NICKEL DISULFIDE SATURABLE ABSORBER AS Q-SWITCHER IN ERBIUM-DOPED FIBER LASER CAVITY

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Q-switched pulse generation has been successfully demonstrated in Erbium doped fiber laser (EDFL) cavity by using Nickel disulfide Poly(vinyl alcohol) (NiS2 PVA) film as a passive saturable absorber (SA). The NiS_2 SA was successfully fabricated by uncomplicated and cost-efficient ultrasonic liquid exfoliation and follow by incorporating into polyvinyl alcohol (PVA) polymer to form a NiS_2-PVA composite thin film SA. Q-switched pulse operation was obtained at low threshold pump power of 25.6 mW. The Q-switched EDFL operated at 1564.8 nm with repetition rate tunable from 48.1 kHz to 85.5 kHz when the pump power is varied from 25.6 mW to 71.5 mW. The minimum pulse width and highest achieved single pulse energy are 5.85 μs and 114.7 nJ, respectively at pump power of 71.5 mW. This result shows that the NiS_2 has immerse potential for photonic applications.

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1. Introduction

Passively Q-switched fiber lasers have attracted tremendous interests in the past decades due to their wide applications in many areas such as optical communications [1], medical implants [2], nonlinear microscopy [3]. They can be achieved by using an acousto-optic modulator or saturable absorber (SA) in active or passive technique, respectively as a Q-switcher. Compared with the active techniques, passive methods are preferable owing to their many advantages such as ease of fabrication, excellent saturable absorption and high nonlinearity [4]. Typical SA materials such as graphene [5], black phosphorus [6], topological insulators [7] and transition metal dichalcogenides (TMDs) [8] have attracted much interest in recent years due to their excellent electrical and optical properties.

Among these materials, TMDs have gained more interests for photonics applications due to their superior properties of non-zero bandgap and layer-dependent second-order optical nonlinearity [9-10]. In TMDs, the atoms in-plane are covalently bonded, while the atoms between each layer are connected by weak van der Waal forces, which is beneficial to the exfoliation of few-layer nanosheets. As typical TMDs, WS_2 and MoS_2 are the two mostly investigated TMD materials encompassing a wide range of applications including optical modulation [11], photodetectors [12] and pulses generations especially in passively Q-switched and mode-locked lasers [9,13]. Nickel (II) sulfide (NiS_2), another new type of TMD, has attracted enormous attention in recent years owing to its superior electrical [14] and optoelectronic properties [15].

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Furthermore, NiS_2 is a semiconductor material, being similar to WS_2 and MoS_2 [16]. Compared with typical big bandgap TMDs (above 1 eV), the bandgap of NiS_2 is 0.37 eV [17], which forms the basis of its application at 1.5 µm wavelength region.

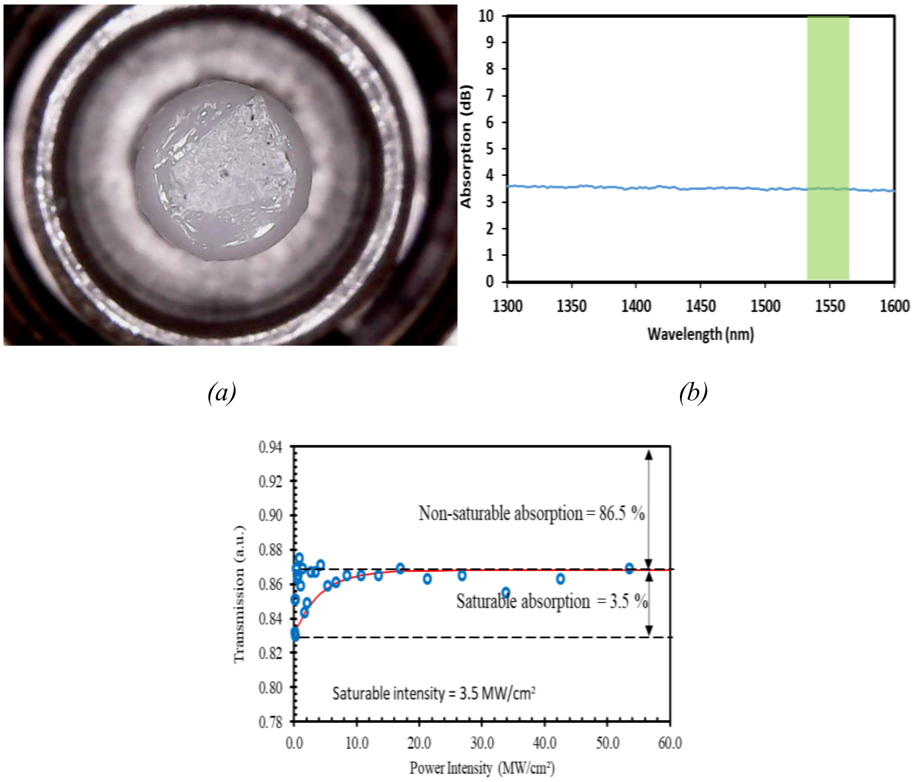
In this paper, the NiS2 is fabricated using chemical synthesis method before it is used as a SA material to generate passively Q-switched pulses in Erbium-doped fibre laser (EDFL) cavity. The fabricated NiS2 presents excellent nonlinear characteristic and this is further proved by the generation of the Q-switched output pulses lasing at 1564.8 nm wavelength. When the pump power was regulated within the pump power of 25.6 to 71.5 mW, the repetition rate of the generated pulses was tunable from 48.1 to 85.5 kHz. The highest pulses energy was obtained at 114.7 nJ at pump power of 71.5 mW. The experimental results clearly indicate that the NiS_2 has excellent potential for use as optical modulator device for realizing Q-switching pulses in an EDFL system.

