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基于二硫化钨可饱和吸收体双波长被动调 Q Yb∶$GdYSiO_5$激光器

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摘　要:基于新型可饱和吸收体二硫化钨在 Yb∶$GdYSiO_5$晶体中实现了双波长调 Q 激光的输出.将二硫化钨纳米薄片溶液涂覆在具有高反射率的 BK7 玻璃基底上,制成二硫化钨可饱和吸收镜用于启动调 Q.采用光纤耦合输出的二极管激光器作为泵浦源,其发射激光的中心波长约为 976 nm.通过调节谐振腔以及选择合适的泵浦功率,在波长为 1 051 nm 和 1 091 nm 附近同时实现了稳定调 Q 激光输出.调 Q 激光脉冲宽度为 8.4 μs,重复频率为 2.9 kHz,平均输出功率为 125 mW.

关键词:被动调 Q;二硫化钨可饱和吸收体;Yb∶$GdYSiO_5$晶体;激光二极管泵浦;双波长

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Dual-wavelength Passively Q-switched Yb∶$GdYSiO_5$ Laser Based on WS_2 Saturable Absorber Mirror

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Abstract: A dual-wavelength passively Q-switched Yb∶$GdYSiO_5$ laser based on a WS_2 saturable absorber mirror was proposed. The WS_2 nanoplatelets solution was coated on a BK7 glass substrate with high-reflective-index thin polymer to be a WS_2 saturable absorber mirror for starting Q-switching operation. By tuning the resonant cavity and selecting a suitable pumping power, the stable Q-switched laser pulses at 1051 nm and 1091 nm were simultaneously generated with a 976-nm fiber-coupled diode laser as pump source. The laser pulses had a pulse duration of 8.4 μs, a repetition rate of 2.9 kHz, and an average output power of 125 mW, respectively.

Key words: Passive Q-switching; Tungsten disulfide saturable absorber; Yb∶$GdYSiO_5$ crystal; Diode-pumped; Dual-wavelength

OCIS Codes: 140.3540; 140.3580; 140.3615; 140.3380

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0 Introduction

As pulse lasers occupy some unique advantages of short pulse width, high peak power, and high pulse energy, they have been widely applied in many areas, such as nonlinear optics, spectroscopy, biomedical diagnoses, and material processing[1-2]. Therefore, how to achieve pulse lasers for different application requirements has always been a research hotspot. Passively Q-switching and mode-locking based on various saturable absorbers are two of important methods to achieve pulse lasers with different orders of magnitude pulse widths. Among all kinds of saturable absorbers, there are some outstanding representatives, such as transition elements-doped host materials, Semiconductor Saturable Absorber Mirrors (SESAMs)[3], and two-dimensional (2D) nanomaterials. Cr^{4+} : YAG is one important saturable absorber of transition elements-doped host materials and widely applied in Q-switched solid-state lasers or fiber lasers for generating picosecond to microsecond laser pulses[4-7]. In order to obtain shorter laser pulses, SESAMs were developed and extensively employed as saturable absorbers in mode-locked lasers for generating femtosecond to picosecond laser pulses[8]. However, SESAMs have some limitations because of their narrow wavelength absorption band, expensive cost and complex fabrication. In recent years, the single layer or few layers graphene[9], a typical representative of 2D nanomaterials, came out and was successfully applied in the generation of pulse lasers due to their unique characteristics including broadband optical modulation, strong absorption, fast relaxation, and easy fabrication. The appearance of graphene opens up a door to new 2D layered nanomaterials with excellent optical and electrical performances. The researchers have developed a series of new 2D layered materials, such as graphene oxide[10], Carbon Nanotube (CNT)[11], Black Phosphorus (BP)[12], Topological Insulators (TIs)[13], Transition Metal Dichalcogenides (TMDs)[14]. Among above saturable absorbers based on 2D layered materials, the family of TMDs, consisting of molybdenum disulfide (MoS_2), molybdenum diselenide ($MoSe_2$), tungsten disulfide (WS_2), and tungsten diselenide (WSe_2), have drawn widespread attention because of their excellent properties introduced by their sizable bandgaps in nature. Recently, there have been a great deal of research on WS_2 as a saturable absorber for generating laser pulses. 2015, MAO Dong et al. successfully demonstrated a WS_2 mode-locked Er fiber laser for the first time, generating laser pulses at 1.557 μm with a duration of 1.32 ps[15]. Since then, WS_2 was adopted in various fiber pulse lasers. For example, LIN Jian et al. firstly demonstrated a wavelength-tunable Yb-doped passively Q-switching fiber laser based on WS_2[16]. 2016, LI Wen-song et al. reported a Pr^{3+}-doped all-fiber Q-switched lasers with transition metal dichalcogenides including WS_2[17]. In addition, WS_2 was also used in all solid-state pulse lasers for generating laser pulses with wavelength ranging from 0.6 μm to 3.0 μm. For example, laser pulses at 0.64 μm with a width of 630 ns were obtained from a Q-switched Pr : $LiYF_4$ laser based on WS_2[18]. Laser pulses around 1 μm were achieved from Nd : $GdY_2Sc_2Ga_3O_{12}$ Q-switched laser by using WS_2[19]. 2016, LUAN Chao et al. demonstrated a Q-switched Tm : LuAG laser by using WS_2, generating 2 μm, 660 ns laser pulses[20]. Recently, 2.95 μm laser pulses have been achieved from a Q-switched Ho,Pr : $LiLuF_4$ laser with WS_2[21]. Above these researches have proved that WS_2 was a successful saturable absorber in pulse lasers.

