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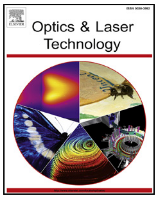

Full length article

Diode-pumped passively Q-switched Nd:GdYTaO$_4$ laser based on two-dimensional WS$_2$ nanosheet

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HIGHLIGHTS

- A novel Nd:GdYTaO$_4$ mixed crystal was used as the laser medium.
- A two-dimensional WS$_2$ nanosheet was prepared and served as saturable absorber.
- The WS$_2$ Q-switched Nd:GdYTaO$_4$ laser was demonstrated for the first time.

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ABSTRACT

A diode laser pumped passively Q-switched Nd:Gd$_{0.69}$Y$_{0.3}$TaO$_4$ laser based on two-dimensional (2D) layered tungsten disulfide (WS$_2$) saturable absorber was demonstrated for the first time. In the continuous wave (CW) operation, the maximum output power of 5.24 W with slope efficiency of 41% was obtained when the absorbed pump power was 14.18 W. The pulsed Nd:Gd$_{0.69}$Y$_{0.3}$TaO$_4$ laser was realized when the 2D material of WS$_2$ saturable absorber was inserted into the cavity. The shortest pulse duration and the highest repetition rate were 640 ns and 231 kHz, respectively. It is believed that a better laser performance can be expected when the quality of 2D material of WS$_2$ and Nd:Gd$_{0.69}$Y$_{0.3}$TaO$_4$ mixed crystal is improved.

1. Introduction

All-solid-state laser always takes a remarkable position among the various lasers for its great significance on many respects, such as material processing, laser ignition and laser diagnostics [1–4]. From ruby to Nd:YAG crystal, the solid-state lasers are always pushed forward by the constant springing up innovative gain medium. Besides the Nd:YAG crystal, the most commercial laser material, the tantalate like GdTaO$_4$ was also proved to be an promising material by doping Nd, Eu and Tb ions [5–8]. With similar ionic radius, replacing Gd^{3+} ions with Y^{3+} ions partly to reduce the structural disorder as much as possible, the Nd:Gd$_{0.69}$Y$_{0.3}$TaO$_4$ mixed crystal was grown by Czochralski method successfully [9]. The remarkable broadening in the absorption bandwidth (12 nm), which results from the disordered nature of mixed crystal, could reduce the demands of pump source and promote its efficiency. In comparison, Nd:YAG and Nd:GdTaO$_4$ have the absorption bandwidth of 0.8 nm and 6 nm, respectively [8,10]. Furthermore, the shorter fluorescence lifetime (182 μs) of mixed crystal is conducive to stimulating the high repetition rates laser. Hence, the further exploration of Nd:Gd$_{0.69}$Y$_{0.3}$TaO$_4$ mixed crystal is mostly appreciated.

Passively Q-switching is one of the most mature and reliable technologies to produce pulsed laser. Saturable absorbers are always used as the passive Q-switch. There are many traditional saturable absorbers such as organic dyes, ion doped crystals and semiconductor saturable absorber (SESAM) [11–14]. For their inherent defects, the application of organic dyes and ion doped crystals was restricted severely. With the advantages of high stability and low loss, SESAM was used widely [15]. But the problems of high price, complex craftwork and uncontrollable modulation depth become more and more impossible to be ignored [16].

Since the graphene was obtained by the mechanical exfoliation (ME) at 2004, the two-dimensional (2D) materials have arisen great interest in physics, which shows totally different characters from its bulk form, including ultrathin thickness, wide operation spectral range and ultrafast recovery time [17–19]. While the graphene points out the new direction of the saturable absorber, the complex operation and the zero band gap limit its application in photoelectric device field. Therefore, as the new type of 2D materials, transition metal

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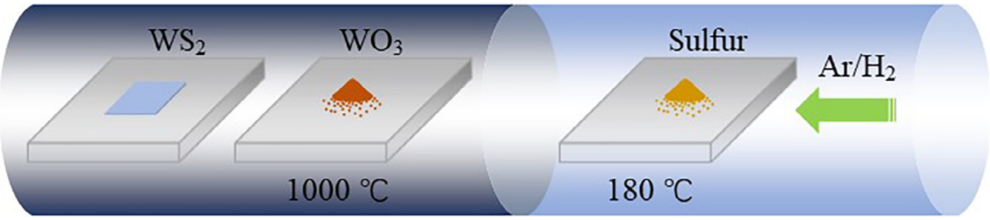

Fig. 1. Schematic of the growth of few-layer WS_2 by CVD method.

