Nanosecond passively Q-switched fibre laser using a NiS₂ based saturable absorber

SHI LI,¹ YU YIN,¹ QIUYUN OUYANG,¹ GUICANG RAN,¹ YUJIN CHEN,¹ ELFED LEWIS,² GERALD FARRELL,³ MASAKI TOKURAKAWA,⁴ SULAIMAN WADI HARUN,⁵ AND PENGFEI WANG¹,⁶,*

¹Key Laboratory of In-fibre Integrated Optics of Ministry of Education, College of Science, Harbin Engineering University, Harbin 150001, China
²Optical Fibre Sensors Research Centre, Department of Electronic and Computer Engineering, University of Limerick, Limerick, Ireland
³Photonics Research Centre, Technological University Dublin, Dublin, Ireland
⁴Institute for Laser Science, University of Electro-Communications, 1-5-1 Chofugaoka Chofu Tokyo 182-8585, Japan
⁵Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
⁶Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Optoelectronic Engineering, Shenzhen University, Shenzhen, 518060, China
*pengfei.wang@dit.ie

Abstract: Q-switched pulse laser generation is successfully demonstrated in both Erbium-doped fibre laser (EDFL) and Thulium-doped fibre laser (TDFL) cavities by employing Nickel disulfide (NiS₂) as a saturable absorber (SA). Q-switched pulse laser operation at 1.55 μm and 2.0 μm is obtained at low pump power levels of 37 mW and 48 mW, respectively. For the EDFL, stable passively Q-switched laser output at a wavelength of 1561.86 nm is achieved, with a minimum pulse duration of 237 ns and a repetition rate of 243.9 kHz. For the TDFL, the centre wavelength of the laser output is 1915.5 nm, with a minimum pulse duration of 505 ns and a repetition rate of 214.68 kHz. NiS₂ is used as SA for Q-switched laser generation over a broadband wavelength for the first time.

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1. Introduction

Pulsed fibre lasers have attracted significant attention in the past few decades, not only being applied in optical communications [1], medical implants [2], nonlinear microscopy [3], but also used to drive other research areas such as nonlinear materials [4], soliton evolution [5], etc. Compared with other techniques to obtain pulsed laser, passive methods based on real saturable absorbers (SA) have rapidly developed for pulsed laser generation owing to simple fabrication and excellent saturable absorption characteristics [6,7]. Typical SA materials including graphene [8], black phosphorus [9], transition metal dichalcogenides (TMDs) [6,10–13] long-term stable Group VA materials Xene (e.g., X = antimon [14], bismuth [15]), flexible gold nano materials (e.g., gold nanorods [16], gold nanostars [17], gold nanobipyramids [18]) etc. have attracted much interest in recent years.

Among the numerous SA materials, TMDs show strong chemical bonds in-plane but display weak Van der Waals interaction between layers [19]. For few-layer TMDs, the atomic structure is characterized by a sandwiched-like structure [20]. The chemical formula of TMDs is written as MX₂. M (represents transition metal atom such as Mo, W, Ni) is a layer sandwiched between two layers of X (chalcogen atoms such as S, Se) [20]. To date, more than 40 types of TMDs have been discovered depending on the combination of the chalcogen and transition metal atoms [20]. Among the numerous TMDs, WS₂ and MoS₂ have been mostly investigated encompassing a wide range of optical functions, such as two-photon absorption [21] and saturable absorption [6]. TMDs have also been used as an SA to achieve...
passive Q-switched and mode-locking fibre laser incorporating side-polished fibres [22], microfibres [6], polyvinyl alcohol-based films [23], etc.

Nickel disulfide (NiS$_2$), another new type of TMD, has attracted significant attention in recent years owing to its superior electrical [24–26] and optoelectronic properties [27,28]. NiS$_2$ is a semiconductor, similar to WS$_2$ and MoS$_2$ [20]. Compared with typical large bandgap TMDs (above 1 eV), the bandgap of NiS$_2$ is 0.3 eV [29], which forms the basis for its application at long wavelengths (about 4.13 $\mu$m). However, the nonlinear optical properties of NiS$_2$ and its application in fibre laser have seldom been reported. Thus, it is a very valuable work to investigate the applications of NiS$_2$ in fibre laser, such as the Q-switched pulse laser in a wideband region using the NiS$_2$-based SA.

In this paper, the NiS$_2$ material was synthesized using a chemical method and used as an SA to generate passive Q-switched pulses in both an Erbium-doped fibre laser (EDFL) and a Thulium-doped fibre laser (TDFL). The NiS$_2$ exhibits excellent nonlinear optical properties and this is further proved by the achieved Q-switched pulsed laser output. The experimental results clearly indicate that NiS$_2$ has excellent potential for use in passive Q-switched fibre lasers, especially for broad waveband operation.

