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Passively Q-switched wavelength-tunable 1-µm fiber lasers with tapered-fiber-based black phosphorus saturable absorbers

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ABSTRACT

In this paper, we demonstrated passively Q-switched wavelength-tunable 1-µm fiber lasers utilizing few-layer black phosphorus saturable absorbers. The few-layer BP was deposited onto the tapered fibers by an optically driven process. The wavelength tunability was achieved with a fiber Sagnac loop comprised of a piece of polarization maintaining fiber and a polarization controller. Stable Q-switching laser operations were observed at wavelengths ranging from 1040.5 to 1044.6 nm at threshold pump power of 220 mW. Maximal pulse energy of 141.27 nJ at a repetition rate of 63 kHz was recorded under pump power of 445 mW.

Introduction

Passively Q-switched fiber lasers based on saturable absorbers (SAs) have attracted substantial research attention for applications in material processing, spectroscopy, medical diagnoses, and fiber telecommunications. Semiconductor saturable absorber mirrors (SESAMs) have been adopted for most commercial applications owing to their mature manufacturing processes [1]. However, disadvantages of SESAMs such as complicated fabrication process, high cost, and narrow bandwidth prompt researchers to explore alternative SAs with novel materials [2]. Single-wall carbon nanotubes (CNTs) and two-dimensional (2D) layered materials including graphene and transition metal dichalcogenides (TMDCs) have been developed as SA candidates because of their ease of fabrication and much lower cost comparing with SESAMs [3–9]. 2D materials, in particular, are considered as potent prospects for the next-generation photonics technology because of their wideband responses and ultrafast carrier dynamics. However, graphene typically has a weak optical absorption (2.3% per layer) and TMDCs are more suitable in the visible due to their large bandgaps [10,11].

Quite recently, black phosphorus (BP), which is the most thermodynamically stable allotrope of phosphorus, has been rediscovered as a 2D material for optoelectronic applications [12]. Layered BP has a direct bandgap depending on the number of layers, 0.3 eV for bulk BP and 2 eV for monolayer BP. It thus has largely adjustable bandgaps and nonlinear absorption over a wide bandwidth [12]. Layered BP becomes a promising prospect in pulsed lasers in the infrared and mid-infrared region [13]. Q-switched and mode-locked pulsed fiber lasers triggered by BP-SAs have been presented in wavelengths ranging from 1 to 3 µm [14–20]. However, the conventional method of fixating BP-SA in between the fiber end facets is far from an ideal approach [16,17]. Such-fabricated BP-SAs are easily exposed to a combination of oxygen and moisture in most environments. They are also vulnerable to optical damage when strong laser pulses are transmitting through. Therefore, it prompts an urgent study for an optimal BP-SA incorporation process for fiber lasers to assure better long-term stability and higher optical damage threshold.

Tapered fibers and side-polished D-shaped fibers have been developed for evanescent coupling between the light and 2D materials for passive Q-switching and mode-locking lasers [20–24]. The fiber taper approach is particularly promising for BP-SA incorporation for several reasons. First, when BP is deposited onto the side of the fiber tapers, it interacts with the evanescent field with a much larger active area. Compared with the conventional method of sandwiching BP between a pair of fiber facets [16,17], the material utilization efficiency is largely improved. Second, the optical damage threshold can be significantly enhanced due to the substantially reduced light intensity. Third, as the evanescent field and BP mostly interacts inside the innermost layers, it can effectively

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mitigate the environmental oxygen and moisture invasion. Eventually, it provides the possibility to completely isolate BP from the outer environment by depositing outer buffer layers.

In this paper, we report a passively Q-switched ytterbium-doped fiber laser (YDFL) employing a tapered-fiber-based BP-SA scheme with wavelength tunability, which has not been reported to date to the best of our knowledge. Few-layer BP was transferred onto the tapered fibers by an optically driven process. Utilizing an ytterbium-doped all-fiber ring cavity, passively Q-switched tunable laser emission was achieved. A Sagnac fiber loop [25,26] was used to provide the wavelength tuning ranging from 1040.5 to 1044.6 nm. The maximal average output power was 8.9 mw at a 63-kHz repetition rate and the maximal pulse energy was 141.27 nJ. The shortest pulse duration was 2.5 μs under 445-mW pump power. With BP-SA integrated onto the fiber tapers, these passively Q-switched fiber lasers can hold the benefits of enhancing laser-induced damage threshold and mitigating BP oxidation process to a large extent.

Fabrication and optimization of tapered-fiber-based BP-SAs

To prompt efficient interaction between the BP material and evanescent wave along the fiber tapers, a few critical challenges remain to be solved that include achieving optimal taper dimensions and high surface quality.

In our experiments, single-mode fibers (NUFERN, HI1060) were tapered down to a minimum of ~15 μm in diameter, as shown in Fig. 1(a). By shrinking the diameter, more evanescent wave couples with the surrounding materials; however, it also costs higher transmission loss and weaker mechanical strength. Tradeoff therefore has to be made regarding the optimal microfiber diameter and its length. In our experiments, we identified the best geometry to be a microfiber 15-μm in diameter and 1-mm in length by try and error with simulations.