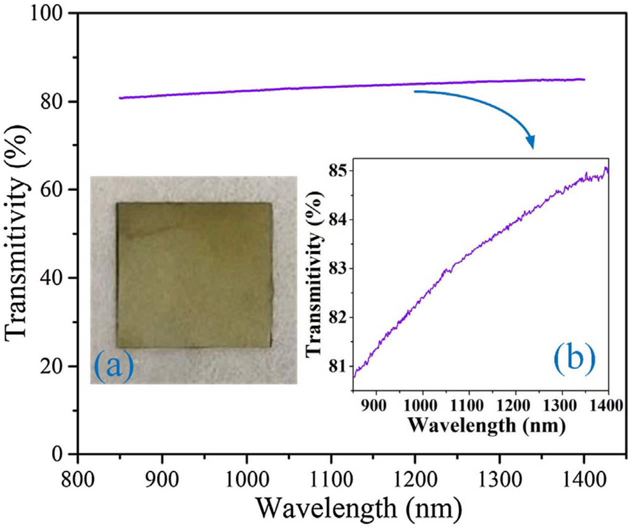

Fig. 2. Transmitted spectrum of WS_2 saturable absorber. inset: (a) Photograph of the WS_2 nanosheet on substrates; (b) Enlarged view of transmitted spectrum.

Fig. 3. The photograph of as-grown $Nd:Gd_{0.69}Y_{0.3}TaO_4$ mixed crystal.

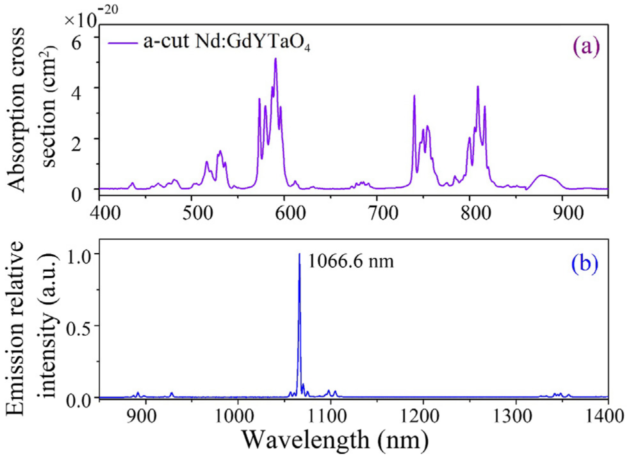

Fig. 4. Absorption and emission spectrum of $Nd:Gd_{0.69}Y_{0.3}TaO_4$ crystal: (a) Absorption spectra; (b) Emission spectra.

dichalcogenides (TMDs), including molybdenum disulfide (MoS_2), tungsten disulfide (WS_2) and so on, are paid close attention. Since its simpler production process, the research on MoS_2 was carried out earlier. MoS_2 has typical TMDs advantages, such as naturally controllable bandgap, fast relaxation times and great saturable absorption compared with the graphene in near-infrared and mid-infrared region [20]. As another promising TMDs, WS_2 have a similar properties with MoS_2 but a higher modulation depth at broadband wavelength [21,22]. These remarkable properties have opened new opportunities for WS_2 nanosheet in optoelectronics and nonlinear photonics.

In this paper, a 808 nm diode-pumped passively Q-switched $Nd:Gd_{0.69}Y_{0.3}TaO_4$ laser based on WS_2 saturable absorber was demonstrated for the first time. The continuous wave (CW) output power was improved through optimizing the beam coupling. The pulsed laser performance was investigated when the WS_2 saturable absorber was adopted.

2. Preparation of WS_2 nanosheet and Nd:GdYTaO$_4$ mixed crystal

2.1. WS_2 nanosheet

The WS_2 saturable absorber was growth by chemical vapour deposition (CVD) method, which significantly decreased the complexity for preparing few-layered WS_2 and offered a more efficient approach to study the optoelectronic properties of WS_2 nanosheet.

Fig. 1 illustrated the grown process of the layered WS_2 nanosheet through CVD method. More specifically, tungsten oxide (WO_3) powder was used as the source of tungsten and positioned closing to the sapphire growth substrates. The sulfur powder was placed near WO_3. Both of them were put in the two-temperature zone tube furnace with diameter of 100 mm. The WO_3 powder was heated to 1000 °C while the sulfur was heated to 180 °C. Employing Ar and H_2 as carrier gas, the furnace kept this temperature for 20 min. The WO_3 powder was reduced to $WO_{3\text{-}X}$ by the evaporated sulfur at high temperature, transmitted and adsorbed on sapphire substrate by the carrier gas. The $WO_{3\text{-}X}$ then reacted with sulfur again to produce the WS_2 layered structure, which can be described as $S + WO_{3\text{-}X} \rightarrow WS_2 + SO_2$. When the heater of the furnace was turned off, the layered WS_2 was stably attached onto the sapphire substrate.

The thickness of WS_2 saturable absorber and sapphire substrate was determined to be ~5 nm and 1 mm, respectively. Furthermore, the transmitted spectrum was presented in Fig. 2 which was measured by the SolidSpec-3700 UV–VIS-NIR spectrophotometer. Measurement ranged from 165 nm to 3300 nm. The transmission kept stable basically among the whole monitored spectral region. If examined closely enough, the transmission of WS_2 saturable absorber increased slowly with the wavelength, as shown in Fig. 2(a). Notably, the transmission at 1066 nm was 83.05%.

2.2. $Nd:Gd_{0.69}Y_{0.3}TaO_4$ crystal

As mentioned before, the $Nd:Gd_{0.69}Y_{0.3}TaO_4$ mixed crystal was grown successfully by Czochralski method and the photography of as-grown crystal is presented in Fig. 3, which shows a pretty good crystalline quality. The corresponding reaction equation is also listed followed: