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Black phosphorus saturable absorber for Q-switched Er:YAG laser at 1645 nm

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ABSTRACT

A Q-switched Er:YAG solid-state laser at 1645 nm based on black phosphorus (BP) saturable absorbers (SAs) was demonstrated firstly to our knowledge. The BP-SA was fabricated by drop-casting BP nanoplatelets dispersion on a YAG substrate and corresponding saturable absorption properties were characterized at 1.6 μm. By employing as-prepared BP-SAs, stable Q-switched laser operations were achieved with a pulse width of 2.8 μs and a repetition rate of 34 kHz, corresponding to the average output power of 0.33 W. The results verify that BP-SAs have great potential for pulsed 1.6 μm lasers.

1. Introduction

Two-dimension (2D) nanomaterials have wide applications in electronic and optoelectronic fields, which are expected to fabricate next-generation field-effect transistors (FET) and novel optical modulators [1,2]. In particular, 2D nanomaterials used as saturable absorbers (SAs) have been a research hotspot for pulse lasers because of their unique optical characteristics, such as large optic nonlinearity, broadband saturable absorption, ultrafast recovery time [3–5]. The success of Q-switched and mode-locked lasers based on graphene-SAs [6,7] motives people to explore other 2D materials including transition-metal dichalcogenides (like MoS_2 [8]) and topological insulators (TIs, like Bi_2Te_3 [9]), which also have been successfully applied in pulse lasers at the infrared and mid-infrared range. But there are some inherent defects limiting their applications, such as the low optical modulation depth for single-layer graphene [10] and the large indirect-gap of ~1.29 eV (961 nm) for bulk MoS_2 [8].

Recently, another 2D material: black phosphorus (BP) with a narrow band-gap and high electronic mobility attracts the attention of researchers [11]. The bulk BP stacked by single atomic layer with a unique puckered honeycomb structure is easily peeled off due to weak interlayer van der Waals forces. It has strong polarization dependent linear and nonlinear optical properties linked with the zigzag and armchair axes of BP thin films [12], which can be used to realize novel thin-film infrared polarizers and infrared polarization sensors [13]. Furthermore, BP has been demonstrated to have enormous potential in pulsed lasers based on its ultrafast recover time (24 ps) and broadband saturable absorption [3,14], from the visible (400 nm) to min-infrared (1930 nm) region [15]. Note that BP is always a direct band-gap semiconductor with layer-dependent band gap increasing from 0.3 eV (bulk) to 2 eV (monolayer) [16], which is different from MoS_2 with the indirect band-gap. In 2012, Zhang et al. reported solid-state lasers operating at 639 nm, 1.06 μm and 2.1 μm with ns-scale pulse widths and more than 100 kHz repetition rates using BP-SAs [17]. In 2016, a passively Q-switched $Er:Lu_2O_3$ solid-state laser with a pulse width of 359 ns and a repetition rate of 107 kHz was demonstrated at 2.84 μm based on multilayer BP-SAs [18]. As we all know, the range of ~1.5–1.6 μm is an important eye-safe wavelength range and optical fiber communication band. There is no relative report on solid-state lasers using BP-SAs, although 1.5 μm wavelengths have been modulated successfully using BP-SAs in erbium-doped fiber lasers (EDFLs).

In this paper, we demonstrated a passively Q-switched Er:YAG solid-state laser operating at 1645 nm based on multilayer BP-SAs for the first time to the best of our knowledge. The BP nanosheets dispersion, prepared by liquid-phase exfoliation (LPE) method [19] in isopropyl alcohol (IPA), was fabricated as BP-SAs

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by drop-casting diluted dispersion on YAG substrates. The morphology and thickness of the BP thin film were characterized and the saturable absorption property was investigated at 1.6 µm. By employing as-prepared BP-SAs, the 0.33 W average output power was obtained with a pulse width of 2.8 µs and a repetition rate of 34 kHz under an absorbed pump power of 6.24 W. Corresponding single pulse energy and peak power were 10 µJ and 3.25 W, respectively.

2. Characterization of BP-SAs

The morphology and thickness of the BP thin film were characterized by transmission electron microscopy (TEM) and atomic force microscopy (AFM). TEM image presented in Fig. 1a shows sheet-like structure exfoliated with lateral size up to hundreds of nanometers. Fig. 1b shows the AFM image (inset) and typical height profiles along two dashed lines. Given that the thickness of mono-layer BP is about 0.6 nm [20], the sample varies from 7 to 11 layers corresponding to the thickness of BP samples ranging from 4 to 7 nm. The multiform thicknesses can be attributed to the drawback of LPE method which cannot control the number of layers accurately. Considering that the band gap (E_g) of BP follows a power law ($Eg = \sim 1.7/n^{0.73} + 0.3$ eV, in which n is the number of layers), corresponding band gap is estimated to be between 0.71 eV and 0.6 eV which is shorter than 0.75 eV (~1645 nm) [12].