2. Preparation and optical characterization of NiS_2

The NiS_2 powder used in this work was synthesized using a chemical synthesis method. At first, a 30 mL of Nickel Nitrate ($Ni(NO_3)_2$) was mixed with thiourea ($RC(S)NR_2$) inside a beaker in the molar ratio of 5:1. The mixture was ultrasonicated for one hour in an ultrasonic cleaner (KQ-300E) and then slowly stirred for 30 minutes using a magnetically actuated stirrer. After the cleaning step, the mixture was sealed into the autoclave (GSHA, Xintai) for 12 hours at a temperature of 200 oC. After the reaction, the mixture was poured into a centrifuge (Sorvall Legend Micro 17) for ten successive centrifugal treatment cycles. The NiS_2 powder obtained after the centrifugal step was cleaned five times using anhydrous ethanol. Finally, the NiS_2 powder was left in a vacuum environment to dry for about 5 hours at 50 ^{o}C.

Then the prepared NiS_2 powder was mixed with PVA solution in a separate beaker to fabricate a SA film. The PVA solution was prepared by dissolving PVA powder (40000 MW, Sigma Aldrich) into 80 ml of DI water and then it is stirred at 145℃ until the powder completely dissolves. The NiS2 PVA mixture was slowly stirred for about 2 hours using a magnetically actuated stirrer. The resulting suspension was then poured into the petri dish and left dry at room temperature. After 2 days, the thin film was slowly peeled from the petri dish. Finally, the NiS_2-PVA film was attached onto a fiber ferrule with a help of index matching gel as shown in Fig. 1(a). The ferrule was then connected to another clean ferrule via a fiber adapter to form a fiber compatible SA device. The absorption property of the NiS_2 based SA device was characterized using a white light source. The result is shown in Fig. 1(b), which indicates an absorption loss of about 3.5 dB at 1550 nm region.

Fig. 1(c) shows the nonlinear transmission curve of the NiS_2 PVA film, which was obtained based on the balanced twin-detector technique. The principle of this technique is to divide the light from the pump source into two parts with the same intensity. Half of the light passes through the SA, and the other half is measured directly. The ratio of the two can reflect the modulation depth of the SA material. The laser source used in this measurement is a homemade mode-locked fiber laser, which operates at 1552 nm with a pulse width of 3 ps and repetition rate of 1.0MHz. The blue circles in Fig. 1(c) represent the experimental data while the red solid curve represents the fitting line of the experimental data based on a simplified two-level saturable absorption model [18]. It is observed that the transmission increases with the increase of pulse intensity until it reaches saturation. From the data, the modulation depth is measured to be about 3.5 % with non-saturable absorption of 86.5 %, with saturation intensity of 3.5 MW/cm^2. The result clearly indicates the presence of a typical saturable absorption characteristic. In order to provide strong evidence that the saturable absorption ability originated from the NiS_2, the saturable absorption capability of a pure PVA thin film was also measured using the same balanced twin-detector technique. No nonlinear response was observed thus conforming that the saturable absorption property solely originated from the NiS_2 material.



(a) *(b)*

(c)

Fig. 1. NiS_2 PVA film features (a) the fabricated film attached onto a fiber ferrule (b) linear absorption (c) non-linear optical curve of the SA film.