Around 1 μm laser area, Yb^{3+}-doped laser materials have been recognized as great candidates for generating laser pulse. On one hand, Yb^{3+} ion has a very simple electronic energy level structure composed of only two manifolds (the ground state $^2F_{7/2}$ and the excited state $^2F_{5/2}$), which leads to very small quantum defect and absence of undesirable effects such as upconversion, excited-state absorption, cross relaxation, and concentration quenching. On the other hand, the absorption peaks of Yb^{3+}-doped materials are in the range from 900 nm to 980 nm, which matches well with the emission bands of commercial high-brightness InGaAs diode lasers. Combination with WS_2 saturable absorbers and Yb^{3+}-doped materials, there have been several reports on the generation of laser pulses. For example, Yb : Lu_2SiO_5, Yb : $GdAl(BO_3)_4$, and Yb:YAG based on a WS_2 saturable absorber have been achieved laser pulses[22-24]. It is worth noting that the WS_2 saturable absorbers based solid-sate pulse lasers is relatively difficult than the WS_2 saturable absorbers based fiber pulse lasers, which may be due to the large modulation depth and unsaturated loss of WS_2 saturable absorbers. Among Yb^{3+}-doped laser materials, Yb:GYSO is also an excellent laser material and possesses a series of advantages, such as the $^2F_{7/2}$ ground state′s splitting of

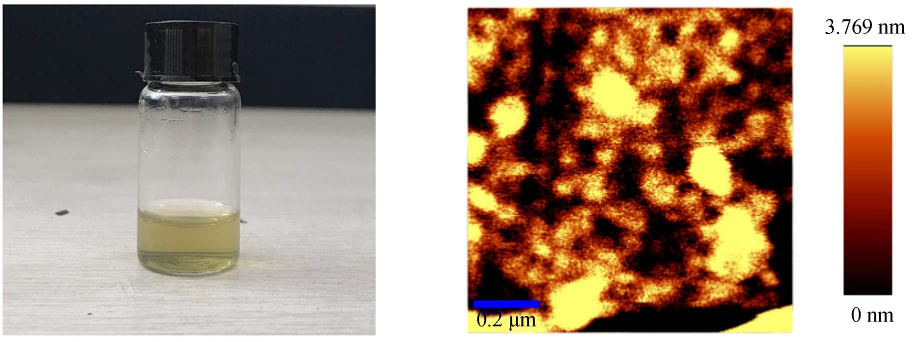
995 cm^{-1}, the fluorescence lifetime of 1.92 ms, good thermo-optical properties and so on. Up to now, the laser pulses from Yb∶GYSO by assisting of SESAMs or Kerr-lens mode-locking have been demonstrated[25-27], however, there is few report on Yb∶GYSO based on WS_2 saturable absorbers generating laser pulses.

