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Er-doped mode-locked fiber laser with WS_2/fluorine mica (FM) saturable absorber

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ABSTRACT

The report presents conventional soliton operation in an anomalous-dispersion fiber laser with a novel WS_2 saturable absorber (SA) based on fluorine mica (FM) substrate. Compared to organic host material such as polymer composite, FM has higher softening temperature, heat dissipation and laser damage threshold. In this work, the modulation depth (MD) and non-saturable loss (NL) of WS_2/FM SA are measured to be 3.1% and 15%, respectively. By employing the SA, a stable conventional soliton mode-locked fiber laser is achieved. The repetition rate is 8.2 MHz and the pulse duration is 830 fs. The fiber laser works in mode locking operation for at least ten days and no damage of the SA is observed. The results indicate that WS_2/FM material is an ideal SA for Er-doped fiber (EDF) lasers.

1. Introduction

High performance SAs with the characters of wavelength independent, high heat dissipation and high laser damage threshold are always the hot research area in ultrafast photonics [1–5]. Up till now, various kinds of SAs have attracted great attentions in recent years. Semiconductor saturable absorber mirrors (SESAMs) [6], carbon nanotubes [7,8], graphene [9–11], topological insulators (TIs) [12,13], semiconducting transition metal dichalcogenides (TMDs) [14,15] and black phosphorus (BP) [16,17] have been experimentally studied, which possess a high third-order nonlinear susceptibility and short recovery time. In particularly, 2D TMDs [18,19], such as MoS_2 [20,21], WS_2 [22,23], $MoSe_2$ [24] and $MoTe_2$ [25] have got a lot of attentions and are considered to be a kind of promising SAs. Depending on the coordination and oxidation states of transition metal atoms, TMDs can either be semiconducting or metallic in nature [26,27].

As a TMD SA device with high quality, it should have two excellent merits: high laser damage threshold and good operability. So far, several forms of SAs have been proposed, including substrate based SAs, solution based SAs, evanescent field based SAs, or SAs film coated on fiber ferrules. In general, substrate based SAs fabricated by chemical vapor deposition (CVD) method provide higher quality material than many other methods [28]. However, such SAs films are generally transferred from the surface of substrate to fiber surface when it is used in mode-locking fiber laser. Solution based SAs are limited by a host solution with low optical absorption [29]. Evanescent field based SAs employed with tapered fiber or side polished fiber (SPF) still suffer from a large insertion loss [30]. Embedding SAs into polymer host materials are very popular and has been widely used for absorbers [31,32]. However, the optical damage threshold of SA/polymer composite film is generally very low and the long-term working stability is undesirable because of the introducing polymer [33].

As everyone knows, inorganic materials generally have higher softening temperature, heat dissipation and laser damage threshold than those of organic materials. FM is a perfect inorganic material with the excellent virtues such as high temperature resistance, high elasticity, good transmission performance and non-absorbing impurities performance. The FM can be stripped into one layer with the thickness of 20 μm and is not easy to break off because of its high flexibility. Inserting such thin SA film into the fiber laser cavity could not cause the laser deviation [34]. Therefore, depositing TMD layers onto 20 μm

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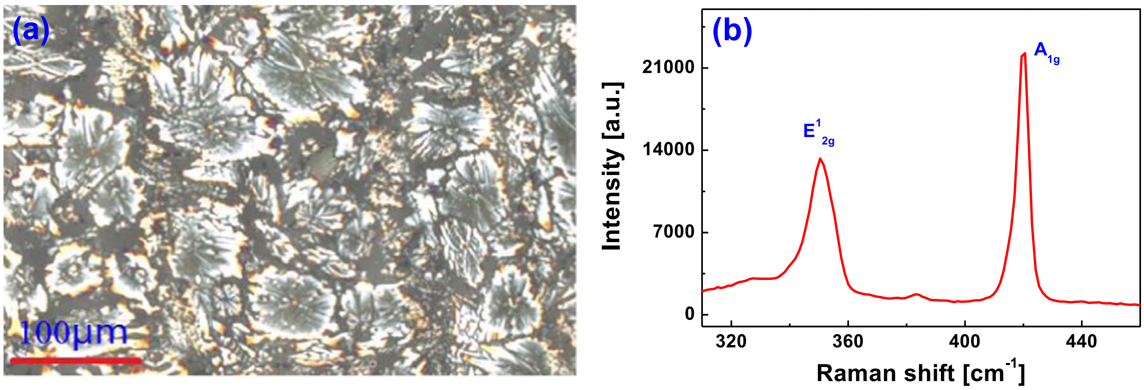

Fig. 1. (a) The morphology of WS2/FM; (b) Raman spectrum of WS2 nanosheets excited by 633 nm laser.

thickness of one layer FM would be helpful for improving the performance of SA.

In this work, we have realized mode-locked operation in EDF laser with WS_2/FM SA. The WS_2/FM SA is fabricated by depositing WS_2 layers onto 20 μm thick one layer FM using a thermal decomposition method. The MD and NL are 3.1% and 15% respectively. By incorporating WS_2/FM slip into EDF laser cavity, the stable conventional pulse operation with pulse duration of 830 fs is achieved at the fundamental repetition rate of 8.2 MHz. The experimental results show that the WS_2/FM SA has the potential to be used in mode-locked fiber lasers in practice.