3. Laser setup

Due to the excellent optical properties of the NiS2-PVA thin film established above, the film was employed inside the pre-designed EDFL cavity to function as SA and hence generate Q-switched pulses. Fig. 2 shows the configuration of the Q-switched laser, which deploys the ring resonator consisting of 2.4 m long Erbium-doped fiber (EDF) as a gain medium. The EDF has an Erbium absorption of 90 dB/m absorption at 980 nm. It was pumped through a 980/1550 nm wavelength division multiplexer (WDM) by a 980 nm laser diode. An isolator was placed between the EDF and the SA device to ensure unidirectional propagation of the oscillating laser in the ring laser cavity. Owing to the filtering capabilities of the isolator, the light in the cavity was forced to propagate only in a specific direction. 80/20 output coupler was used to tap out 20% of the magnified light to realize the real-time detection of pulses while allowing 80 % of the remaining light to oscillate inside the cavity. The NiS2 SA is the main nonlinear device in the laser cavity that compresses the pulse energy into a narrower time range. The 20 % port of the coupler was connected to the optical spectral analyzer (OSA, YOKOGAWA, AQ-6370C) to measure the laser’s output spectrum. A high-speed photodetector linked to an oscilloscope (GWINSTEK: GDS-3352) was used to monitor the output pulse train, while a 7.8 GHz Radio Frequency (RF) spectrum analyser (Anritsu MS2683A) was used to measure the frequency spectrum and stability of the Q-switched laser. The average laser power was measured by an optical power meter (Thorlabs PM 100D) coupled with an InGaAs power head operating between 800-1700 nm (Photodiode Power Sensor S145C Integrating Sphere). The laser cavity's total length was approximately 13.5 m.

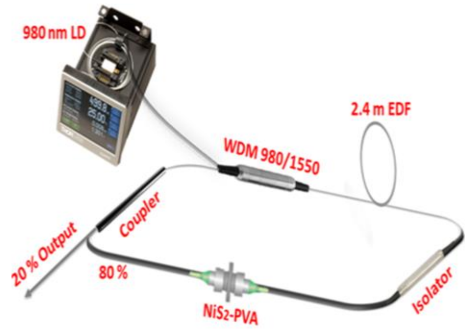
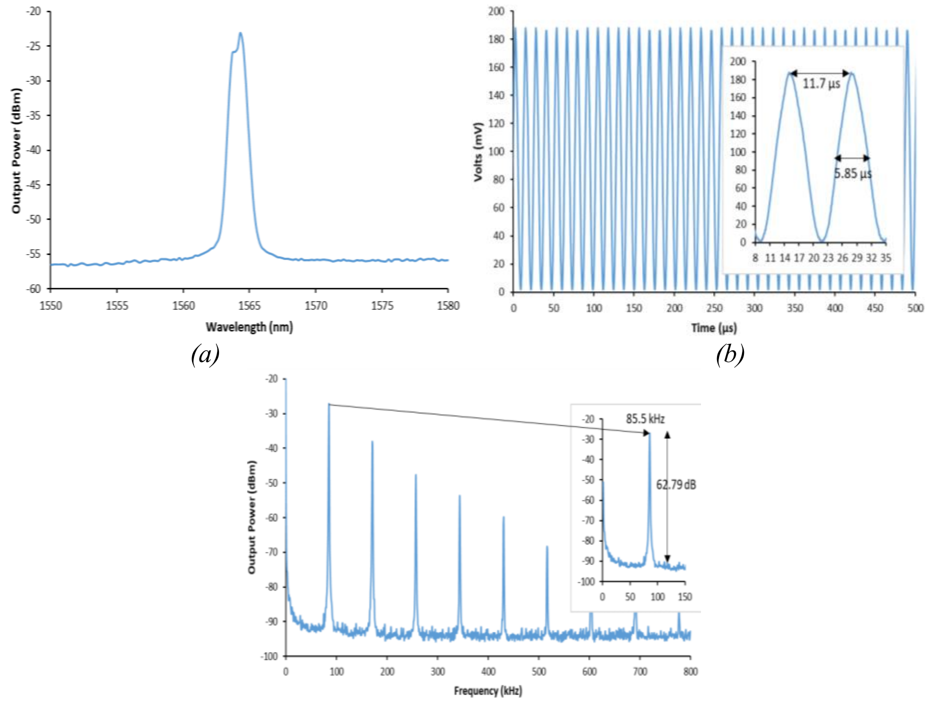


Fig. 2. Schematic diagram of the Q-switched EDFL utilizing NiS2 PVA film as SA.

