Q-Switched Ring-Cavity Erbium-doped Fiber Laser Based on Tungsten Disulfide (WS_2)

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***Abstract*—Applying liquid-phase exfoliation method, we prepare WS_2 dispersions with ethanol and fabricate WS_2-PVA polymer composite film. As a saturable absorber, the WS_2-PVA film is used to Q-switch a ring-cavity erbium-doped fiber laser. The Q-switched fiber laser can generate stable pulses when the pump power varies from 400 mW to 720 mW. The repetition rate and pulse duration can be tuned with pump power from 47 kHz to 77 kHz and from 6.7 μs to 4.1 μs, respectively. The radio frequency (RF) spectrum with a 58 dB extinction ratio at fundamental frequency also shows a good stability of Q-switching operation. Our work provides an easy and feasible method to fabricate WS_2-PVA polymer composite film and demonstrates the possibility for WS_2 to be a promising saturable absorber for Q-switched laser or even mode-locked laser.**

Keywords—Transition metal dichalcogenide; tungsten disulfide; Q-switched laser; fiber laser; saturable absorber

I. INTRODUCTION

The discovery of graphene in 2004 [1] has propelled the naissance of a novel optical research domain, that is, the promising applications in optoelectronics of two-dimensional (2D) materials. Up till now, 2D nano-materials have been investigated in ultrafast photonics to generate femtosecond laser [2, 3] and optoelectronic devices such as light emitter and photodetector [4]. Recently 2D transition metal dichalcogenides (TMDs), such as molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2), have attracted enormous attentions and investigations [4-9]. Even though bulk MoS_2 is a kind of semiconductor with an indirect band gap of 1.3 eV [10], monolayer MoS_2 has a direct-gap about 1.8 eV [11]. Reference [12] adopted chemical vapor deposition (CVD) method to synthesize multilayer MoS_2 film and used it as saturable absorber in an erbium-doped mode-locked fiber laser near 1569 nm. Ref. [13] wielded optical trapping approach to deposit MoS_2 onto the end facet of fiber and generated stable mode-locked laser pulses centered at 1054.3 nm with a pulse duration of 800 ps. In addition, Reference [14] demonstrated a tunable Q-switched ytterbium-doped fiber laser which can be tuned from 1030 nm to 1070 nm. It also proposed a mechanism to interpret the traits of wideband nonlinear optical absorption of MoS_2. As for WS_2, relevant research work is just started out but delightful results have been found. Since molybdenum and tungsten lie in the same group at the periodic table of elements, it could be inferred that WS_2 has similar optoelectronic properties compared with MoS_2. Reference [15] demonstrated WS_2 can be used to act as saturable absorber to generate both mode locking and Q-switching operations. WS_2 was prepared by liquid-phase exfoliation using ionic surfactant sodium cholate (SC). In this paper, we adopt an easy and feasible method to prepare WS_2 dispersions with the help of ethanol to exfoliate WS_2 powder. Using this home-made WS_2 dispersions, we fabricate WS_2-PVA and construct a Q-switched erbium-doped fiber laser which can generate stable Q-switched pulses centered in conventional band (C-Band) with tunable repetition rate and pulse duration.

II. WS_2 SATURABLE ABSORBER

Analogous to MoS_2 saturable absorber, WS_2 is necessary to be exfoliated to few layer nanosheets. Here, we adopt ethanol as dispersant. Firstly, ultrasound process was applied to 5 mg/ml WS_2 ethanol mixture to exfoliate the large-size WS_2 powder, shown in Fig.1(a). Then 50 mg/ml polyvinyl alcohol (PVA) aqueous solution was prepared.

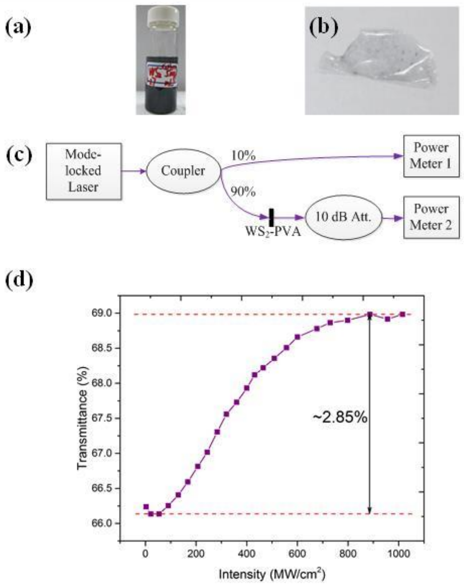

Fig.1 (a) 5 mg/mL WS_2 ethanol dispersions; (b) WS_2-PVA polymer composite film; (c) Experiment setup of nonlinear optical properties measurement of WS_2-PVA; (d) Measured results with a modulation depth of 2.85%.