2. Synthesis and optical measurements of NiS$_2$

The NiS$_2$ was synthesized entirely using a chemical method. Initially, a 30 mL mixture of Nickel Nitrate and thiourea was poured into a beaker with a molar ratio of 5:1 and stirred at 25 °C for 2 h. Then the mixture was transferred into an autoclave for hydrothermal treatment at 200 °C for 5 h. The precipitates were separated using centrifugation, washed using distilled water and ethanol, and dried at 40 °C for 10 h under vacuum. In order to fabricate the NiS$_2$-PVA film, the NiS$_2$ powder was poured into another beaker with the PVA solution and then slowly stirred at 130 °C for 2.5 h. The resulting suspension was then poured into a petri dish and dried at 25 °C for 10 h. Finally, the NiS$_2$-PVA film was carefully peeled from the petri dish.

The nonlinear absorption (NLA) properties of NiS$_2$ were investigated using an open-aperture Z-scan method [30]. The excitation laser pulses were generated using a femtosecond Ti:sapphire laser system (center wavelength: 800 nm, pulse duration: 200 fs, repetition rate: 2 kHz). The nonlinear transmission ability was measured using a balanced twin-detector technique [6]. A femtosecond fibre laser (center wavelength: 1550 nm, Pulse width: 300 fs, Repetition rate: 15 MHz) and a picosecond fibre laser (centre wavelength, 1.91 $\mu$m; pulse duration, ~3.6 ps; repetition rate, ~22 MHz) were used as the pump sources.

3. Results and discussion

The image of NiS$_2$-PVA film is shown in Fig. 1(a). The film is nearly colorless and transparent, and is highlighted by the green circle in 1 (a). The sample was characterized using Raman spectrometry in order to confirm its chemical composition. The Raman spectrum was obtained and the result is shown in Fig. 1(b). Two weak peaks were observed at 274.0 cm$^{-1}$ and 284.8 cm$^{-1}$ which correspond to the S-S pair vibrational modes ($T_g$ and $E_g$). The two strong peaks at 479.7 cm$^{-1}$ and 489.8 cm$^{-1}$ correspond to stretching modes of the S-S pair ($A_g$ and $T_g$). The Raman spectrum agrees well with earlier findings [31,32].

The NLA curve is shown in Fig. 2(a). It is clear that NiS$_2$ exhibits a typical saturable absorption effect. In addition, the nonlinear transmission of the NiS$_2$-PVA film SA is also investigated. Figure 2(b) and Fig. 2(c) show the nonlinear transmission curves at the wavelength of 1.55 $\mu$m and 1.9 $\mu$m, respectively. The blue points in Fig. 2(b) and Fig. 2(c) represent the experimental data, which confirms the trend of nonlinear absorption. The red solid curves in Fig. 2(b) and Fig. 2(c) represent the fitting lines of the experimental data based on a simplified two-level saturable absorption model [33], which clearly indicates the presence of a typical saturable absorption effect. The trend of the nonlinear transmission curves indicates that the transmission increases with the increase of pulse intensity until it
reaches saturation. The saturable absorption modulation depth, the nonsaturable loss and the saturable intensity are about 5.3%, 11.4% and 8.3 MW/cm² at the wavelength of 1.55 μm, respectively. The saturable absorption modulation depth, the nonsaturable loss and the saturable intensity are about 4.3%, 16.3% and 8.8 MW/cm² at the wavelength of 1.9 μm, respectively. The NiS₂ based SA effect beyond 2 μm (with broadband emission) is mainly due to its small bandgap of 0.3 eV. The above results confirm that NiS₂-PVA thin film is well suited for application as saturable absorption material in the near-infrared region and mid-infrared wavelength regions. The insertion loss of the SA device was measured to be 2.5 dB.

Fig. 1. (a) Image of NiS₂-PVA thin film and NiS₂ SA device with NiS₂-PVA thin film transferred on the fibre connector. (b) Raman spectrum of NiS₂ sample.