4. Results and discussion

Stable self-starting Q-switched pulses were observed as the pump power was increased above the starting threshold of 25.6 mW. The laser always maintains a stable Q-switching operation with the increase of the pump power up to 71.5 mW. However, when the pump power raised beyond 71.5 mW, the Q-switched pulses were vanished due to the over saturation of the SA at high input fluence. The output spectrum, typical pulse train waveform and RF spectrum at a pump power of 71.5 mW are shown in Figs. 3(a), (b) and (c), respectively. The center wavelength of the Q-switched laser output is 1564.8 nm as shown in Fig. 3(a). The repetition rate is 85.5 kHz corresponding to the two adjacent pulses of 11.7 μs as shown in Fig. 3(b). The uniform intensity and smooth waveform of the pulse strings indicate that the NiS2 has a certain ability to restrain noise. Fig. 3(b) also indicates that the Q-switched laser has the shortest pulse duration of 5.85 μs with an almost symmetric Gaussian distribution. We believe that the pulse duration can be further narrowed by reducing the length of the laser cavity. The repetition rate of the basic pulses is measured as 85.5 kHz with a signal to noise ratio (SNR) of approximately 62.8 dB as shown in Fig. 3(c). As the SA device is removed from the cavity, there was no evidence of any pulse-like behavior in the time-based waveforms observed on the oscilloscope.

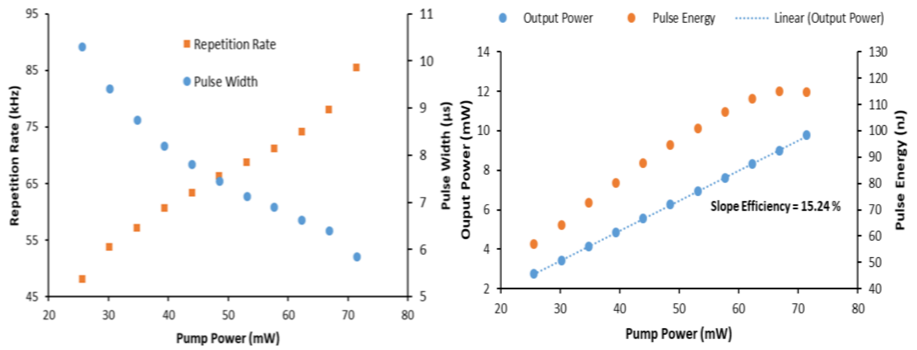


(a) *(b)*

(c)

Fig. 3. Spectral and temporal characteristics of the proposed Q-switched EDFL with NiS_2 SA when the pump power is fixed at 71.5 mW (a) Output spectrum (b) Typical oscilloscope trace (c) RF spectrum

The evolution of repetition rate and pulse width against pump power was also investigated and the result is shown in Fig. 4(a). As shown in the figure, the modulation ranges of the repetition rate and the pulse width (Full width at half maximum) are 48.1 kHz to 85.5 and 10.3 µs to 5.85 µs respectively when the pump power is raised from 25.6 mW to 71.5 mW. The minimum pulse duration can be further shortened by either enhancing the modulation depth of the SA or reducing the total length of ring cavity [19]. The average output power and pulse energy were also measured with respect to the pump power as shown in Fig. 4(b). It is observed that the output power increased from 2.74 to 9.80 mW as the pump power is varied from 25.6 mW to 71.5 mW. The slope efficiency of the laser is measured as 15.24%. The maximum recorded single pulse energy is about 114.7 nJ which is comparable to previous literatures [20-22]. The fluctuation of repetition rate and output power of the Q-switched laser are less than 5% within the test time of about 60 minutes during the measurement. These results indicate that the NiS_2 PVA film exhibits saturable absorption in the EDFL working region and thus it could work as a good SA device to achieve Q-switched operation.



(a) *(b)*

Fig. 4. Q-switching performance for the NiS_2 based EDFL (a) Repetition rate and pulse width as functions of pump power (b) Output power and single pulse energy as functions of pump power.

5. Conclusion

The passively Q-switched EDFL based on NiS_2 saturable absorber was succesfully demonstrated. A stable Q-switched operation was illustrated from 1564.8 nm fiber ring cavity. The achieved repetition rate and pulse width range are 48.1 kHz to 85.5 and 10.3 µs to 5.85 µs, respectively. The maximum pulse energy of 114.7 nJ was obtained at 71.5 mW pump power. Stability of Q-switched EDFL is proven with SNR of 62.8 dB. This demonstration proves the new application of NiS_2 for Q-switching pulse generation.

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