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Bilayer Bismuth Selenide nanoplatelets based saturable absorber for ultra-short pulse generation (Invited)

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ABSTRACT

Based on an efficient and bottom-up synthesis technique, Bismuth Selenide (Bi_2Se_3) nanoplatelets with uniform morphology and average thickness down to 3–7 nm had been fabricated. Its nonlinear absorption property under high power excitation had been well characterized by our Z-scan measurement system at different illumination wavelengths, and we found that the as-fabricated bi-layer Bi_2Se_3 nanoplatelets show unique nonlinear optical responses, that is, with a saturable optical intensity of 32 GW/cm^2 (resp. 3.7 MW/cm^2) and a modulation depth of 88% (resp. 36%) at 800 nm (resp. 1565 nm). By implementing its saturable absorption property, we designed an optical saturable absorber device based on bilayer Bi_2Se_3 nanoplatelets through deposited them onto the end-facet of optical fiber. The as-fabricated optical saturable absorber device allows for the generation of mode-locking pulses at 1571 nm with pulse duration of 579 fs and a repetition rate of 12.54 MHz at a pump power of 160 mW. The method on fabricating ultrathin Bi_2Se_3 nanoplatelets may pave a new way to massive production of large-area topological insulator thin films that can be used in two-dimensional layered materials related photonics device.

1. Introduction

Passively mode-locked fiber laser with the advantages of producing simple and cost-effective ultra-short laser pulse have attracted much attention, and have been opening up some important applications in laser material processing, remote sensing, telecommunications, medicine, etc [1–4]. Saturable absorber (SA) is an essential optical element that can lead to the generation of ultra-short pulses in fiber lasers [5–9]. To search for suitable optical material that can be developed for practical saturable absorber device is a key influencing factor. Since that Bao et al. had demonstrated the applications of atomic-layer graphene-based saturable absorber for ultrafast photonics [10], many researchers have paid attentions onto two-dimensional (2D) nano-materials, which are widely used for SAs in fiber laser due to their distinguished advantages in terms of ultrafast recovery time, low insertion loss, controllable modulation depth, and easy fabrication [11–23]. Graphene has a relatively low modulation depth of about 6.2% when the number of graphene layer increases upto 10 ± 1 [10], and atomic layered transition-metal dichalcogenides (TMDs) also limited in photonic applications because of their relatively poor thermal optical damage threshold [19–27]. Therefore, many researchers are still making some efforts to seek for new types of 2D materials which are expected to possess the ideal characteristics of moderate optical nonlinearity, broadband saturable absorption, low saturable optical intensity, large modulation depth, fast response time, high damage threshold, low cost and ease of integration.

Topological insulators (TIs) including Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 are another a new type of Dirac materials [28–30], which have small band gap in their bulk state and a gapless metallic state in their edge/surfaces, both the surface and the bulk absorb the excitation light, and can be saturated under strong excitation [31].

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Their surface state in three-dimension exhibits graphene-like band structure, but the directions of spin and momentum are locked together, which provides the basis for a source of highly spin-polarized electrons with tunable polarization direction [32,33]. TIs have been widely investigated for broadband saturable absorption at 800 nm [34], 1064 nm [35,36], 1645 nm [37], 2000 nm [38], telecommunication wavelength [39] and microwave band [31], respectively. More importantly, TI as a saturable absorber (SA) had been employed to generate femtosecond laser pulse [40,41]. However, only TIs with thick multi-layers are investigated in the previous work and up to now, the optical nonlinear absorption of bilayer Bi_2Se_3 thin nanoplatelets had not yet been investigated. It was reported that the surface states of Bi_2Se_3 are sensitive to thickness. The conducting states of the top and bottom surfaces couple together and lead to an insulating state when the film is thinner than ~5 nm [42]. More importantly, TI-based SAs in the above-mentioned research findings are produced by the liquid-phase exfoliation method of thin sheets from bulk crystals [31,35,38], hydrothermal intercalation/exfoliation method [37], mechanical exfoliation [43,44], mechanical triturating [45], and a polyol method [39,46]. These approaches suffer from slow reaction rate or produce relatively thick plates with poorly defined. Massive production of bilayer Bi_2Se_3 films may pave a new way to generate large-area topological insulator thin films, which can be developed for SAs in fiber laser. So it is necessary to find a quick process to guarantee uniformity and massive production.

In this work, we synthesized ultrathin bilayer Bi_2Se_3 nanoplatelets (about 4–7 nm) through a simple and quick solution process and investigated nonlinear optical abosorption of Bi_2Se_3 at different excitation wavelength by using the open aperture Z-scan technique. Then we inserted the Bi_2Se_3 saturable absorber in an erbium-doped fiber laser cavity. The passive mode locked fiber laser can generate the stable mode locked solitons with a pulse width of 579 fs at the telecommunication band.

2. Preparation of bilayer Bi_2Se_3 nanoplatelets

Here, we used a simple and quick synthetic route to prepare ultrathin single-crystal Bi_2Se_3 nanoplatelets [47]. First step, a solution of poly (vinylpyrrolidone) (PVP) (1.0 g in 40 ml of ethylene glycol (EG)) was poured in 250 ml round-bottom flask under magnetic stirring at room temperature. Second step, a solution of sodium selenite (0.242 g in 35 ml of EG) and bismuth nitrate pentahydrate (0.452 g in 25 ml of EG, and hydroxylamine solution 2.4 ml in 20 ml of EG) were poured into the flask from different bottle necks. The flask was sealed and heated to 160 °C under nitrogen environment. As the reaction mixture turned to yellow–white, the hydroxylamine solution (2.4 ml in 20 ml of EG) was rapidly injected to the mixture by syringe, the reaction mixture turned dark purple immediately, which indicates the formation of Bi_2Se_3 nanoplatelets. The reaction was allowed to proceed for 10 min for a complete reaction and cooled down to room temperature. We took the final products which were precipitated by centrifuging (5000 rpm, 10 min) and washed three times with a mixture of acetone (50 ml) and D.I. water (10 ml) into isopropyl alcohol (IPA). Then we fabricated the Bi_2Se_3 nanoplatelets solution. Fig. 1(a) shows a TEM image of the Bi_2Se_3 nanoplatelets synthesized at 160 °C in the presence of PVP as surfactant. The nanoplatelets had a good uniformity in size with an average lateral diameter of ~80 nm. Fig. 1(b) is AFM image of the bilayer Bi_2Se_3 nanoplatelets, which reveals that the first layer of the nanodisc had a thickness of ~4 nm, corresponding to a stack of 4 QLs, while the second layer had 3 or 4 QLs. In Bi_2Se_3, five covalently bonded atomic sheets (e.g., Se–Bi–Se–Bi–Se) compose one quintuple layer (QL, ~1 nm) [48]. The linear transmission of Bi_2Se_3 is shown as Fig. S1(c) in Supporting information.

3. Experimental setup and results

3.1. Optical properties of Bi_2Se_3 at 800 nm and 1565 nm

In order to investigate the nonlinear optical properties of Bi_2Se_3 nanoplatelets, we fabricated bilayer Bi_2Se_3 film by drop-casting Bi_2Se_3 nanoplatelets solution on the surface of the quarz substrate and drying in the vacuum drying oven. Then we experimentally studied the saturable absorption property of Bi_2Se_3 film using the open aperture Z-scan technique at 800 nm and 1565 nm. The experimental setup is the same as the existed experiments [34]. Femtosecond laser pulses obtained from a Coherent femto-second laser (center wavelength: 800 nm, pulse duration: 100 fs, 3 dB spectral width: 15 nm and repetition rate: 1 kHz) was used as the incident laser source. The 50% of the laser beam was separated as the reference beam that was monitored with a photo-detector 1, while the residual laser beam was focused by an objective lens perpendicularly to the Bi_2Se_3 film surface. According to the CS_2 measurement, the incident beam waist was fitted to be about 30 μm, corresponding to a peak intensity up to 354 GW/cm^2. By using optical attenuators, the average power could be deliberately

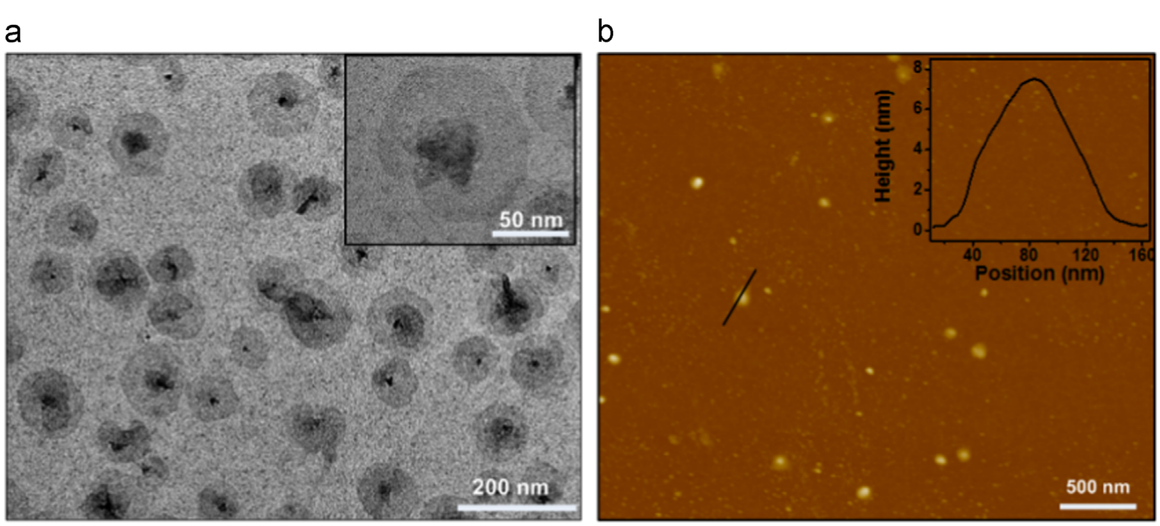

Fig. 1. (a) TEM images of the Bi_2Se_3 nanoplatelets, (b) AFM analysis of bilayer Bi_2Se_3 nanoplatelets with 4 QLs thickness in each layer.

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