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基于β相硒化铟的被动调Q及锁模掺镱光纤激光器(特邀)

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摘　要：利用层状半导体β相硒化铟作为可饱和吸收体，在掺镱光纤激光器中实现稳定的调Q及锁模运转。经测量该可饱和吸收体在1 μm波段调制深度及非饱和损耗分别为47%及20%。将可饱和吸收体插入掺镱光纤激光器中，可获得53.42 kHz到217 kHz重频可调的调Q脉冲。其最窄脉冲宽度为630 ns，最大单脉冲能量为47.9 nJ。优化激光谐振腔后可进一步实现稳定的锁模输出，其重频为10.82 MHz，最大输出功率为51.2 mW，最大单脉冲能量为4.7 nJ。实验证明了β相硒化铟作为可饱和吸收体在近红外超快非线性光学方面的潜力。

关键词：可饱和吸收体；调Q激光；光纤激光器；锁模激光；硒化铟

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Passively Q-switched and Mode-locked All-fiber Yb-doped Laser with β-InSe Saturable Absorber (Invited)

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Abstract: A stable Q-switched and mode-locked Ytterbium Doped Fiber Laser (YDFL) based on layered semiconductor β-InSe as Saturable Absorber (SA) were demonstrated for the first time. The modulation depth and non-saturable absorbance of the SA were 47% and 20%, respectively. After inserting the SA

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into YDFL, the stable Q-switched pulse operation can be easily obtained with the repetition rate range from 53.42 kHz to 217 kHz. The minimum pulse duration was 630 ns and the maximum single pulse energy was 47.9 nJ. By optimizing the laser resonator, a stable mode-locking pulse with repetition rate of 10.82 MHz, maximum output power of 51.2 mW and maximum single pulse energy of 4.7 nJ can be achieved. The experimental results demonstrated that β-InSe SA has great potential in near infrared ultrafast nonlinear optical.

Key words: Saturable absorbers; Q-switched lasers; Fiber lasers; Mode-locked lasers; Indium selenides
OCIS Codes: 140.3510; 140.3540; 140.3615; 140.4050; 160.4330

0 Introduction

Compared with Continuous Wave (CW) fiber lasers, pulse fiber lasers have the advantage of narrow pulse duration and high pulse energy. In recent years, it has developed rapidly in many fields, such as optical frequency comb, laser waveguide, optical fiber communication, biomedicine and so on[1]. In order to modulate the laser operation from CW into pulsed regime, passive Q-switching and passive mode-locking technology have become the mainstream of the laser development due to their low cost and all-fiber structure. SA is the most critical device for pulse generation. At present, the most stable saturable absorber is Semiconductor Saturable Absorber Mirrors (SESAMs)[2]. However, some problems, such as high production cost and low damage threshold that limit the maximum output power, remain to be solved. Therefore, the SAs with high modulation depth, high damage threshold and high stability have attracted more attentions. Two dimensional layered semiconductor materials, a kind of SAs with ultrafast recovery time, wide absorption range and adjustable band gap, mainly divided into three types: Transition-Metal Dichalcogenides (TMDs)[3-5], Black Phosphorus (BPs)[6-8], and III-VI compound layered semiconductors[9-10].

III-VI compound layered semiconductors have great application prospects in infrared detection, photoelectric devices and solar cells due to the characteristics of small band gap and high environmental stability[9]. III-VI compound layered semiconductors with a variety of crystal structures and stacking arrangements are mainly divided into MX (such as InSe, GaSe, GaS and GaTe) and M_aX_b (such as In_2Se_3 and In_3Se_4). For example, InSe has four different crystal configurations, which are β, ε, γ, δ[11]. The two most common configurations are β-InSe and γ-InSe. InSe and In_2Se_3 have a direct band gap of 1.26 eV and 1.36 eV, respectively. Fiber laser based on In_2Se_3 SA have been widely reported recently. In 2018, YAN Peiguang, et al[12] studied the wideband saturable absorption property of In_2Se_3 at 800, 1 560, and 1 930 nm, and by using In_2Se_3 as SA, which a mode-locking operation can be achieved. The same year, AHMAD H, et al[13] demonstrated passively Q-switched Bi-EDF laser with an In_2Se_3 SA, the maximum available pump power of 134 mW and a wide tuning range of 40 nm, covering a wavelength range of 1 533 nm to 1 573 nm. In 2020, HAI Ting, et al[14] proved In_2Se_3 SA can be used for fiber lasers in the 3 to 4 μm waveband. WANG Lizhen, et al[15] reported stable mode-locked soliton pulses with 158 fs pulse duration and 2.72 mW average power based on graphene/α-In_2Se_3 heterostructure SA. In 2021, LI Lu, et al[16] obtained a dual-wavelength Q-switched EDF laser. The narrowest pulse duration and largest pulse energy was 556 ns and 376 nJ, respectively. However, most report based on In_2Se_3 operate in anomalous dispersion region, and the 1 μm fiber laser based on InSe SA had not been studied yet.