Few-layer BP ethyl alcohol (EA) solution of a concentration of 0.5 mg/ml was utilized for BP-SA preparation. In the BP-EA solution, BP flakes were ~2 to 10 layers with lateral thickness of ~0.5 to 5 μm. To transfer BP flakes onto the fiber tapers, we adopted an optically driven (OD) method. With the tapered fibers fixed on top of a glass slide, we applied a few drops of solution onto the taper waists. At the same time, a continuous-wave laser power at 975 nm was transmitting through the fiber tapers for a few minutes. BP flakes could be deposited onto the taper side due to the combined effect of optical trapping force and heat convention. During this OD process, the enabling laser power level was also critical; otherwise, BP flakes would not be appropriately trapped onto the taper. The optimal laser power was found to be ~100 mW and the duration was ~15 min. Afterwards, the tapered fibers were air dried for about an hour. Compared with other methods of continuously dripping and air drying [14–17], the OD method possesses advantages of better repeatability and reliability. Fig. 1(a) illustrates the tapered microfiber and the BP deposition region; Fig. 1(b) is the microscopic image showing the micro-morphology of deposited BP.

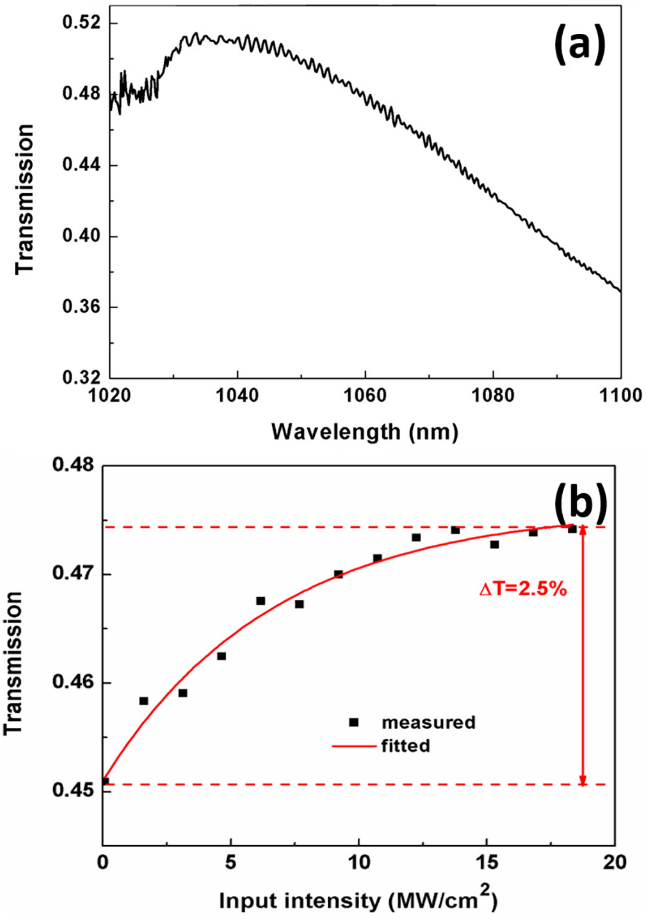

Fig. 2. (a) The transmission spectrum; (b) the saturable absorption of fabricated BP-SAs.

To study transmission properties of the fabricated BP-SAs, we utilized a wideband 1-μm ASE light source (CONNET, VASS-Yb-B:

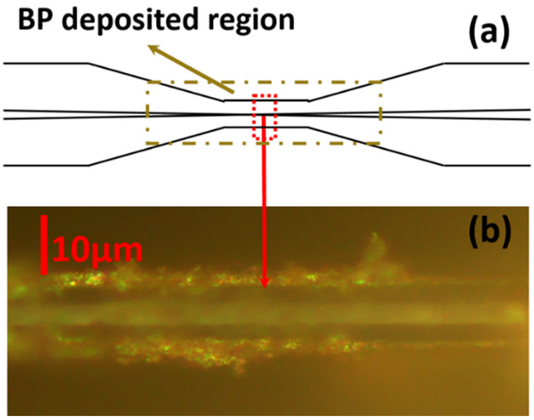

Fig. 1. (a) Tapered fiber illustration; (b) tapered fiber with BP deposited onto.

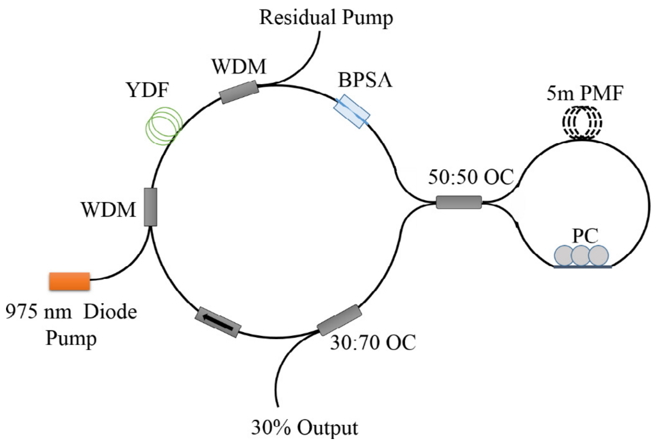

Fig. 3. The scheme of passively Q-switched BP-SA-based tunable all-fiber ring laser.