In this work, we demonstrated a passively Q-switched Yb∶GYSO laser by using a WS_2 saturable absorber mirror. Both single-wavelength and dual-wavelength Q-switched laser operation were observed. Under single-wavelength Q-switched operation, laser pulses with shorted width of 5.8 μs at wavelength of 1 048 nm were obtained. The maximum laser pulse energy and peak power were about 14.7 μJ and 2.5 W, respectively. Under dual-wavelength Q-switched operation, laser pulses operated at wavelength of 1 051 nm and 1 091 nm simultaneously with a pulse duration of 8.4 μs and a repetition rate of 2.9 kHz.

1 Experimental setup

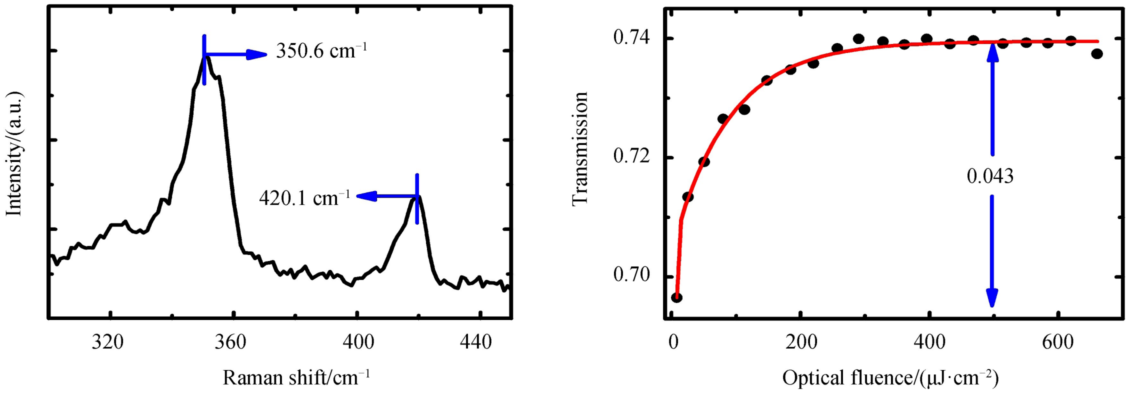
1.1 Preparation and characterization of a WS_2 saturable absorber mirror

In order to fabricate a WS_2 saturable absorber mirror, we first prepared WS_2 nanoplatelets solution by using a liquid exfoliation method. We added WS_2 powder with a purity of 99.99% into a volume ratio of 1∶1 ethanol and water. Then, the mixed solution was agitated by ultrasound for about 200 min, and centrifuged at 3000 r/min for about 10 min to generate WS_2 nanoplatelets solution. Previously relevant experiment shows that such a WS_2 solution has high transmittance in the range from 800 nm to 1 100 nm[28]. Fig.1 shows the photo and Atomic Force Microscope (AFM) image of WS_2 nanoplatelets solution. As shown in Fig.2(a), we tested the Raman spectrum of WS_2 nanoplatelets sample by using a Confocal Raman Microscopy (WITEC alpha300R), where the used geometric mode was back scattering. From this diagram, it can be observed that there are two characteristic peaks E_{2g} and A_{1g} at 350.6 cm^{-1} and 420.1 cm^{-1}, which are consistent with Ref. [15]. The nonlinear transmission curve of WS_2 sample was measured by using a near - field Z - scan method , shown as Fig.2(b). In this experiment , we used a pulsed