In this work, we constructed a YDFL by using β-InSe nonoflakes as SA, which was sandwiched into two FC/APC fiber end face with a fiber flange. After inserting the SA into YDFL system, a stable Q-switched pulse with minimum pulse duration of 0.63 μs and the maximum pulse energy of 47.9 nJ can be achieved. Meanwhile, A stable mode-locked pulse operation was generated after optimization with the maximum output power of 51.2 mW, corresponding to the maximum pulse energy of 4.7 nJ. Our YDFL system based on β-InSe SA have the advantage of the compact structure, low production cost and independent of the polarization evolution in the cavity. All polarization-maintaining structure can be used to further enhance its stability.

1 β-InSe SA fabrication and characterization

Bulk InSe was prepared in a tube furnace by the Bridgman method. In addition, InSe nanoflakes were prepared by mechanical exfoliation with 3M Scotch tape. β-InSe, belonging to the D^4_{6h} space group, consists of four atomic layers (Se-In-In-Se), and each layer is connected by van der Waals (vdWs) interactions arranged in a hexagonal atomic lattice. The structure and composition of β-InSe were confirmed by Raman spectroscopy, X-Ray Diffraction (XRD), Scanning Electron Microscope (SEM), and Energy Dispersive Spectrometer (EDS). Three prominent peaks at 118, 181, and 230 cm^{-1} were observed, which correspond to the A^1_{1g}, E^1_{2g}, and A^2_{1g} vibration modes of β-InSe, respectively (Fig. 1(a)). As shown in Fig. 1(b), typical XRD pattern matches well with the standard data file PDF 34-1431, indexing a=b=0.40 nm and c=1.66 nm of each unit cell. Fig. 2 displays the appearance and the composition of bulky β-InSe crystal. The two elements (In and Se) were uniformly distributed in the material, and the atomic ratio of In/Se was around 1∶1. All of those measurements indicate the high crystalline quality of the as-grown β-InSe crystal.

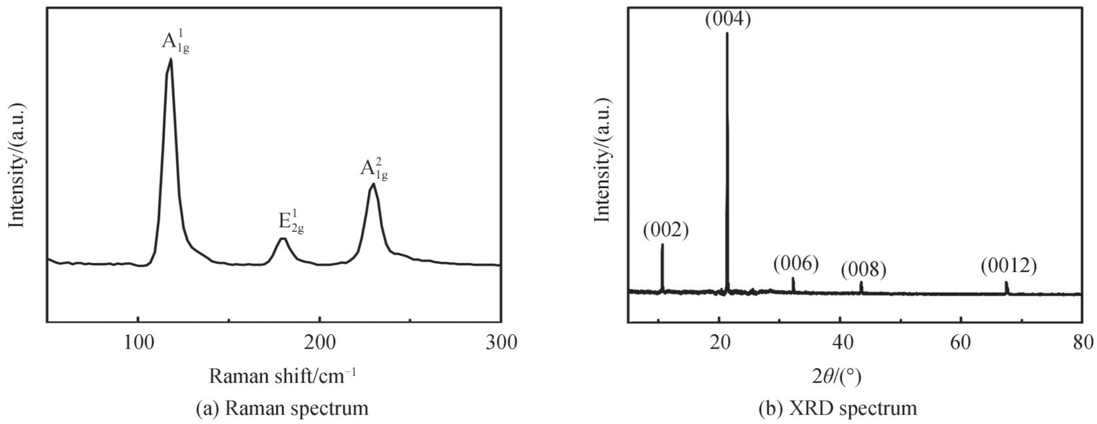


Fig. 1 The Raman and XRD spectrum of bulky β-InSe

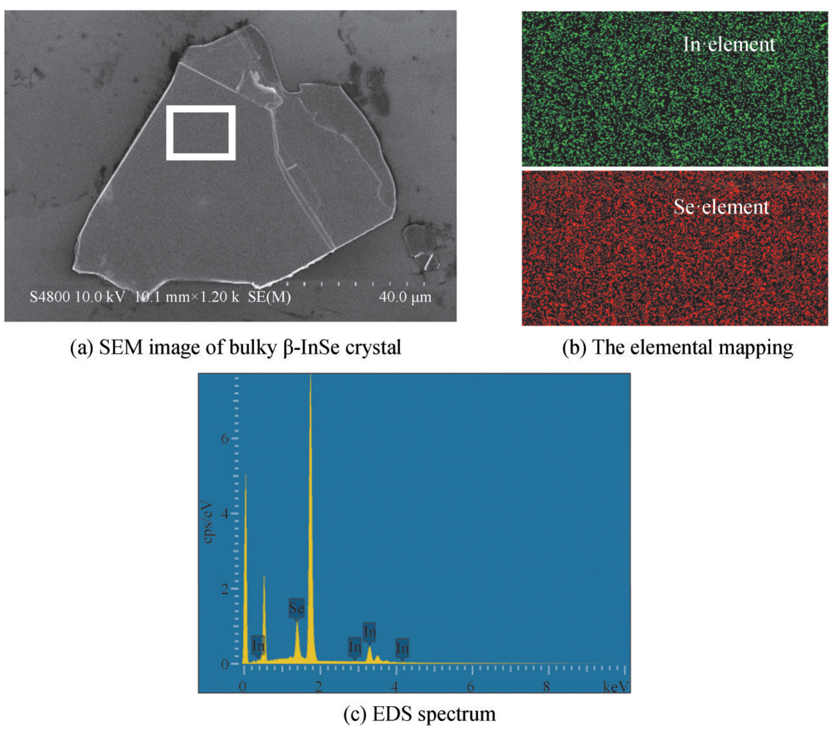
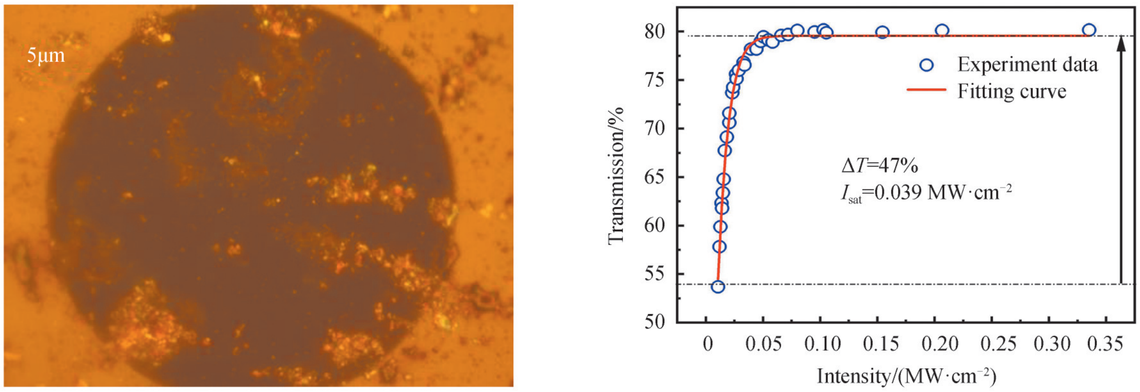


Fig. 2 The appearance and the composition of bulky β-InSe

We used the Liquid Phase Exfoliation (LPE) method[17] to fabricate the β-InSe SA. The β-InSe alcohol solution was prepared by mixing 1 mg β-InSe powder with 7 mL alcohol solution, then subjected to bath sonication for 3.5 h. Finally, we take the supernatant and drop it on the FC/APC fiber end face. The β-InSe will be transferred onto FC/APC fiber end face after the alcohol volatilized. The microscope image of the FC/APC fiber end face was shown in Fig. 3(a). It can be seen that the FC/APC fiber core was covered with β-InSe nanoflakes.



