared few-layers BP; (c) and (d) thickness scan of BP nanoflakes across different regions.

2. Fabrication of the black phosphorus saturable absorbers

Commercially available BP powder was obtained as the base material for SA preparation. The measured Raman spectrum of BP powder from a standard Raman spectrum analyzer is shown in Fig. 1(a). Three Raman peaks are located at 363.3 cm^{-1}, 438.9 cm^{-1}, and 464.5 cm^{-1}, corresponding to the A_g^1, B_{2g} and $A^2{}_g$ vibration modes of BP lattice respectively. The fabrication of few-layer BP was carried out by a widely used LPE method for 2D material processing [20]. First, 100 mg black phosphorus powder was added into 20 ml isopropyl alcohol (IPA) solvent, and the BP/IPA mixture was then bath sonicated at 40 kHz frequency and 300 W for 30 h at room temperature followed by a centrifugation at 3000 rpm for 15 min, and supernatant liquor was isolated for the next process. We used an atom force microscope (AFM) to investigate the micro-morphology of the as-prepared few-layer BP, as shown in Fig. 1(b)–(d), and it was observed that the thickness of BP nanoflakes ranged from 5 nm to 15 nm. While BP has a thickness of ~0.6 nm for a single layer, the as-prepared BP samples are estimated to be around 8–25 layers. The relationship between the bandgap energy and the number of layers of BP could be characterized with equation Eg≈(1.7/n^0.73+0.3) eV (n represents the number of layers) [17]. Therefore, we estimated the bandgap energy of the as-prepared few-layer BPs was lower than ~0.673 eV, indicating these samples could work with wavelength shorter than ~1.84 μm.

To fabricate the SAs with the as-prepared BP samples, an optically driven processing method was conducted as illustrated in Fig. 2(a). FC/UPC fiber connector was immersed in the prepared BP-IPA dispersions with 980 nm continuous-wave laser injected. By adjusting the power level and time duration of the pump laser, BP nanoflakes of various thickness could be attached to the fiber end facet due to the cooperation of optical trapping force and heat convention effect [21]. Pump laser with given power too high or too low would not successfully trap BP nanoflakes onto the fiber facet. In our experiments, it was found that laser power of around 60 mW lasting about 20 min was appropriate for SA fabrication. After the optically driven deposition, the fiber connectors were placed into a vacuum chamber for 12 h to remove the liquid impurities. The finished sample was coupled with another clean fiber connector through a fiber barrel for later testing.

The nonlinear absorption properties of BP nanoflakes deposited onto the fiber facets were measured with an in-lab mode-locked fiber laser that possessed a central wavelength of 1030 nm and a pulse duration of 5 ps at 58 MHz repetition rate. The optical absorption of the as-made SA changed with varying laser powers and their relationship could be presented by the following equation:

$$\alpha(I) = \frac{\alpha_S}{1 + I/I_S} + \alpha_{NS} \tag{1}$$

where $\alpha(I)$ is the absorption coefficient, α_S presents the saturable absorption, α_{NS} the nonsaturable absorption and I_s is the saturable intensity. The measured transmittance curve vs laser power is plotted in Fig. 2(b). It is observed that the fiber based BP-SA has a low unsaturable absorption at 80 mW mode-locking laser injected and the modulation depth of the fabricated SAs is estimated to be ~8.5%.

3. Experiments of the passively mode locked fiber lasers

The experimental setup for the passively mode-locked YDF fiber laser is schematically shown in Fig. 3. The ring cavity was pumped by a single mode 980 nm diode laser via a 980/1030 nm wavelength division multiplexer (WDM). A 60 cm long ytterbium-doped fiber (YDF, NUFERN SM-YSF-HI), with an absorption coefficient of 250 dB/m core at 975 nm and a dispersion coefficient of −43 ps/(nm km) at 1030 nm, was utilized as the gain fiber. An inline polarization controller (PC) was used to calibrate the polarization state of laser in the cavity and stabilize the mode-locking operation. The fabricated SA was incorporated to achieve the mode locking state with a