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Generation of High Peak Power Pulses With Controllable Repetition Rate in Doubly Q-Switched Laser With AOM/ $SnSe_2$

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By simultaneously employing self-made $SnSe_2$ saturable absorber (SA) and an acous-to-optic modulator (AOM), a dual-loss-modulated Q-switched Nd:YVO_4 laser with short pulse width, high peak power and adjustable pulse repetition rate is presented. The maximum pulse peak power of 37.57 KW with the minimum pulse duration of 5.52 ns were obtained under the pump power of 8 W and the pulse repetition rate of 5 kHz. The experimental results demonstrate that the dual-loss modulation technology with AOM and $SnSe_2$ SA is a simple and efficient method to generate short pulses with high peak power and adjustable low repetition rates.

Keywords: solid-state laser, dual-loss modulation, high peak power, $SnSe_2$ saturable absorber, controllable repetition rate

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1 INTRODUCTION

Stable solid-state pulsed laser sources with large pulse energy and peak power are used in a variety of applications, ranging from basic research to industrial material processing, medicine and telecommunications [1–3]. The use of a saturable absorber (SA) to generate pulsed lasers has been the most popular approach nowadays. In recent years, stimulated by the successful application of graphene, many two-dimension (2D) materials with layered structure have been rediscovered as promising and interesting SA materials due to their advantages of ultra-fast recovery time, broadband saturable absorption and simple fabrication process [4–7]. Tin diselenide ($SnSe_2$), an environmentally friendly and earth-abundant material, as a member of the 2D materials family, has gained wide attention in communications, microelectronics, lasers and nonlinear optical fields due to its unique properties, low toxicity and low cost [8, 9]. Because of the adjustable band gap characteristics, $SnSe_2$ has obvious broadband saturable absorption characteristics. The indirect band-gap of few layers and large bulk SnSe2 ranges from 1.07 (~1159 nm) to 1.69 eV(~734 nm), corresponding to the direct band-gap ranges from 1.84 to 2.04 eV, respectively [10]. The indirect band-gap of few layers $SnSe_2$ indicates the ability of the SnSe2 saturable absorber at 1 μm. The nonlinear optical property of multilayer $SnSe_2$ at 1 μm was first reported by Cheng et al in 2017, a passively Q-switched waveguide solid-state laser based on $SnSe_2$-SA was achieved with a minimum pulse width of 129 ns and pulse energy of 6.5 nJ [10]. In 2018, Zhang et al. reported a high power passively Q-switched Yb-doped fiber laser based on $SnSe_2$-SA [11]. So far, the nonlinear optical response of $SnSe_2$ has been widely studied by Q-switched or mode-locked lasers of different wavebands [12–15]. However, researches on pulse modulation characteristic of $SnSe_2$ in solid-state laser is not enough.