(a) Photo (b) AFM scan image

Fig.1 The photo and AFM scan image of WS_2 nanoplatelets



(a) Raman spectrum (b) Nonlinear transmission curve

Fig.2 Measured raman spectrum of WS_2 nanoplatelets as a function of raman shift and the nonlinear transmission curve of WS_2 nanoplatelets as a function of optical fluence at room temperature laser with a pulse width of 4 ps, a wavelength at 1 035 nm, and a repetition rate of 70 MHz, as a laser source. The saturable optical intensity and modulation depth of WS_2 nanoplatelets sample are about 328 $\mu J/cm^2$ and 4.3%, respectively. For easy operation in solid-state lasers, the WS_2 nanoplatelets solution with polyvinyl alcohol was coated on a BK7 glass substrate, where the average thickness of WS_2 layer was about a few nanometers and the BK7 glass substrate had a high-reflective-index thin polymer of 99% at about 1 030 nm with a bandwidth of about 60 nm. After implementing above processes, a WS_2 saturable absorber mirror was completed and can be applied to subsequent Q-switching laser experiment. It should be pointed out that the WS_2 saturable absorber mirror possesses both saturable absorber and high reflected mirror, which may simplify passively Q-switched laser system.

1.2 Experimental setup of Q-switching operation

In this work, the used Yb∶GYSO crystal with 5 at.% Yb concentration is provided by the Shanghai Institute of Optics and Fine Mechanics of CAS, and its absorption and emission spectra can be found in Ref.[29]. The Yb:GYSO crystal sample is with a thickness of 3 mm and an aperture of 6 mm×5 mm. As shown in Ref.[29], the absorption bandwidth of Yb∶GYSO crystal was from 880 nm to 1 040 nm with main absorption peaks at 900, 918, 950 and 976 nm. The highest peak at 976 nm belongs to zero phonon line of Yb^{3+} and is highly suitable for diode pumping at room temperature. The main fluorescence peaks include four bands around 1 004, 1 039, 1 056, and 1 080 nm and the emission intensities of these fluorescence bands decrease in turn. By combing the absorption and emission spectra of Yb∶GYSO crystal[29], it is easily understand that the laser outputs at emission bands around 1 004 nm and 1 039 nm are relatively difficult to achieve due to the strong reabsorption losses, and the simultaneous generation at emission bands around 1 056 nm and 1 080 nm is possible. In fact, the efficient laser at emission band around 1 080 nm is most easily to achieve because of few-populated terminal laser level. Fig.3 shows the schematically experimental setup of Q-switched Yb∶GYSO laser. A 7 W, 976 nm high-brightness fiber-coupled diode laser (Jenoptik, JOLD-7.5-BAFC-105) was used as the pump source. The numerical aperture of fiber core was 0.22 and the diameter of fiber core was 50 μm. The pump output from fiber was reimaged into the Yb∶GYSO crystal by a telescope with magnification of 1∶0.8. The focusing beam diameter in the crystal was estimated to be about 40 μm. To reduce the heat, the Yb∶GYSO crystal was wrapped with indium foil and mounted on a water-cooled copper kept at about 14℃. M_1 was a dichroic mirror with high transmission at 976 nm and high reflection at about 1 020~1 100 nm. M_2 was a concave mirror with a Radius Of Curvature (ROC) of 200 mm and high reflection at about 1 000~1 100 nm. M_4 was a WS_2 saturable absorber mirror. In order to realize Q-switching operation, a concave mirror with ROC of 300 mm (M_3) and high reflection at about 1 000~1 100 nm was used to focus the laser on the WS_2. On one hand, the WS_2 mirror had a transmission of about 0.7% due to that the transmission of WS_2 solution was between 70 and 74% and the BK7 glass substrate had a high-reflective-index of 99%, and then the laser output from the WS_2 mirror was too small. On the other hand, the laser output from the WS_2 mirror is divergent since the WS_2 mirror is located at the focus point of M_3. As a result, a plane Output Coupler (OC) mirror with a transmission of 1.5% at about 1 020~1 100 nm was used in this experiment. Based on above design and ABCD matrix calculation[30], the laser beam diameter in Yb:GYSO crystal and WS_2 was calculated to be about 58.8 μm and 89.8 μm, respectively. The folding angles of the mirrors in cavity were less than 10°, which were mainly limited by the distances and sizes of the mirrors.

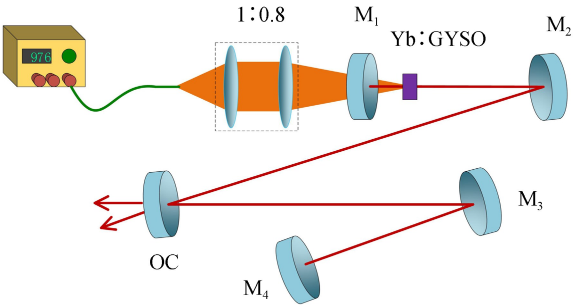


Fig.3 Experimental setup of the Q-switched Yb∶GYSO laser

2 Experimental results and discussion

At first，a High Reflection (HR) mirror was set at the position of M_4. Under this condition，we adjusted the cavity to obtain continuous-wave laser. The threshold pump power was about 0.9 W. When the pump power was up to 6.0 W，the maximum average output power of about 1.53 W can be obtained. The corresponding light-to-light efficiency and slope efficiency were about 25.5% and 33.4%，respectively. Next，we used a WS_2 saturable absorber mirror to replace the HR mirror. Experiments show that single- or dual-wavelength Q-switching operations can be achieved by finely adjusting the position of WS_2 saturable absorber mirror . As the pump power was increased，the Q-switching operation came out. The threshold pump power of Q-switched laser was about 2.0 W. The relationship between the average output power and pump power under continuous-wave and Q-switched operations was shown as Fig.4，where the continuous-wave，single-wavelength Q-switched，and dual-wavelength Q-switched laser operated at about 1 091 nm，1 048 nm，and 1 051 & 1 091 nm，respectively. For single-wavelength Q-switched operation，when the pump power was in the range of 2.0 W to 3.5 W，the stable single-wavelength Q-switched laser pulses were obtained. The maximum output power of single Q-switched laser was about 206 mW. The corresponding light-to-light efficiency and slope efficiency were about 5.9% and 10.2%，respectively. If the pump power was beyond 3.5 W，the WS_2 sample would be damaged. Therefore，the low damage threshold of WS_2 sample limited the output power of Q-switched laser. As for dual-wavelength Q-switched operation，under the pump power with the small range of 2.0 W to 2.4 W，the dual-wavelength Q-switched would be occurred and the output power was always about 125 mW with a light- to-light efficiency of 6.25%. Based on above investigations，we can conclude that the cavity loss is the largest under single-wavelength Q-switching operation，which may be due to that the gain of Yb：GYSO crystal under lasing operation are related to wavelengths and the loss of WS_2 are related to the laser intensity. In addition，both single-wavelength and dual-wavelength Q-switched lasers are very stable and can be self-started. By using a commercial beam profiler (Beam Analyzer USB，Duma Optics)，we measured the beam profiles of Q-switched lasers shown in Fig.5，which shows that both single-wavelength Q-switched laser and dual-wavelength Q-switched laser run in fundamental mode with near diffraction-limited beam quality.

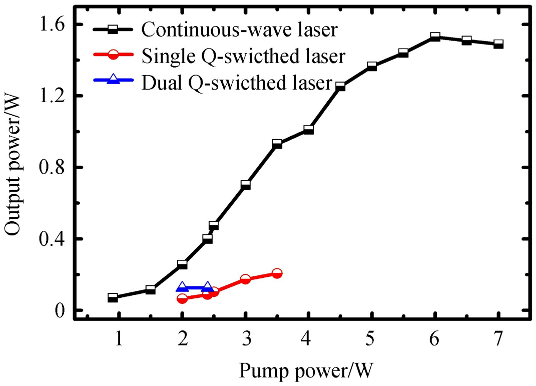
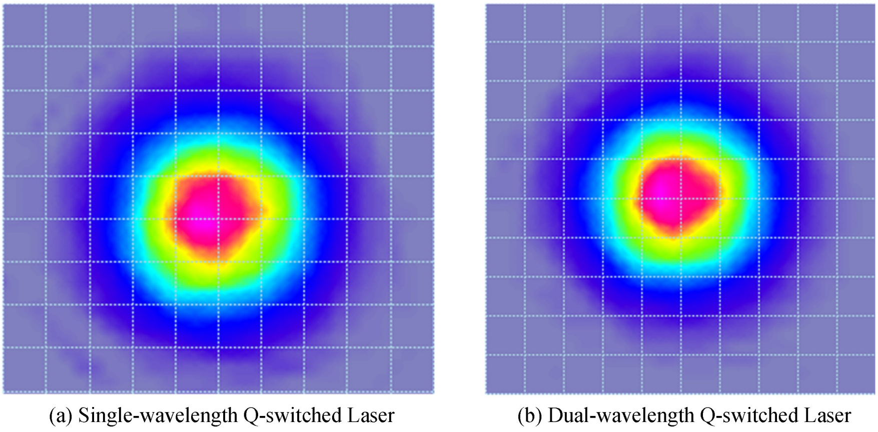


Fig.4 The average output power as a function of pump power under continuous-wave and Q-switched operations

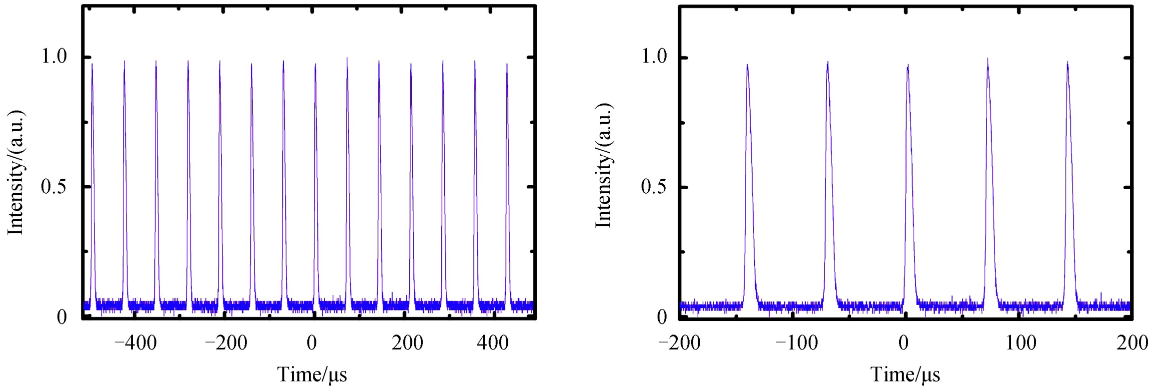


(a) Single-wavelength Q-switched Laser (b) Dual-wavelength Q-switched Laser

Fig.5 The beam profiles of Q-switched laser after OC

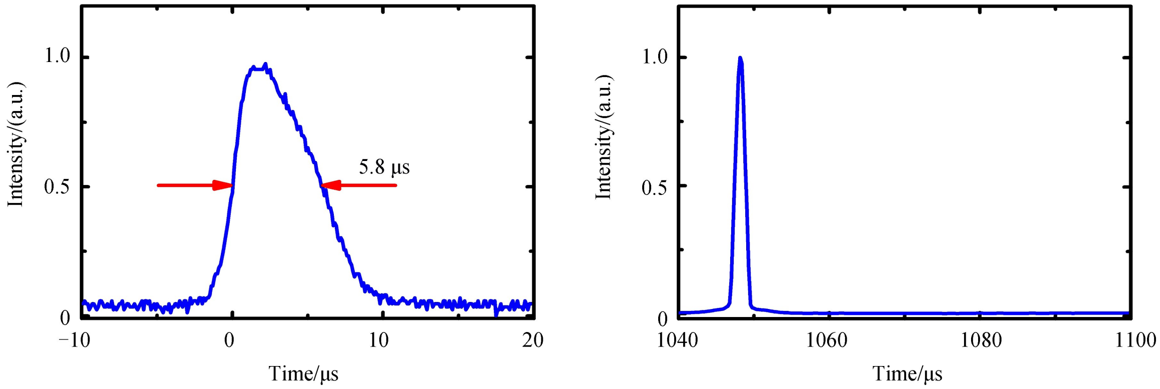
During following test experiment，we used a fast photodiode and a digital phosphor oscilloscope (Tektronix DOP 3052) to detect and record the Q-switched pulse trains. Meanwhile，the corresponding spectrum of the pulses trains was measured by using an optical spectrum analyzer (Ocean Optics, HR2000+).

The single-wavelength pulses trains under different time scale were shown as Fig.6(a) and 6(b).



(a) Typical pulse train

(b) Typical pulse train



(c) Pulse duration

(d) Optical spectrum

Fig.6 Typical pulse train with different time scales, pulse duration of the shortest pulse, and the corresponding optical spectrum under single-wavelength Q-switching operation

According to these graphs of pulses trains, we can see that there was no multi-pulses and the single-wavelength Q-switched laser was relatively stable. When the pump power was up to 3.5 W, the shortest pulses duration was measured to be about 5.8 μs at the central wavelength of 1 048 nm, and the according results are presented in Fig. 6(c) and 6(d). Fig.7 shows the pulses repetition rates and durations varied with the pump power. As the pump power was increased from 2.0 W to 3.5 W, the pulses repetitions was from 7.0 kHz to 14.0 kHz, and the corresponding pulses widths were from 9.1 μs to 5.8 μs. When the pump power was up to about 3.5 W, the shortest pulses at the central wavelength of 1 048 nm were obtained. The maximum laser pulses energy and peak power were calculated to be 14.7 μJ and 2.5 W, respectively.

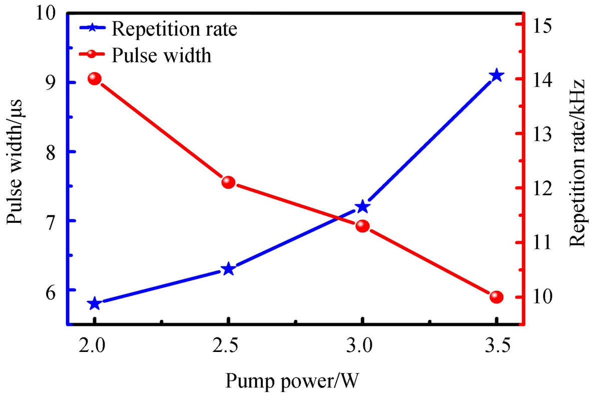
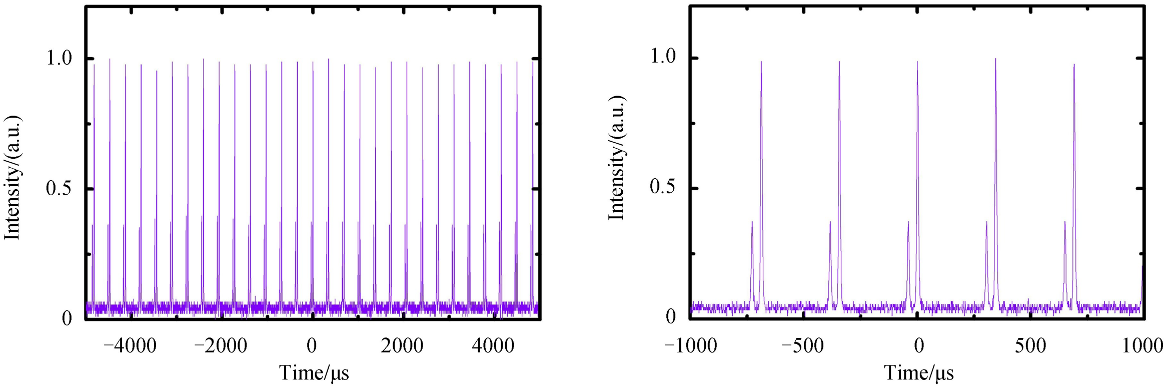