(a) Microscope image of FC/APC fiber end face (b) The transmission curve of β-InSe nanoflakes

Fig. 3 The microscope image and the transmission curve of β-InSe SA

Used the twin-detector technique to investigate the nonlinear absorption properties of the β-InSe SA. A home-made Yb-doped Nonlinear Polarization Evolution (NPE) mode-locked fiber laser was used as seed source, which has a pulse duration of 120 fs, center wavelength of 1042 nm and repetition rate of 41.58 MHz. A Variable Optical Attenuator (VOA) was used for power regulation. The light splitted by a 50:50 fiber coupler, and one port passing through the SA was signal port and another was reference port. The transmittance curve of the SA as a function of pump power was demonstrated in Fig. 3(b). The saturable absorption mode was based on the following formula

$$T(I)=1-\Delta T\times\exp\left(-I/I_{sat}\right)-A_{ns}$$

where T is transmission, ΔT is modulation depth, I is input intensity of the laser, I_{sat} is saturable power intensity and A_{ns} is non-saturable absorbance. By fitting the experimemtal results, the modulation depth and non-saturable absorbance in 1 μm were 47% and 20%, respectively. The saturation intensity was 0.039 MW/cm^2.

2 Experiment setup and results

2.1 Q-switched Ytterbium-doped fiber laser

The experiment setup was shown in Fig. 4. A commercial 976 nm laser diode was used as pump source. The pump light was coupled by a 980/1 030 wavelength division multiplexer. A 20 cm single-mode Ytterbium doped fiber (Liekki Yb 1200-4/125, Vancouver, USA) was used as gain medium, and Polarization Controller (PC) was used to adjust intracavity nonlinearity. The polarization independent isolator keeped unidirectional operation in the cavity. A coupler (SR4889, AFR, Zhuhai, China) with 20% output was employed to output the laser. An 8 nm bandpass filter (BPF-1030, OF-Link, Suqian, China) was added to the cavity for wavelength selection. The total length of the cavity was 6.4 m.

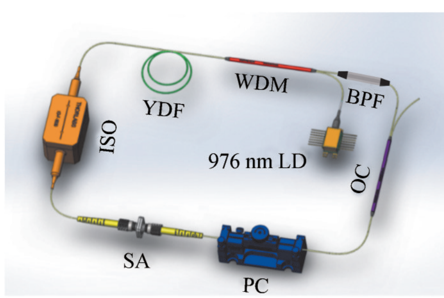
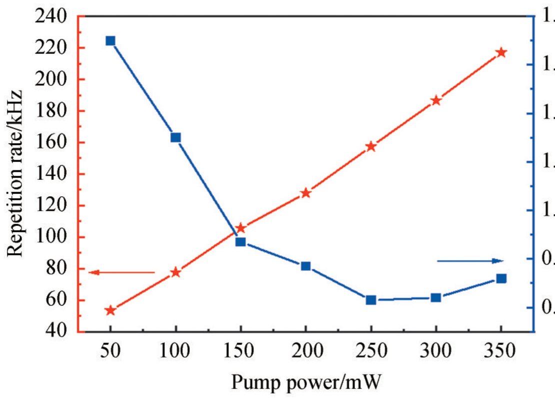


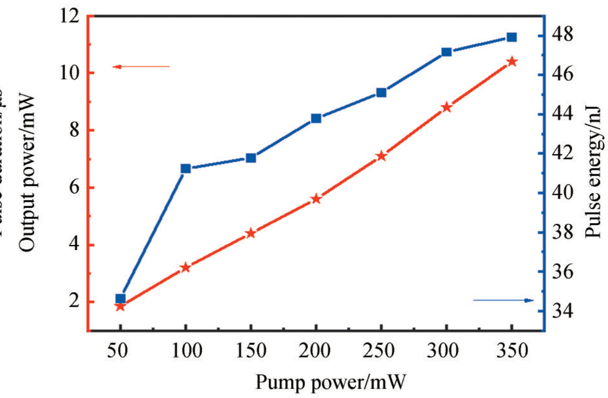
Fig. 4 Schematic of Yb-doped all-fiber laser

The laser characteristics were monitored by a real-time sampling oscilloscope (Tektronix DPO3052, 500 MHz, 2.5 GS/S, Shanghai, China) and an optical spectrum analyser (Ocean Optics HR2000, Shanghai, China) was utilized to record the optical spectrum. A photodetector (Thorlabs DET10A/M, Shanghai, China) was employed to monitor the temporal evolution and output power of the output pulse train.

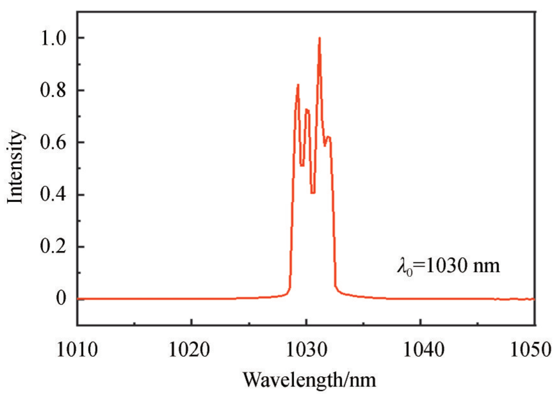
The Q-switched operation was realized by adjusting the PC and increasing pump power at 50 mW and the output power was 1.85 mW. The low Q-switching threshold benefited from the low saturation intensity and large modulation depth of SA. Besides, the low output power also indicated that there was a large loss in the cavity. The output power increased linearly with the increasing of pump power. With pump power increased to 350 mW, the maximum output power was 10.2 mW. However, when the pump power exceeded 350 mW, the Q-switched operation disappeared, because the SA was over bleached under the high pump power. As shown in the Fig. 5(a), with the pump from 50 to 350 mW, the repetition rate increasing from 53.42 to 217 kHz, while the single pulse duration decreasing from 1.7 to 0.63 μs. As shown in Fig. 5(b), the maximum single pulse energy was 47.9 nJ. Figs. 5(c) and 5(d) illustrated the maximum 3-dB bandwidth of 3 nm and the minimum pulse duration of 630 ns at the pump power of 250 mW.



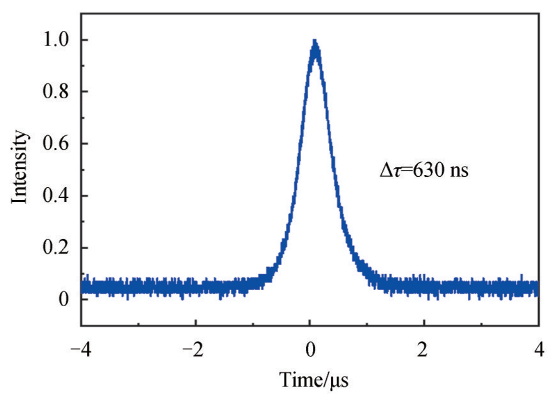
(a) Repetition rate and pulse duration under different pump power



(b) Output power and pulse energy under different pump power



(c) Optical spectrum



(d) Oscilloscope trace

Fig. 5 The characteristics of Q-switched pulse in Yb-doped fiber laser

We compare with the passively Q-switched YDFL performance based on different 2D materials. As Table 1 shows, our work achieved the shortest pulse width of 0.63 μs, highest pulse energy of 47.9 nJ.

Table 1 Comparison of passively Q-switched YDFL performance based on different 2D materials

SA	Q-Switched threshold/mW	Repetition rate/kHz	Min. pulse width/μs	Max. pulse energy/nJ	Wavelength/nm	Ref.
Fe_3O_4	80	25.9~73.4	3.4	38.8	1 049.8/1 053.3	[18]
MoS_2	211.2	6.4~28.9	5.8	31.1	1 066.5	[19]
Bi_2Te_3	114	35~77	1	38.3	1 056	[20]
WTe_2	110	19~79	1	28.3	1 044	[21]
Lu_2O_3	99	54.7~65.9	3.6	30	1 037	[22]
β-InSe	50	53.42~217	0.63	47.9	1 030	This Work

2.2 Mode-locked Ytterbium-doped fiber laser

No mode-locking phenomenon was observed when we increasing the pump power or adjusting the PCs. The possible reason was that the cavity loss was too large to obtained the mode-locking operation. Therefore, we increased the YDF length to 40 cm. Then check the loss of devices in the cavity, and changed the FC/APC fiber connector.

We removed the bandpass filter because the actual spectrum was much smaller than the bandwidth of the BPF. In addition, the total cavity length was adjusted to 18.5 m, corresponding to a net dispersion of 0.247 ps^2.

When the pump power increased to 210 mW and carefully adjusted the PC, stable passive mode-locking operation was obtained. Under the maximum pump power of 700 mW, stable mode-locking operation can still be obtained by slightly adjusting the PC. As shown in Fig. 6(a), the output power increased linearly with the increasing of pump power. The maximum output power was 51.2 mW, corresponding to a single-pulse energy of 4.7 nJ. The output power against pump power showed a slope efficiency of 8%. The spectrum and oscilloscope trace at 700 mW pump power was shown in Fig. 6(b) and Fig. 6(c), respectively. the 3 dB bandwidth was 1.2 nm. and the repetition rate was 10.82 MHz corresponding to the cavity length of 18.5 m. It was worth noting that under the condition of high pump power. Obvious pulse splitting can be observed in the oscilloscope by adjusted the tightness of PC. As shown in Fig. 6(d), the repetition rate of 34.48 MHz was not an integral multiple of the fundamental frequency. Therefore we can eliminated the possibility of harmonic mode locking operation. The stable single pulse mode-locking operation can be achieved again by return the PC to its previous state. This phenomenon can be explained as follow: Pulse splitting usually occured when the pump light was too strong or the single pulse energy was too large. Therefore, we can adjust the tightness of PC, which was equivalent to introducing some loss, to reduce the pulse energy and avoid the pulse splitting. However, the pulse duration of mode-locking pulse can not be obtained by using the autocorrelator (APE Pulse CheckUSB) in our laboratory, probably because the actual spectrum was relatively narrow. In addition, there was no dispersion compensation part in the cavity. A large number of positive chirps were accumulated in the

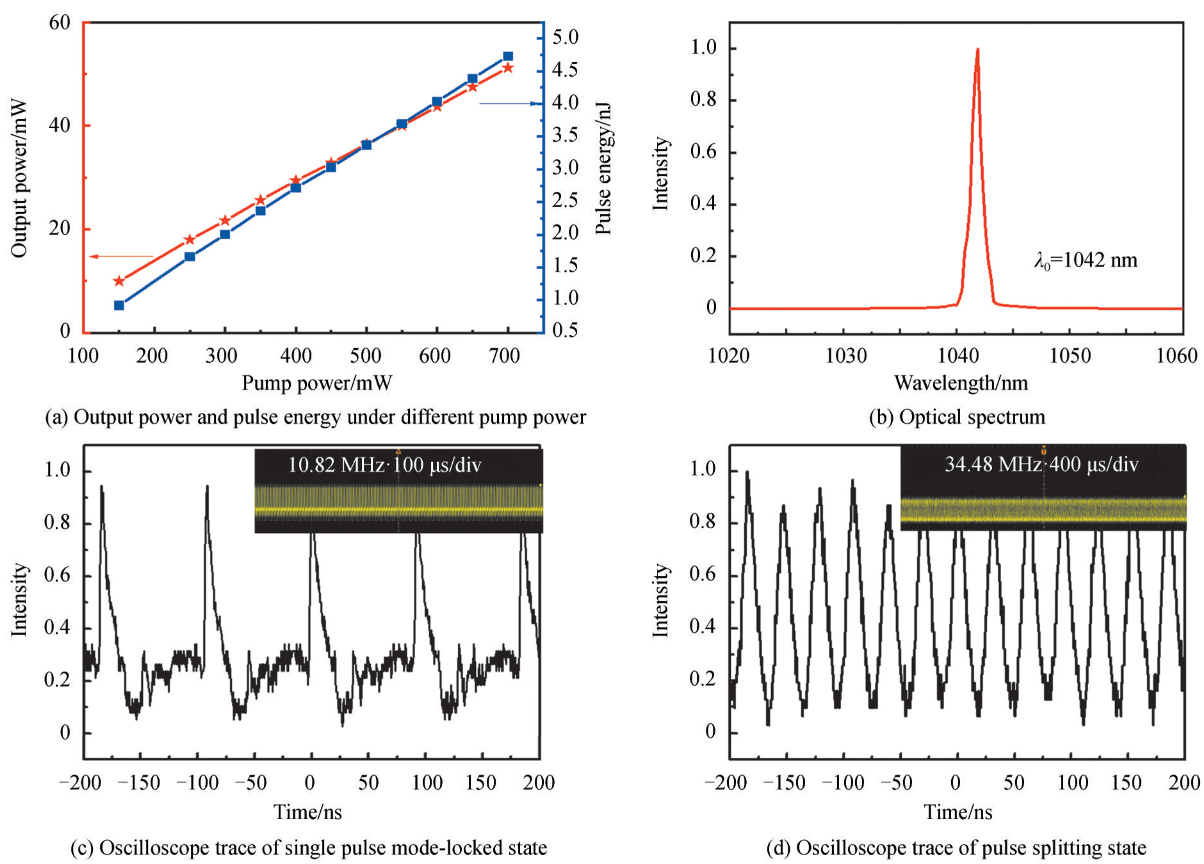


Fig. 6 The characteristics of Mode-locked pulse in Yb-doped fiber laser

cavity. Positive chirp would caused pulse broadening in time domain so that pulse duration of mode-locking pulse might exceeded the 50 ps maximum range of autocorrelator. Moreover, to further analyzed the stability of our YDFL system. We measured the function between time and the output power, which was shown in Fig. 7. The whole state was recorded for 24 h using a power meter. The calculated Root-Mean Square (RMS) is around 0.5% with mode-locked pump power of 550 mw and output power of 39.7 mW.

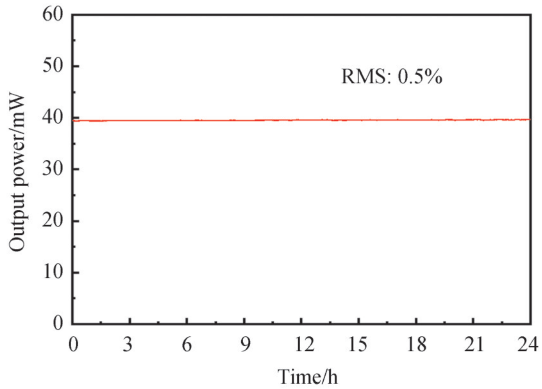


Fig. 7 The stability of mode-locked Yb-doped fiber laser

Table 2 shows the performance of previously reported passively mode-locked YDFLs based on different 2D materials as SAs. It can be clearly reflected that we obtained the highest output power of 51.2 mW, and highest pulse energy of ring laser cavity. Such laser with high output power is very promising for various applications such as fiber sensors, laser-machining, and many other industrial applications.

Table 2 Comparison of passively mode-locked YDFL performance based on different 2D materials

SA	Repetition rate/MHz	Max. pulse Output power/mW	Max. pulse energy/nJ	Wavelength/nm	Laser resonator	Ref.
Bi_2Se_3	44.6	33.7	0.756	1 031.7	Ring cavity	[23]
Sb_2Te_3	19.28	25.7	0.82	1 065.3	Ring cavity	[24]
MoS_2	6.58	9.3	1.41	1 054.3	Ring cavity	[25]
WSe_2	15.44	2	0.13	1 040	Ring cavity	[26]
SWCNT	27.3	3.47	0.13	1 030	Ring cavity	[27]
Bi_2Se_3	0.527	32.6	61.8	1 065	Linear cavity	[28]
β-InSe	10.82	51.2	4.7	1 042	Ring cavity	This work

3 Conclusion

In summary, we report Q-switched and mode-locked Yb-doped fiber laser based on β-InSe SA for the first time. The maximum pulse energy of Q-switched pulse was 47.9 nJ and the minimum pulse duration was 630 ns. Stable mode-locking operation was successfully achieved with maximum output power of 51.2 mW, corresponding to a single-pulse energy of 4.7 nJ. The output power and pulse energy can be further improved by using a higher power pump source. Due to laboratory equipment limited, the pulse duration was not measured yet. It can be solved by introducing dispersion management element to compensate the positive chirp. This work proved the feasibility and application value of using β-InSe as saturable absorber in Ytterbium doped fiber laser. The saturable absorption characteristics and ultrafast nonlinear optical applications in other near infrared bands are also investigated in the future work.

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