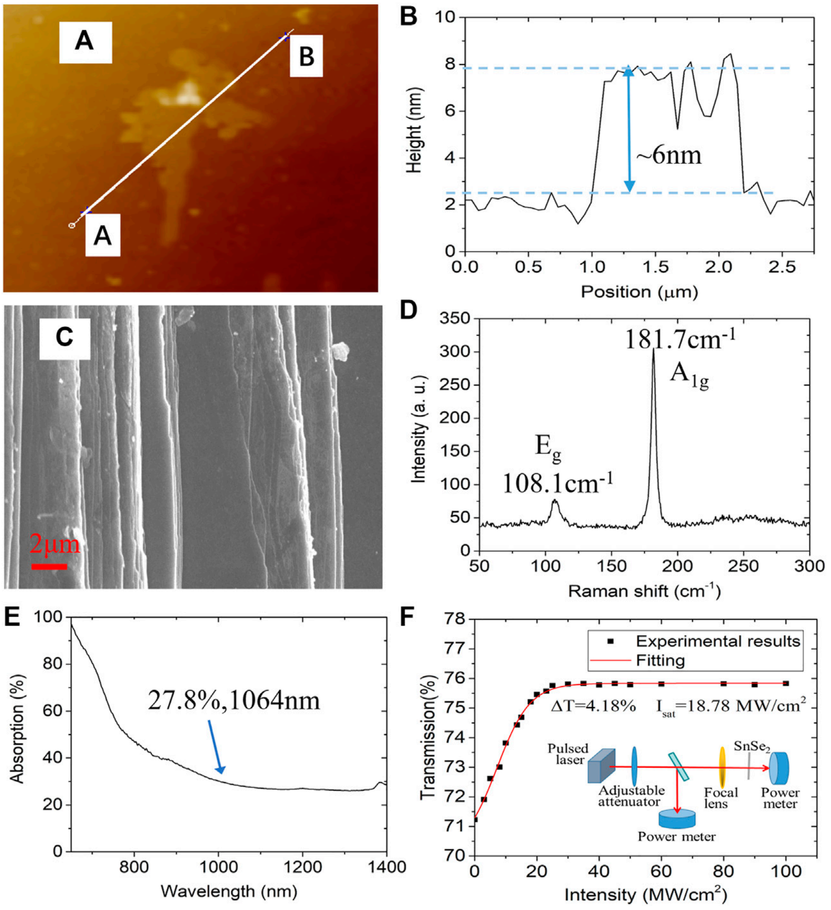

FIGURE 1 | (A) AFM image; **(B)** the corresponding heights of the AFM image; **(C)** SEM image; **(D)** Raman spectrum; **(E)** Absorption spectrum of the $SnSe_2$ film; **(F)** Nonlinear transmittance curve of the $SnSe_2$-SA.

As we know, using the dual-loss modulation mechanism, the poor stability and the difficult controllability of pulse characteristics in singly passively Q-switched lasers can be significantly improved [16–19]. Especially in the active-passively doubly Q-switched laser, the pulse duration can be compressed greatly to shorter than that of single passive modu-lated laser, while the pulse repetition rate can be controlled by the active modulator. Thus, pulses with high peak power, controllable repetition rate and excellent stability could be expected. However, there is no report on $SnSe_2$ for all-solid-state dual-loss modulation Q-switched lasers at 1.06 μm.

In this work, with our self-made $SnSe_2$-SA and an acous-to-optic modulator (AOM), a diode-pumped doubly Q-switched laser was presented. With the maximum pump power of 8 W and AOM repetition rate of 5 kHz, the maximum pulse peak power of 37.57 KW with minimum pulse duration of 5.52 ns were obtained. For comparison, the output performances of single passive Q-switched laser with $SnSe_2$-SA and single active Q-switched laser with AOM in our experiment were also investigated.

2 PREPARATION AND CHARACTERIZATION OF FEW-LAYERED SNSE$_2$-SA

The $SnSe_2$ nanosheet we used as SA was fabricated by the liquid-phase exfoliation method. 30 mg $SnSe_2$ powder and 10 ml absolute ethylalcohol were mixed in a centrifuge tube. After 12 h sonication process, the $SnSe_2$ dispersions used in our experiment can be obtained. In order to fabricate evenly distributed $SnSe_2$ film, the spin coating method was used to prepare $SnSe_2$ SA. 10 μl dispersions was absorbed by suction pipet and dripped onto a quartz plate with a size of 30 mm × 30 mm × 0.5 mm. The quartz substrate was placed in the center of a spinner with a speed of 300 rpm. Soon, the $SnSe_2$ dispersions on the substrate was dried and a high quality $SnSe_2$-SA was well prepared.

The flake thicknesses of $SnSe_2$ were measured via atomic force microscopy (AFM), which is shown in **Figure 1A**. The corresponding height profile, presented in **Figure 1B**, shows the average thickness of ~6 nm, corresponding to about ~10 layers [10].

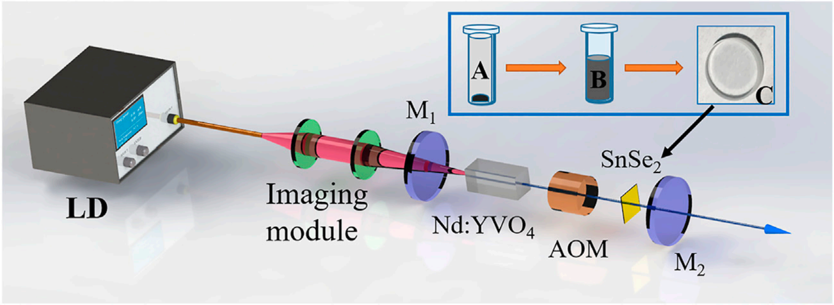

FIGURE 2 | Schematic of the doubly Q-switched laser with AOM and $SnSe_2$-SA.