2. Preparation and characterization of WS_2/FM

The WS_2/FM SA is fabricated as reference [34]. Fig. 1(a) is the morphology of WS_2/FM. As a kind of inorganic material, the melting point and thermal conductivity of FM are 6 times and 10 times higher than those of polyvinyl alcohol (PVA) respectively, which indicate that WS_2/FM can operate in high power regime [34]. A Raman spectroscopy system with an excitation wavelength of 633 nm is utilized to confirm the existence of WS_2. Fig. 2 shows two typical bands which are identified as $E_{2g}{}^1$ at 350.5 cm^{-1} and A_{1g} at 420.7 cm^{-1}, where $E_{2g}{}^1$ is assigned to the in-plane mode and A_{1g} corresponds to the out-of-plane vibration mode of WS_2 [35].

The linear transmission is measured from 1300 nm to 1700 nm. As depicted in Fig. 2(a), the transmission spectrum of WS_2/FM SA is very flat and the transmission is as high as 81.8% at 1560 nm. A picosecond pulsed EDF laser (central wavelength: 1550 nm, pulse duration: 1 ps, repetition rate: 100 MHz) works as the illumination source to study the nonlinear saturable absorption of WS_2/FM SA. Fig. 2(b) shows the nonlinear transmission curve as a function of peak power intensity. As can be seen here, the MD and NL of WS_2/FM SA are measured to be 3.1% and 15%. It should be pointed out that NL is a key parameter to evaluate whether the SA is good or bad. Too much NL is harmful for high power fiber laser operation. Most of the NL is relevant to the impurities in the absorbers. The impurities brought by thermal decomposition method fabricating WS_2 are negligible compared to those in the absorbers fabricated by chemical solution method. In Table 1, we compare the nonlinear parameters of different types of TMD SAs. The 15% NL of our SA is comparable to reference [34], which is the best reported result excepted evanescent field method as far as now. To the best of our knowledge, only evanescent field based SAs could have less NL than 10%. However, evanescent field method would bring additional problems such as complicated fiber machining and mechanical stability.

3. Experimental setup

The schematic diagram of EDF laser is depicted in Fig. 3. The ring laser oscillator cavity consists of a gain fiber, a wavelength division multiplexer (WDM), a polarization independent isolator (PI-ISO), optical coupler (OC), a polarization controller (PC) and a WS_2/FM SA. A 4 m long EDF with absorption coefficient of 3 dB/m at 976 nm is employed as the gain medium. The EDF is pumped by a 976 nm laser diode (LD). The PI-ISO is used to force the unidirectional operation in the fiber ring cavity. The PC is engaged in achieving different polarization sates. The optical coupler is used and 10% portion of the laser is coupled out from the laser cavity. The other fibers and pigtails of the optical components are single-mode fibers (SMFs) with a total length of 25.5 m. The dispersion parameters D at 1550 nm for EDF and SMF are −16 and 17 ps/(nm km), respectively. The net cavity dispersion β_2 is calculated to be −0.47 ps^2. The output prosperities of the fiber laser are monitored by a power meter, an optical spectrum analyzer (YOKOGAWA AQ6370D), an autocorrelator (Alnair HAC 200), and a digital oscilloscope (Tektronix TDS3024C) together with a home-made 2.5-GHz photodiode detector.

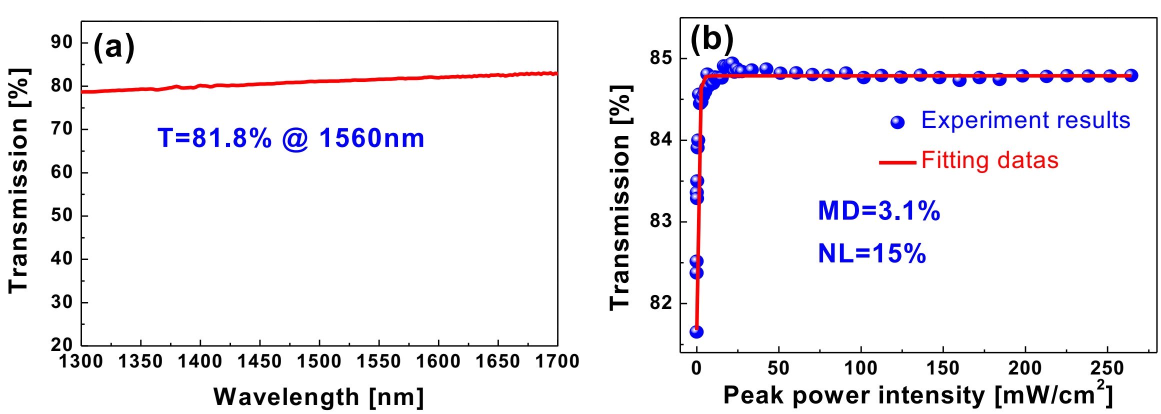

Fig. 2. Linear transmission (a) and nonlinear absorption (b) of WS_2/FM SA.