Fig. 2. (a) The typical Z-scan peak curve of NiS₂ at 800 nm. (b) The nonlinear absorption of NiS₂-PVA film at 1.55 μm. (c) The nonlinear absorption of NiS₂-PVA film at 1.9 μm. (d) Schematic of the NiS₂-PVA based fibre laser.
Due to the excellent optical properties of the NiS$_2$-PVA thin film, the film as a SA was deployed inside the pre-designed cavity to generate Q-switched laser output pulses. The proposed fibre lasers based on an Er-doped fibre laser (EDFL) and Tm-doped fibre laser (TDFL) have the same configuration, as shown in Fig. 2(d). The pump source provides source lasing to pump the gain medium, a short section of rare earth doped (Er-doped or Tm-doped) fibre was optically coupled via a wavelength division multiplexer (WDM). The generated photons then propagate into the polarization independent isolator (PI-ISO) which is pigtailed with the gain medium. In the designed laser cavity, the PI-ISO not only maintained lasing in a unidirectional operation, but also reduced Brillouin back-scattering, which could potentially disturb the stability of the pulsed operation [34]. The SA device was spliced between the 90%-port of the optical coupler (OC) and the WDM to complete the ring cavity. The 10% port of the OC was connected to an optical spectral analyzer (OSA, YOKOGAWA, AQ-6370C) to measure the output spectrum of the laser. The time resolved output signal of the pulsed laser was also measured using a digital storage Oscilloscope (Tektronix MDO4054-6, 6 GHz) and a photodetector (Kemai, PDA, 10 GHz). An optical power meter (Newport 1918-R) was used to measure the output power.

In the case of the Er-doped fibre laser (EDFL), the 4.5 m Er-doped fibre (Likkie-8/125) was pumped using a 976 nm laser diode (MCPL-980-SM), the total length of the cavity being ~24 m. When the pump power was increased to 35 mW, continuous wave (CW) lasing was observed. There was no evidence of any pulse-like behavior in the time-based waveforms observed on the oscilloscope. As the power was further increased to 37 mW, passive Q-switched operation was initiated and recorded. The Q-switched threshold is at a low level mainly due to the fact that no polarization controller (PC) was used in the designed laser configuration, which uses fibre bending to introduce significant losses in the cavity. In addition, the absence of the PC in the cavity ensured that no nonlinear polarization evolution (NPE) effect occurred, which can potentially limit the output pulse energy [35]. The whole evolution of the Q-switched pulse operation is shown in Fig. 3. The output spectrum and typical pulse train waveforms with a pump power of 200 mW are shown in Figs. 3(a) and 3(b), respectively. The centre wavelength of the Q-switched laser output is 1561.86 nm. The temporal pulse separation (between two adjacent pulses) is 4.1 μs corresponding to 243.9 kHz repetition rate. The narrowest pulse duration of the Q-switched operation shown in Fig. 3(c) was 237 ns, which can be further reduced by using the shorter laser cavity [36]. The repetition rate and pulse width versus the pumping power are shown in Fig. 3(d). In the NiS$_2$-based EDFL, the pump power was varied from 37 mW to 200 mW, the repetition rate increased from 195.3 kHz to 243.9 kHz with the pulse width in the opposite state: decreased from 822 ns to 237 ns. The evolution of the repetition rate and pulse width indicates that the NiS$_2$-based EDFL exhibits typical passive Q-switched behavior, respectively [37]. When the pumping power was adjusted over 200 mW, the pulse train would be in unstable state. It is mainly due to the overbalanced of NiS$_2$-PVA SA in high power.
Fig. 3. Characteristics of the single Q-switched pulse in the EDFL. (a) Optical spectrum with 200 mW pumping power, (b) Typical oscilloscope pulse waveform with 200 mW pumping power, (c) Single pulse characteristics of Q-switched pulsed laser for a pump power of 200 mW, (d) Repetition rate and pulse width versus pumping power.

Applications of the NiS₂-PVA film were further investigated near the 2.0 μm wavelength region. In the TDFL case, the 5 m Tm-doped fibre (Nufem SM-TSF-9/125) was pumped using a tunable laser (Santec TSI-710) with a centre wavelength of 1562 nm and an Erbium-doped fibre amplifier (EDFA, MC-230) in a 28 m cavity. The Q-switched pulse operation was successfully achieved at a pump power of 48 mW without a PC in order to avoid large losses and the NPE effect. Figure 4 summarizes the typical characteristics of the Q-switched operation at 220 mW. Figure 4 (a) shows that the centre wavelength is located at 1915.5 nm. Figure 4 (b) shows the oscilloscope pulse waveform with a pump power of 220 mW; the temporal pulse separation is 4.66 μs corresponding to the repetition rate of 214.7 kHz. The single pulse operation of the Q-switched pulsed laser can be clearly observed in Fig. 4(c), the pulse duration being 505 ns. The characteristics describing the repetition rate and pulse width variation versus the pump power are shown in Fig. 4(d). The repetition rate increased from 182.6 kHz to 214.7 kHz and pulse duration decreased from 1.14 μs to 505 ns, with the pump power increasing from 48 mW to 220 mW. The experimental results indicate that the NiS₂-PVA film exhibits saturable absorption in the TDFL described in this article. The NiS₂-PVA film can also work as a good SA device to achieve Q-switched operation around a wavelength of 2.0 μm. It is worth noting that the pulse can become unstable with higher pumping power, for the same reason outlined in the case of the EDFL.
The relationship between the average output powers and pump powers of the EDFL and TDFL are shown in Fig. 5(a). For the EDFL (blue line), the maximum average output power was recorded as 30.2 mW for a pump power of 200 mW, corresponding to a slope efficiency of 15.1%. The maximum pulse energy was calculated to be 1.23 μJ. For the TDFL (red line), the slope efficiency was 12.9% with a maximum output power of 28.4 mW, and the maximum pulse energy was calculated to be 1.32 μJ. It is possible that the slope efficiency values of the EDFL and TDFL still have potential to be improved, mainly due to the low output ratio of the optical coupler (OC). As much as 90% of the total power was circulated in the fibre laser, with only a maximum of 10% being extracted. In future, the output power could be increased by adjusting the output ratio of the OC, to yield improvement of the slope efficiency. It is worth noting that the passively Q-switched EDFL and TDFL became unstable when the pump power was too high, which might result in the SA being damaged due to the occurrence of the photothermal effect in the NiS$_2$-PVA film [37]. To overcome this weakness, the SA device was fabricated using a new method in an efficient way, which included transferring the NiS$_2$ onto the microfibre, which can also take full advantage of the evanescent field effect between the NiS$_2$ and the microfibre [6]. This opens the possibility of enlarging the interactive areas between the pump source and NiS$_2$ materials, and hence further reducing the photothermal effects of the NiS$_2$ SA. Further work will be undertaken to increase the damage threshold by using microfibre-based SAs.
Fig. 5. (a) Relationship between the average output powers and pump. (b) Measured long-term stability of the proposed fibre laser.

Among the characteristics of the fibre laser of this investigation, the long-term stability is an important index for measuring the device’s performance. Thus, the stability of the fibre laser in this paper was measured over a continuous ten-hour period of operation. As shown in Fig. 5(b), NiS\textsubscript{2}-PVA film based EDFL and TDFL both exhibit excellent long-term stability. The fluctuations of highest pulse energy of EDFL (blue line) and TDFL (red line), both exhibit a high degree of invariance with time. The normalized root-mean-square (RMS) value in the EDFL and TDFL cases were calculated as 0.3% and 0.26% respectively, which confirms that both fibre lasers have excellent long-term stability.

In order to provide strong evidence that the broad band saturable absorption effect originated from the NiS\textsubscript{2}, the NiS\textsubscript{2}-PVA film was replaced by a pure PVA film of the same size. In both laser cavities of EDFL and TDFL, even if the pump power was adjusted gradually and carefully over a large range (from 0 mW to 250 mW), the passively Q-switched pulse could not be observed. The results fully confirmed that the Q-switched pulse laser in both EDFL and TDFL is due to the saturable absorption of the NiS\textsubscript{2}-SA.

4. Conclusion

Both EDFL and TDFL achieved Q-switched laser based on NiS\textsubscript{2}-SA, which confirm the NiS\textsubscript{2} can be used in fibre laser application. The saturable absorption effect has also been investigated for a thin film configuration, which exhibits a modulation depth of 5.3% and 4.3% at around the 1.55 \textmu m and 2.0 \textmu m wavelength regions, respectively. The fabricated 1.55 \textmu m and 2.0 \textmu m region based fibre laser have both exhibited Q-switched pulse operation, which further confirm the saturable absorption capability of NiS\textsubscript{2} material. The narrowest pulse widths obtained were 237 and 505 ns in the 1.55 \textmu m and 2.0 \textmu m wavelength regions respectively. Compared with fibre lasers based on other TMDs whose saturable absorption comes from the atomic defect, the NiS\textsubscript{2} has a much smaller bandgap (0.3 eV) and hence achieves a broad band SA effect, which ensure the NiS\textsubscript{2} can be used in fibre laser application to achieve pulse laser over a long waveband. The pulse energies of the EDFL and TDFL of this investigation were observed and recorded for ten hours to confirm the stability of the fibre lasers and the results indicate that pulse energies exhibit no discernible change. The work reported in this paper has demonstrated that the suitability of NiS\textsubscript{2} as a SA material for use in a broad range of wavelength laser applications.

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