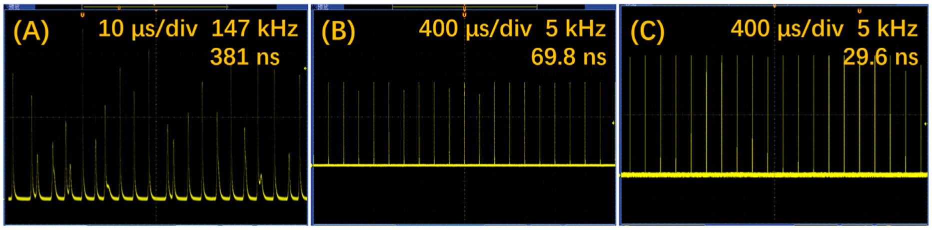

FIGURE 3 | Oscilloscope traces of the Q-switched pulse trains at the pump power of 2W: **(A)** single $SnSe_2$ SA Q-switching; **(B)** single AOM Q-switching; **(C)** double Q-switching.

The AFM is still not intuitive to observe the layered structure of the $SnSe_2$ SA. Therefore, the microstructures of $SnSe_2$ were recorded by a scanning electron microscope (SEM) with an optical resolution of 2 µm, shown in **Figure 1C**. From the figure, it can be found that well-layered structure of the $SnSe_2$ nanosheets were prepared in our work. The Raman spectrum was recorded and shown in **Figure 1D**, which demonstrated the atomic structural arrangement of the fabricated film. From the figure, the E_g mode and the A_{1g} mode can be observed and located at 108.1 cm^{-1} and 181.7 cm^{-1}, respectively. The linear absorption of $SnSe_2$ was measured by a Hitachi U-4100 spectrophotometer and shown in **Figure 1E**. One can see the $SnSe_2$ film possesses broadband absorption characteristics and the measured absorption of the $SnSe_2$ film was 27.8% at 1,064 nm. In order to confirm the saturable absorption capability of the $SnSe_2$-SA sample near 1 µm, the nonlinear transmission was measured and given in **Figure 1F**. By fitting the experimental data, the modulation depth and saturation intensity were determined to be 4.18% and 18.78 MW/cm^2, respectively.

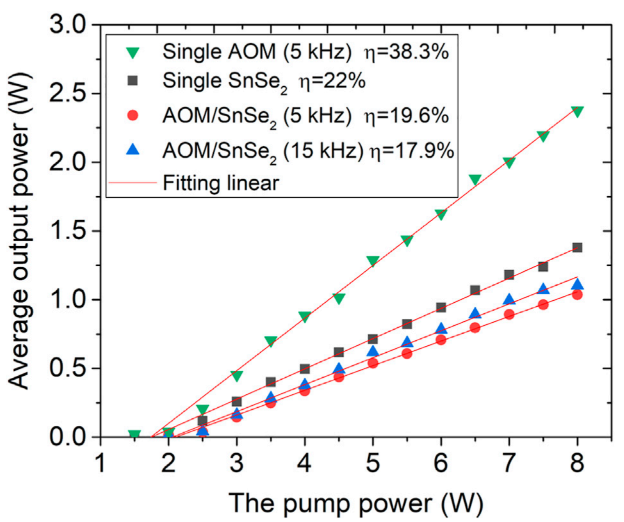

FIGURE 4 | Dependence of the average output power on the pump power for AOM singly, $SnSe_2$ singly and AOM/$SnSe_2$ doubly Q-switched lasers with different f_A.

3 EXPERIMENTAL SETUP AND RESULTS

3.1 Experimental Setup

The schematic of the doubly Q-switched laser with AOM and $SnSe_2$-SA was demonstrated in **Figure 2**. Mirrors M_1 and M_2, acting as the resonator mirrors, are both plane mirrors. M1, as the input mirror, is high antireflection (AR) coated at 808 nm and high-reflection (HR) coated at 1,064 nm. The transmittance of the output mirror M_2 is 15% at 1,064 nm. A 3 × 3 × 6 mm Nd:YVO_4 crystal, which is AR coated at 808 and 1,064 nm on both light-pass faces, is used as the laser medium with the Nd-doping concentration of 0.5 at. %. The laser is pumped by a commercial fiber-coupled diode laser at 808 nm with a 1:0.8 optical coupling system. An acousto-optic modulator (AOM) (GOOCH &

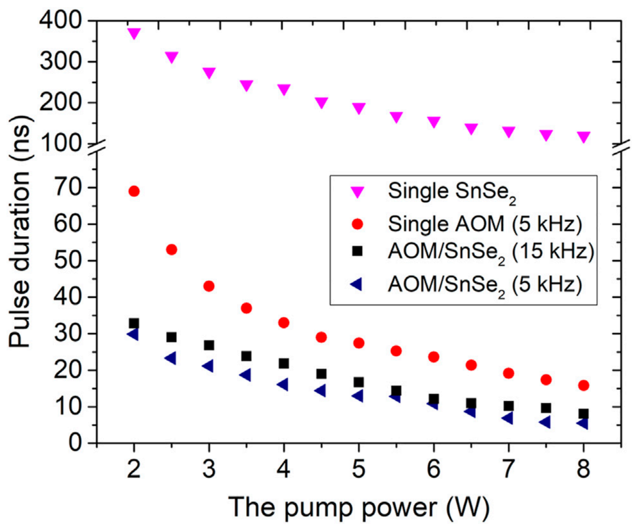

FIGURE 5 | Pulse duration versus pump power of $SnSe_2$ singly, AOM singly and AOM/$SnSe_2$ doubly Q-switched lasers with different f_A.

trains for the three kinds of lasers are shown in **Figure 3**. Obviously, the pulse stability of dual-loss-modulated laser was greatly improved.

The output performances of Nd:YVO_4 Q-switched laser with AOM/$SnSe_2$ and single $SnSe_2$ were all investigated, respectively. **Figure 4** shows the output powers versus the pump power for $SnSe_2$ singly, AOM singly and AOM/$SnSe_2$ doubly Q-switched lasers, respectively. With the increase of the pump power, the average output power increased linearly with slope efficiencies of 38.3%, 22%,19.6% and 17.9% for $SnSe_2$ singly, AOM singly (f_A = 5 kHz) and AOM/$SnSe_2$ doubly Q-switched lasers at f_A = 5 and 15kHz, respectively. For the singly actively Q-switched laser with AOM (f_A = 5 kHz) and singly passively Q-switched laser with $SnSe_2$, the maximum output power of 2.38 and 1.38 W were obtained at the pump power of 8W, respectively. Because of the higher insertion loss, the output power of dual-loss-modulated laser with AOM/$SnSe_2$ was smaller than that of single modulated laser. At the pump power of 8W, the maximum output power of 1.03 and 1.1 W were obtained for f_A = 5 and 15kHz, respectively. A larger modulation frequency is conducive to get a higher output power.

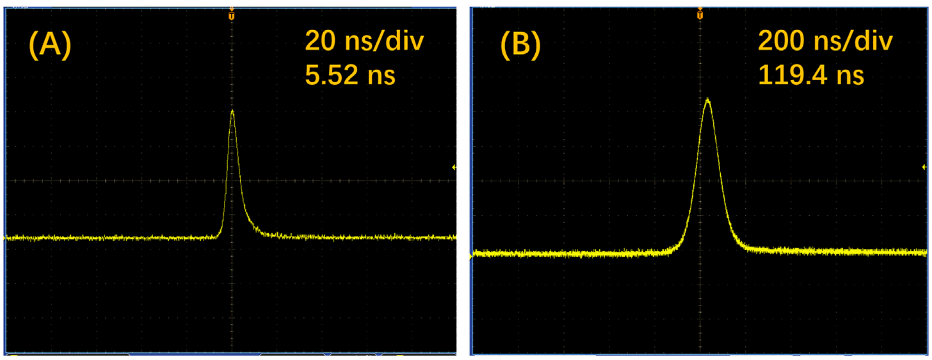

FIGURE 6 | The temporal profiles of Q-switching pulses at the pump power of 8 W: **(A)** double Q-switching; **(B)** single $SnSe_2$ SA Q-switching.

HOUSEG) is employed as the active modulator. The total cavity length is about 13.5 cm, which refers to the distance between M_1 and M_2.

3.2 Experimental Results and Discussion

Firstly, for comparison, the output performance of Nd:YVO_4 singly actively Q-switched laser with AOM was investigated. Then, add the $SnSe_2$-SA into the cavity, the dual-loss-modulated Q-switched laser with AOM and $SnSe_2$-SA can be obtained. In this doubly Q-switched laser, the repetition rate of the Q-switched pulses mainly depends on the modulation frequency (f_A) of AOM. In order to study the influence of different modulation frequencies on pulse characteristics, the doubly Q-switched laser performances at f_A = 5 and 15 kHz were recorded, respectively. If the AOM is off, the laser operated in the singly passively Q-switched state, in which the Q-switched pulse repetition rates varied with the pump power. The oscilloscope traces of the Q-switched pulse

The variation of the pulse duration versus the pump power is shown in **Figure 5**. For Q-switched lasers with single AOM (f_A = 5 kHz) and single $SnSe_2$, the shortest pulse durations of 15.8 and 119.4 ns were obtained at the pump power of 8 W, respectively. Here, the pulse durations we obtained are the shortest one ever reported in passively Q-switched lasers with $SnSe_2$ SA [10, 14, 20–23]. To the best of our knowledge, in near-infrared region, the shortest pulse durations of 129 ns was achieved in a passively Q-switched Nd:YAG waveguide laser with $SnSe_2$ SA [10].

For the doubly Q-switched lasers with AOM/$SnSe_2$, the pulse width was much smaller than that of singly Q-switched lasers. The shortest pulse durations of 5.52 and 8.1 ns were obtained at f_A = 5 and 15 kHz, respectively. Obviously, a lower repetition rate can bring about a shorter pulse duration. The maximum compression ratio calculated from **Figure 5** is approximated to 95.4% from 119.4 ns (in $SnSe_2$ Q-switched lasers) to 5.52 ns (in

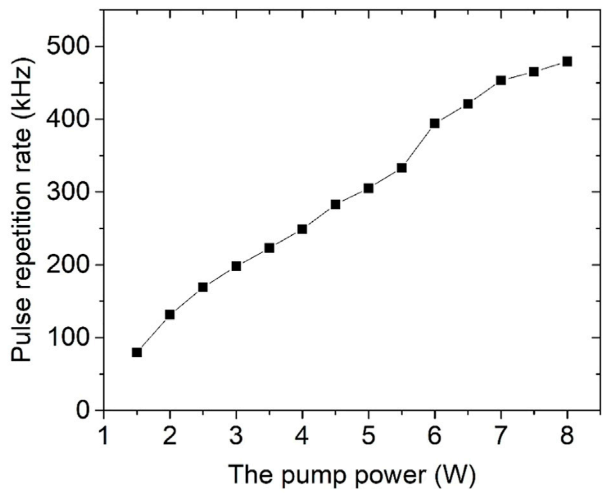

FIGURE 7 | Pulse repetition rate versus the pump power for $SnSe_2$ singly Q-switched laser.

8 W, 2.8, 475.2, 207.4, and 81.7 μJ pulses energies were achieved for $SnSe_2$ singly, AOM singly (f_A = 5 kHz) and AOM/$SnSe_2$ doubly Q-switched lasers at f_A = 5 and 15kHz, respectively, corresponding to the peak power of 0.247, 30.1, 37.6, and 10.1 W. The pulse energy of AOM/$SnSe_2$ doubly Q-switched laser (f_A = 5 kHz) was 74 times higher than that of $SnSe_2$ singly Q-switched laser. Because of the pulse compression and pulse energy improvement in doubly Q-switched laser, compared with the singly Q-switched laser with $SnSe_2$, the pulse peak power of doubly Q-switched laser with AOM/$SnSe_2$ (f_A = 5 kHz) was basically raised 152 times.

Considering the degradation of optical parameters of $SnSe_2$-SA, in order to check the robustness of $SnSe_2$-SA, the doubly Q-switched laser with AOM and $SnSe_2$-SA was kept operating at the maximum radiation power for at least 6 h every day during 1 week. The fluctuation of the average output power ΔP is measured less than 4.1% at the pump power of 8 W. Besides, no damage and optical degradation of the $SnSe_2$-SA was observed in the experiment.

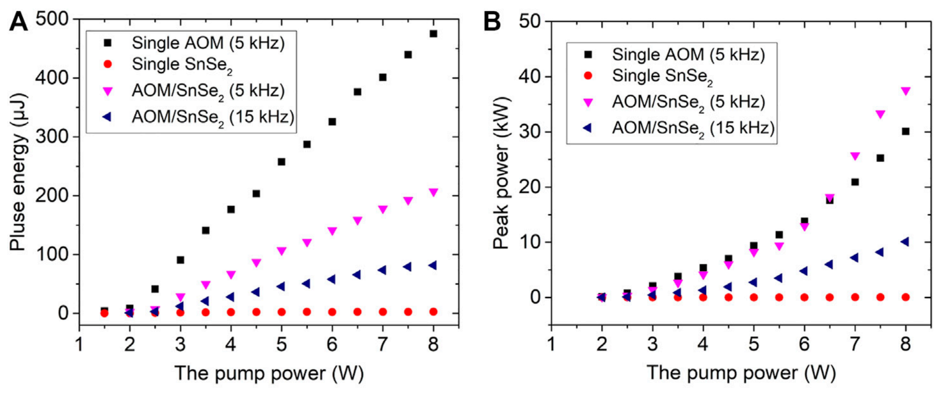

FIGURE 8 | (A) Pulse energy and **(B)** pulse peak power versus pump power of $SnSe_2$ singly, AOM singly and AOM/$SnSe_2$ doubly Q-switched lasers with different f_A.

AOM/$SnSe_2$ Q-switched laser), at 8 W maximum pump powerand f_A = 5 kHz. The typically extended temporal profiles of Q-switching pulses at the pump power of 8 W was illustrated in **Figure 6**. As a solid state laser with free space configuration, the beam quality was measured by the 90.0/10.0 scanning-knife-edge method, the beam quality factors (M^2) in the horizontal and longitudinal planes are 1.68/1.38.

The pulse repetition rate versus the pump power for $SnSe_2$ singly Q-switched laser was given in **Figure 7**. The pulse repetition rates varied from 79.6 to 479 kHz within the pump range of 1.5–8 W. The dependences of pulse energies and peak powers on the pump power are depicted in **Figure 8**. Both pulse energies and peak powers increase monotonically with the increasing of the pump power. Under the maximum pump power of

4 CONCLUSION

In conclusion, based on the AOM and $SnSe_2$ film, a diode-pumped doubly Q-switched laser with high peak power and adjustable repetition rate was presented. The experimental results show the relations of the pulse width, pulse energy and pulse peak power of the Q-switched pulses versus the repetition rate of AOM and the pump power. In our experiment, the maximum pulse peak power of 37.57 KW with minimum pulse duration of 5.52 ns was obtained with the maximum pump power of 8 W and AOM repetition rate of 5 kHz. A lower repetition rate is conducive to obtaining pulses with high peak power. Compared with the singly passively Q–switched lasers with $SnSe_2$-SA, the pulse characteristics of this doubly Q–switched laser were improved significantly. The experimental results demonstrate that the dual-loss modulation technology is an effective method to compress the pulse width and obtain the pulses with controllable repetition rate and high peak power.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

JX conceived and designed the experiments, performed the experiments and analysed the data, drafted the manuscript; XD fabricated and characterized the $SnSe_2$ saturable absorber; HY contributed to perform the theoretical analysis, all authors contributed to writing and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.