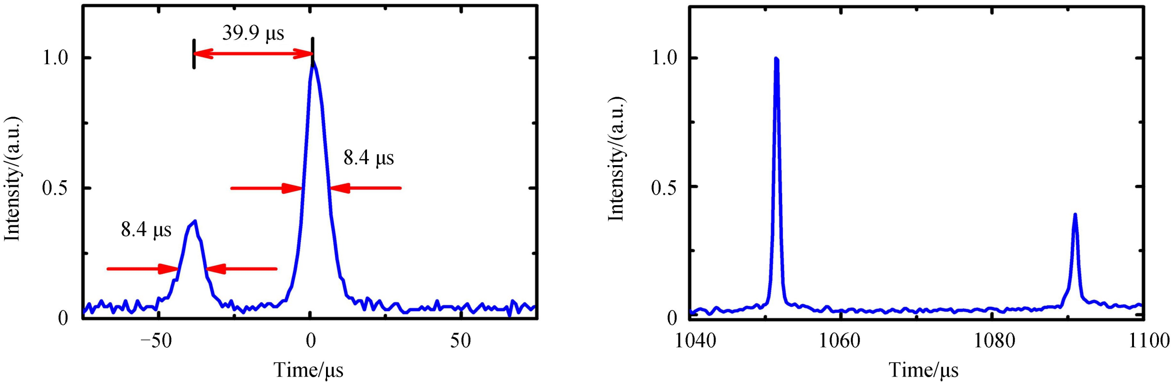
Fig.7 Dependence of pulse repetition rate and pulse width on pump power under single-wavelength Q-switching operation

Fig.8 shows the pulses trains, profile, spectrum of dual-wavelength Q-switched Yb∶GYSO laser. We used a digital phosphor oscilloscope and a spectrometer to observe the pulses trains and spectrum, simultaneously. Under the single-wavelength Q-switched operation pumped at about 2.0 W, we adjusted the position of WS_2 and the single-wavelength Q-switched pulses trains would be changed, which were shown as Fig.8(a) and 8(b). At the same time, the corresponding spectrum was from single wavelength (1 048 nm) to double wavelength (1 051 nm and 1 091 nm). It should be pointed out that laser wavelengths at 1 048 nm and 1 051 nm are both belong to the emission band around 1 056 nm, and the phenomenon that 1 048 nm laser at single-wavelength operation is red-shifted to 1 051 nm laser at dual-wavelength operation may be due to the incident power density variation induced by adjusting the position of WS$_2$ mirror. Once the laser is operating at dual-wavelength Q-switched state, this state is very stable and cannot change back to the single-wavelength Q-switched operation unless adjusting the position of WS$_2$ mirror. The dual-wavelength Q-switched laser was only obtained with the range of 2 W to 2.4 W pump power. Within the range of pump power, the pulses duration of double wavelengths was about 8.4 μs. The corresponding pulses profile and spectrum of dual-wavelength Q-switched laser were shown as Fig.8(c) and 8(d). In Fig.8(c), the lower pulse was at 1091 nm and the higher pulse was at 1 051 nm, and their power ratio approximately remained to be 1 : 3 within the range of pump power. The laser pulses repetition rate remained about 2.9 kHz.



(a) Typical pulse train

(b) Typical pulse train



(c) Pulse duration

(d) Optical spectrum

Fig.8 Typical pulse train with different time scales, pulse duration, and the corresponding optical spectrum under dual-wavelength Q-switching operation

The single-wavelength operation is easily understood. As for the dual-wavelength operation in this work, the reason may be as follows. As we know, a laser will oscillate at a wavelength whose net gain is the highest, where the net gain is that the gain of laser medium minuses the laser losses. On one hand, as mentioned above, the Yb : GYSO crystal possesses four emission peaks within 1 000～1 100 nm, where these peaks usually vary with pump. On the other hand, the laser losses in this system include medium, mirrors and WS$_2$, where the loss of WS$_2$ is further related to laser power density. Based on above two factors, under certain operation conditions, two peaks may simultaneously reach the threshold and then result in dual-wavelength operation.

3 Conclusion

We demonstrated a passively Q-switched Yb:GYSO laser based on a WS$_2$ saturable absorber mirror. The single-wavelength Q-switched laser has a central wavelength of 1 048 nm with pulse width of 9.1 μs to 5.8 μs and a repetition rate of 7.0 kHz to 14.0 kHz. The maximum output power and pulse energy were about 206 mW and 14.7 μJ, respectively. Under 2.0～2.4 W pump power, the dual-wavelength Q-switched

laser could simultaneously operate at the center wavelengths of 1 051 nm and 1 091 nm. The pulse duration, output power and repetition rate were about 8.4 μs, 125 mW, and 2.9 kHz, respectively. Such result reveals that, the WS$_2$ can be widely used as a saturable absorber in solid-state pulse lasers.

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