A smooth upward linear transmission curve depicted in Fig. 2a exhibits broadband absorption characteristics in the 500–3000 nm spectral range measured by an UV/VIS/NIR spectrophotometer (U-4100, Hitachi, Japan). The transmission of about 72.3% was observed at 1645 nm. Fig. 2b exhibits the saturable absorption characteristics of the BP-SA at 1645 nm. By fitting the experimental data with equation $T(F) = 1 - \Delta T * \exp(-F/F_{sat}) - \alpha_{ns}$ (T is normalized transmittance, ΔT is normalized modulation depth, F is the fluence of the incident laser, F_{sat} is saturable fluence, and α_{ns} is non-saturable loss) [21], the modulation depth, the non-saturable loss and the saturable fluence were deduced to be 16%, 20%, and 2 mJ/cm^2, respectively. The small signal transmission was 63% which is lower than the linear transmission due to the Fabry–Perot effects derived from the plane-parallel YAG substrate.

3. Experiment results and discussions

To investigate the Q-switched performance of BP-SAs, the experimental diagram of a passively Q-switched Er:YAG laser with 60-mm-long plane-plane cavity is shown in Fig. 3. A 40-mm-long, 0.25 at.%-doped Er:YAG crystal with an aperture of 4-mm diameter was pumped by a 1532 nm fiber-coupled CW laser diode with a core diameter of 400 µm and numerical aperture of 0.22. End surfaces of the rod were polished and AR coated at both the lasing and pump wavelengths. By the 1:2 optics coupling system with the focal length of 100 mm, the pump beam was focused into the gain medium in one-third of the rod near the front end face with the diameter of 800 µm. The Er:YAG crystal was wrapped with indium foil and tightly mounted in a copper heat sink water-cooled to 14 °C. M1 was AR-coated for 1532 nm and HR-coated for the spec-

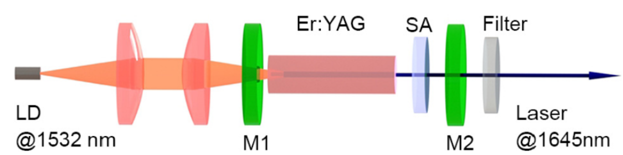

Fig. 3. Schematic of Q-switched Er:YAG laser based on BP-SAs.

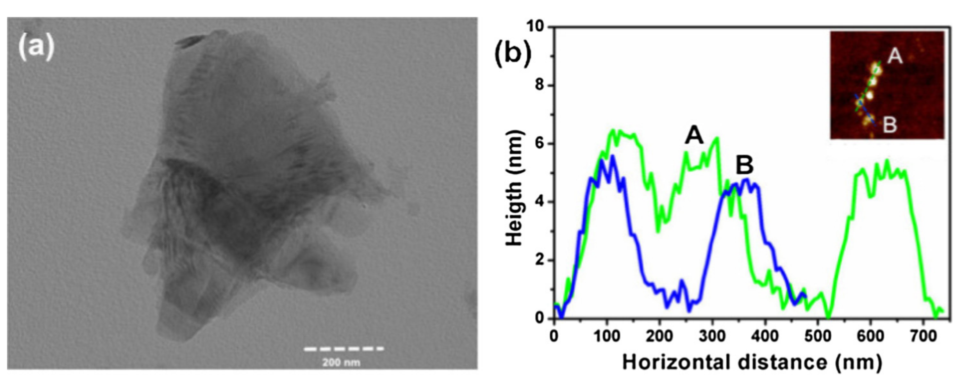

Fig. 1. (a) TEM image of BP nanosheets. (b) AFM images (inset) and typical height profiles.

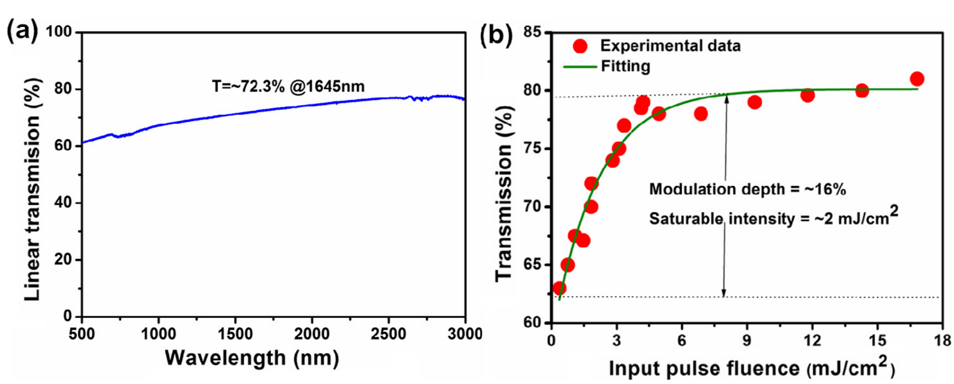

Fig. 2. (a) The linear transmission characteristics of BP films. (b) The nonlinear transmission of the BP-SA.