In order to fabricate WS_2-PVA polymer composite film, we drop aqueous PVA solution onto the surface of a glass slide and then drop WS_2 ethanol dispersions drips onto the surface of PVA. The mixture is dried under 25 degrees in air circumstance. PVA film forms after 4 hours with air seasoning and it can be stripped from glass slide with ease by a clean knife. A free standing WS_2-PVA polymer composite film is then fabricated with this easy method and can be used in subsequent experiments, shown in Fig.1(b).

In order to transfer the film to the end surface of optical fiber, we cut it into small square pieces of which the size (approximately 1 mm × 1 mm) is suitable to be sandwiched between fiber connectors. The nonlinear optical properties can be measured with ultra-short laser pulses. The experiment setup is shown in Fig.1(c). The mode-locked laser generates femtosecond laser pulses. The pulses propagate through a 90:10 coupler so that 10% optical power is measured by power meter 1 as a reference and 90% optical power passes through the WS_2-PVA saturable absorber and is measured by power meter 2 for the measurement. A 10-dB attenuator is applied before the power meter 2 to meet the measurement range of the power meter. Adjusting the output power of mode-locked laser, we measure the transmittance at different optical power. The result is shown at Fig.1(d).

III. WS_2-PVA Q-SWITCHED ERBIUM-DOPED FIBER LASER

The nonlinear optical properties of WS_2 indicate that this material can be used to act as saturable absorber to modulate the loss of laser cavity for Q-switching operation. To achieve this, we insert the WS_2-PVA polymer composite film into the cavity of the laser. The laser setup is shown in Fig.2. 980 nm laser diode (LD) acts as pump source (pump power can be tuned between 0 and 720 mW). Wavelength division multiplexer (WDM) couples pump light into the ring cavity. Single mode fiber (SMF) enables a negative chromatic dispersion environment. Erbium-doped fiber (EDF) is the gain medium. 2 polarization controllers (PCs) are used to adjust the polarization of intra-cavity. Polarization independent isolator (PII) ensures unidirectional propagation. A 90:10 coupler (coupler 1) extracts 10% of the laser out of the cavity and a 50:50 coupler (coupler 2) divides the output laser equally into photodetector (PD) and optical spectrum analyzer (OSA, YOKOGAWA AQ6370C). The total cavity length is approximately 17.4 m.

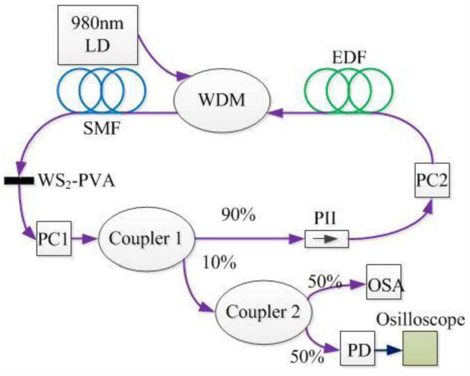

Fig.2 WS_2 Q-switched erbium-doped fiber laser schematic

Turning on pump source and increasing pump power, the laser works firstly at free running state. Many wavelengths participate in mode competition and optical spectrum is unstable. By further increasing pump power to 400 mW and adjusting the polarization controllers, a series of stable Q-switched pulses are generated in the ring cavity. We utilize OSA to record optical spectrum and oscilloscope (Agilent Technologies, DSO9254A) to record pulses regenerated by the PD. A signal source analyzer (ROHDE & SCHWARZ) is used to analyze the electrical signal recovered by the PD. The laser output properties under 550 mW pump power are summarized in Fig.3. The output power is 4.89 dBm, corresponding to 3.08 mW. The conversion efficiency is around 0.56%. Repetition rate is 51.749 kHz and the pulse duration is 4.416 μs. This corresponds to a pulse energy of 59.6 nJ. Fig.3 (c) depicts the optical spectrum of Q-switched pulses of which the center frequency situates in 1562.2 nm. The radio-frequency spectrum of the electrical signal (see Fig.3 (d), the inset depicts the fundamental spectrum of Q-switched laser and demonstrates a remarkable extinction ratio of 58 dB) indicates a prominent pulse stability which is higher than MoS_2 Q-switched fiber laser introduced in [14].

