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Passively mode-locked ytterbium-doped fiber laser operation with few layer MoS_2 PVA saturable absorber

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ABSTRACT

A passive mode-locked Ytterbium-doped fiber laser (YDFL) is experimentally demonstrated using a multi-layered molybdenum disufide (MoS_2) as a Saturable Absorber (SA). The MoS_2 film was obtained based on a liquid phase exfoliation of MoS_2 crystal. A small slice of MoS_2 film was sandwiched in between two optical ferrules via a fiber adapter and linked into an YDFL cavity to generate a stable mode-locked operation at a wavelength of 1073.86 nm with repetition rate of 18.8 MHz. At pump power of 202.9 mW, the maximum pulse energy of 0.1 nJ was achieved with an output power of 1.84 mW. The MoS_2 film was fabricated through a simple process and it has a modulation depth of 9.7% and saturating intensity of 40 MW/cm^2.

1. Introduction

In the recent years, mode-locked fiber lasers have extensively engaged interest due to their application benefits, such as micromachining, communication, and optical systems; as well as their nature being compact, cost-effective and easy to setup [1,2]. Active mode-locking pulse train can be achieved by inserting electronic switching such as acousto-optic modulator [3]. Passively mode-locked fiber lasers are also widely explored in recent years by utilizing saturable absorption of optical materials. Various saturable absorbers (SAs) have been demonstrated so far such as semiconductor saturable absorption mirror (SESAMs) [4,5], carbon nanotubes (CNTs) [6,7], and graphene [8,9].

Semiconductor saturable absorption mirrors (SESAM) are good SA device which can be used to generate a mode-locked fiber laser in both 1 μm and 1.5 μm regions [5,10]. However, its application is still limited due to their difficult fabrication methods, complex design, expensive cost and narrower wavelength operation range. Graphene and carbon materials have the advantages of low cost, easy fabrication and operable in a wide wavelength range. Mode-locking pulses have been demonstrated using graphene and carbon nanotubes (CNTs) as SA in the various fiber laser cavities based on erbium- [6,11,12], ytterbium- [13–15] and thulium- [16,17] doped fiber gain medium. The operation wavelength of CNT is related with diameter of the nanotubes. Graphene has a 2D zero-bandgap semiconductor material and low absorption co-efficiency, which gives it the advantages of wideband saturable absorption as well as ultra-fast recovery time. These advantages lead researchers to 2D materials. Topological insulators have also joined the 2D materials for ultra-fast fiber laser applications such as Bi_2Se_3, Bi_2Te_3 and many others [18,19].

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To date, another 2D nanomaterial, molybdenum disulfide (MoS_2), is also drawing more interest especially for mode-locked fiber laser applications. The reason for this growing interest is due to its material's thickness, which gives an excellent optical laser properties as well as the band-gap [20,21]. Until today, only a few works have been reported on MoS_2 based SA [20–24]. For instance, Zhang et al. demonstrated tunable mode-locked fiber laser that operates from 1535 to 1565 nm using MoS_2, which was obtained through liquid phase exfoliation [22]. Du et al. reported the generation of 656 ps pulse duration and repetition rate of 6.74 MHz which operated at 1042.6 nm wavelength based on a few layers MoS_2 SA, which fabricated through the conventional hydrothermal intercalation process [23]. Sathiyan et al. proposed mode-locked Ytterbium-doped fiber laser (YDFL) using few-layer MoS_2 prepared by mixing MoS_2 solution with polyvinyl alcohol (PVA) [24].

In this paper, we demonstrate a passively mode-locked YDFL using a few layered molybdenum disulfide (MoS_2) as a Saturable Absorber. The few layer of MoS_2 polymer is a composite of liquid phase exfoliation (LPE) of chemically pristine crystal. A small piece of MoS_2 PVA was inserted in the YDFL cavity, sandwiching it in between two fiber optical ferrules with a connector to obtain mode-locking pulses with repetition rate of 18.8 MHz and pulse energy of 0.1 nJ. In this work, the liquid phase exfoliation method was used to get the MoS_2 layer. This method is simple, cheap and does not require any complicated procedures.

2. Fabrication and characterization of the MoS_2 film

The liquid phase exfoliation (LPE) process for MoS_2 exfoliation was carried out in 2 steps. The bulk MoS_2 crystals were first mixed together with a solvent that gets a comparable surface energy with MoS_2 ($\sim$75 mJ m^{-2}) [25]. Likewise, Dimethylformamide (DMF) solvent was chosen with a concentration of 5 mg/ml for this work. Following, the second step was to exfoliate the material through a sonication process. In this process, local pressure variations were generated to sufficiently separate the atomic layers of the bulk crystal [26,27] in the solvent to produce a dispersion, which was rich in few-layer flakes [26]. Then, the MoS_2 dispersion was kept to be ultra-sonicated for 24 hours before it was centrifuged for 1 hour at $\sim$3000 rpm. This allowed the un-exfoliated sediment to settle at the bottom since the larger flakes descended more rapidly than the exfoliated few-layer flakes in the centrifuge cell [28]. The top portion of the dispersion containing few-layer flakes was taken out for further composition fabrication process.

A few steps were followed in order to produce MoS_2 polymer film for this experiment. Firstly, $\sim$10 ml of decanted MoS_2 dispersion was put together with a 10 mg/ml concentrated $\sim$20 ml of polyvinyl alcohol (PVA) solution. This solution was a result of $\sim$200 mg of PVA being dissolved in 20 ml of deionized water. By this, 30 ml of MoS_2-PVA was prepared, which was then heated at a temperature of $\sim$80 °C and stirred with a magnetic object until the solution was brought down to an approximate volume of $\sim$10 ml. These series of actions took around 7 hours to be done, following which the resulting MoS_2-PVA solution was placed in a glass substrate and put in an oven for 4 hours at a temperature of $\sim$80 °C in order to dry and obtain a composite film with a thickness of $\sim$40 μm.

Field emission scanning electron microscopy (FESEM) and Raman spectroscopy were performed on the fabricated MoS_2–PVA film sample. Fig. 1a shows the FESEM image that illustrates a MoS_2 flakes, which were embedded into the PVA polymer film. The scanning electron microscopy (SEM) image for a single flake is shown in Fig. 1b, which was obtained from the prepared MoS2 dispersion solution. It shows a lateral size of about 400 nm with thickness of around 5-8 layers. Fig. 1c presents the Raman spectrum recorded using a spectrometer at a 514 nm beam of an Argon-ion laser that was radiated on the film for 10 seconds with an exposure power of 10 mW. As shown in the figure, the sample displays two signature peaks at 383 cm^{-1} and 407 cm^{-1} which are related to in-plane vibration of Molybdenum and Sulfide atoms and out of plane vibration of Sulfide atoms respectively. The frequency difference was recorded to be 24 cm^{-1}. It was observed that the E^1_{2g} mode according to the in-plane motion shifted to a shorter wavelength after complete exfoliation. This indicated that the number of layers of MoS_2 were in the range of 2–5 layers [29]. Fig. 1d shows the Raman spectrum of a pure PVA solution, which shows a peak at 3000 cm^{-1} region for comparison purpose.

A nonlinear absorption measurement was also performed on the fabricated MoS_2-PVA film to confirm its saturable absorption as shown in Fig. 2a. In the experiment, a stable mode-locked fiber laser operating at 1565 nm wavelength with repetition rate of 15 MHz and pulse width of 0.9 ps, was employed as the input pulse source. The mode locking signal results were then amplified using an erbium-doped fiber amplifier (EDFA) in order to obtain a high peak power output to efficiently saturate the MoS_2 sample. The output port of the amplifier was connected with a variable optical attenuator to control the launching output power to the system before it is launched into a 3 dB optical coupler and two optical power meters. The first optical power meter was linked to one port of coupler and the second port of coupler was linked to the MoS_2 film sample then connected into the second optical power meter. The resultant characteristic of MoS_2 film as SA is shown in Fig. 2b. The absorpation power was recorded as a function of incident intensity on the device by modifying the input optical laser power. The experienatal data for absorption were prepared depending on the two-levels of SA model [30].

$$a(I) = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns}$$

where $a(I)$, αs,I, I_{sat} and α_{ns} are stand for absorption, modulation depth, input intensity, saturation intensity, and non-saturation loss respectively. For the MoS_2 sample that was used in this work, the modulation depth, non-saturable intensity, and saturation intensity were measured to be approximately 9.7%, 10.9%, and 40 MW/cm^2, respectively.