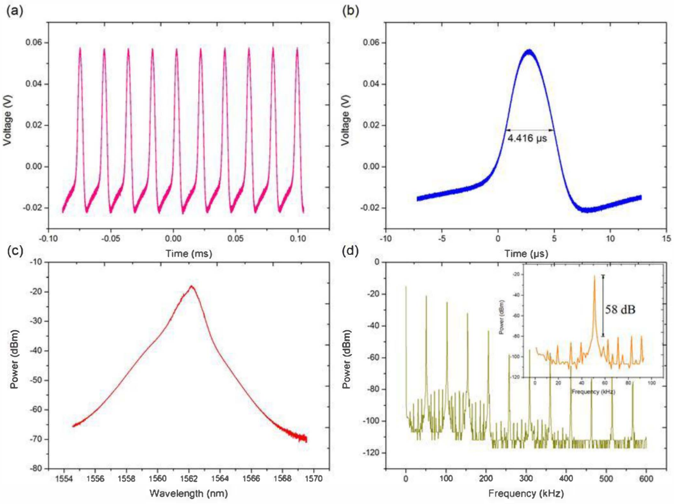

Fig.3 Q-switched laser characteristics under 550 mW pump: (a) Pulse train, (b) Single pulse profile, (c) Optical spectrum, (d) RF spectrum from 0 Hz to 600 kHz with a resolution of 100 Hz. The inset shows the spectrum around fundamental and has a 58 dB extinction ratio.

The pulse duration and repetition rate can be tuned by adjusting pump power. Q-switching operation takes place stably as long as pump power is between 400 mW and 720 mW, and is limited to the output power of pump source. Increasing pump power, the output power and the repetition rate both increase while the pulse duration decreases. The results are summarized in Fig.4. From Fig.4 we know that the output power increase from 4.4 dBm to 5.0 dBm and the repetition rate can be adjusted from 47 kHz to 77 kHz while the pulse duration decline from 6.7μs to 4.1μs.

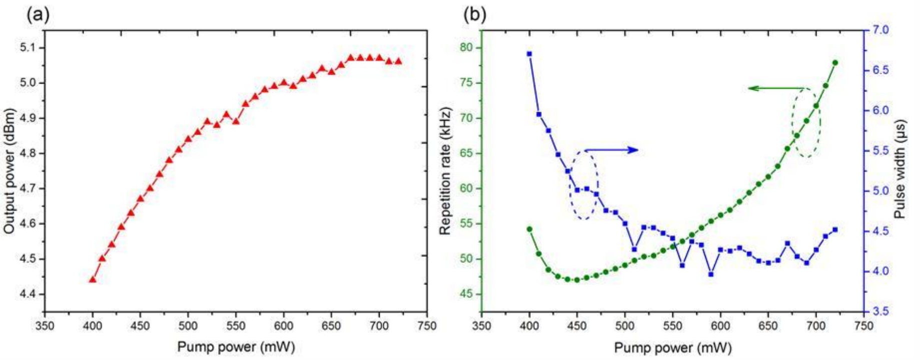

Fig.4 Q-switched laser characteristics: (a) Variation of output power with pump power. (b) Variation of repetition rate and pulse duration with pump power.

In our experiment, the method to prepare WS_2 suspension is straightforward. Ethanol is common in laboratory and low-cost to purchase. Since the evaporation of ethanol is quite fast, it takes less time to form WS_2-PVA polymer film than some other solvents such as sodium cholate or dimethyl formamide (DMF). So it's efficient to fabricate WS_2-PVA polymer composite film in this method. Given the fact that molybdenum and tungsten situate in the same group (i.e. VIB group), we can infer analogous mechanism of saturable absorption of WS_2 as MoS_2. According to [14], the saturable absorption in MoS_2 is related to presence of edge states within the material band gap that arise due to the boundaries of a finite crystal structure. Therefore the edge states within WS_2 could be the origin of nonlinear optical properties of this material at conventional band. Besides the Q-switching operation of WS_2, reference [15] has demonstrated the mode-locking operation of WS_2-PVA which was fabricated with sodium cholate. So there is the possibility that our WS_2-PVA generated with ethanol could be used to mode lock fiber laser and generate femtosecond pulses. Other transition metal dichalcogenides which have similar 2-D structure, such as $MoSe_2$ and WSe_2, could also have nonlinear optical properties analogous to MoS_2 and WS_2. We will investigate their application in ultrashort pulse laser in the near future.

IV. CONCLUSION

In conclusion, we utilize ethanol to prepare WS_2 dispersions and use PVA to fabricate WS_2-PVA polymer composite film. With this well-fabricated film, we measure the saturable absorption of WS_2 and use it as saturable absorber to Q-switch a ring-cavity erbium-doped fiber laser. The laser generates stable Q-switched pulses and can operate between 400 mW to 720 mW of pump power. The output power can be tuned from 4.4 dBm to 5.0 dBm, repetition rate can be tuned from 47 kHz to 77 kHz and the pulse duration can simultaneously tuned from 6.7μs to 4.1μs. Under 550 mW pump power, the laser generates pulses of which the power is 4.89 dBm, the repetition rate is 51.749 kHz and the pulse duration is 4.416 μs. RF spectrum shows a 58 dB extinction ratio which indicates a good stability. Mode-locking operation with this WS_2-PVA fabricated with ethanol is in expectation. The experiment proves WS_2 is a promising saturable absorber for Q-switching operation, which could offer some applications in nonlinear optics and ultrafast optoelectronics.

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