2-μm mode-locked nanosecond fiber laser based on MoS_2 saturable absorber*

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We demonstrated a 2-μm passively mode-locked nanosecond fiber laser based on a MoS_2 saturable absorber (SA). Owing to the effect of nonlinear absorption in the MoS_2 SA, the pulse width decreased from 64.7 to 13.8 ns with increasing pump power from 1.10 to 1.45 W. The use of a narrow-bandwidth fiber Bragg grating resulted in a central wavelength and 3-dB spectral bandwidth of 2010.16 and 0.15 nm, respectively. Experimental results show that MoS_2 is a promising material for a 2-μm mode-locked fiber laser.

Keywords: nanosecond mode-locked pulses, Tm-doped fiber laser, MoS_2, fiber Bragg grating

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1. Introduction

In recent decades, 2-μm fiber lasers have received extensive attention owing to their broad emission spectrum[1] and practical applications in medicine, material processing, molecular spectroscopy, and laser lidar and as a pumping source for 3–5 μm fiber lasers.[2,3] Various approaches have been developed to generate 2-μm mode-locked fiber lasers.[4–6] One of the most convenient and effective techniques is to exploit different types of saturable absorbers (SAs), such as the semiconductor saturable absorber mirror (SESAM),[7] single-wall carbon nanotubes (SWCNTs),[8] and graphene.[9] Because of its stable operating performance, the SESAM is widely used in passively mode-locked fiber lasers. However, it has a narrow tuning range, a complex manufacturing process, and expensive packing. Although SWCNTs have the advantages of simple fabrication, low cost, and subpicosecond recovery time,[10] their operating wavelength is limited by the nanotube diameter and chirality.[11] Graphene is widely studied because of its unique Dirac-like electronic band structure and ultrafast recovery time.[12] The successful use of graphene greatly encourages scientific researchers to explore other two-dimensional nanomaterials. Recently, MoS_2 has attracted considerable attention as a novel graphene-like material owing to its exceptional optical properties, such as ultrafast carrier dynamics[13] and wideband saturable absorption behavior.[14] In particular, MoS_2 nanosheets exhibit an even better saturable absorption response and higher relaxation time than graphene nanosheets under the same excitation condition.[15] Few-layer MoS_2 generally has a higher damage threshold than monolayer MoS_2. The indirect band gap of few-layer MoS_2 is around 1.2 eV, whereas the direct band gap of monolayer MoS_2 is about 1.8 eV.[16] The band gaps of few-layer MoS_2 become inhomogeneous owing to blending of the 1T (metallic-like) and 2H (semiconducting) phases.[17] Similar to the zero band-gap of graphene, the 1T phase of few-layer MoS_2 could also provide saturable absorption characteristics at 2 μm because of the Pauli blocking effect. Nevertheless, to date, most research on mode-locked fiber lasers based on few-layer MoS_2 as the SA has focused on the 1- or 1.5-μm band and realized femtosecond or picosecond pulses.[18–20]

In recent years, nanosecond mode-locking technology has attracted strong research interest.[21–23] Nanosecond pulses have a large pulse width, a low peak power, a strong chirp, and little nonlinear phase accumulation during energy amplification.[23] Thus, mode-locked fiber lasers with nanosecond pulses, in contrast to picosecond or femtosecond pulses, have potential applications in chirped pulse amplification systems. Recently, Zhan and Wang[24] reported a Yb-doped mode-locked fiber laser with a 2.17-MHz repetition rate by using a MoS_2-poly(vinyl alcohol) film, where the output pulse width was 22.88 ns owing to the long cavity length. However, 2-μm mode-locked fiber lasers producing a tunable nanosecond pulse width and based on a MoS_2 SA have not yet been explored.

In this paper, a few-layer MoS_2 film was synthesized by chemical vapor deposition (CVD). By employing a 1-m-long unpumped Tm/Ho-codoped fiber, we achieved stable nanosecond mode-locked pulses. The tunable pulse width can be changed from 64.7 to 13.8 ns only by increasing the pump power. The fiber laser has a central wavelength, 3-dB spec-

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tral bandwidth, and repetition rate of 2010.16, 0.15 nm, and 2.17 MHz, respectively.

2. Characterization of MoS_2 and experimental setup

The few-layer MoS_2 SA was fabricated by CVD.[16] The Raman spectrum of the MoS_2 film was measured using a Renishaw 100 Raman spectrometer with a 514-nm laser. As shown in Fig. 1(a), the MoS_2 film exhibited two characteristic Raman bands at 406.8 and 381.9 cm^{-1}, which correspond to the A_{1g} and E^1_{2g} modes, respectively. The peak frequency difference (Δ) between the A_{1g} and E^1_{2g} modes can be used to identify the number of MoS_2 layers.[19] In our work, the Δ value was 24.9 cm^{-1}, implying a layer number of 4 or 5. The few-layer MoS_2 film was cut into $\sim 1 \times 1$ mm^2 pieces and then sandwiched between two fiber connectors (FC/APC) to form a MoS_2 SA. The total insertion loss of the MoS_2 SA, which was measured with a power meter, was ~ 2.1 dB. The nonlinear transmission of the MoS_2 SA was measured using a balanced twin-detector measurement system with a SESAM mode-locked Tm/Ho-codoped fiber laser (pulse width of 51 ps, center wavelength of 1931 nm, and output power of 45 mW). The optical transmission of the MoS_2 SA at different pump powers was recorded, as shown in Fig. 1(b). The MoS_2 SA parameters of modulation depth ($\Delta\alpha$), saturation intensity (I_{sat}), and nonsaturation loss (α_{ns}) are 4.5%, 5.12 MW/cm^2, and 19.9%, respectively.

A schematic diagram of the passively mode-locked Tm-doped fiber laser is displayed in Fig. 2. It is a ring cavity with a total cavity length of ~ 55 m. The fiber laser is pumped by a 12 W/793 nm laser diode through a (2+1) $\times$1 signal–pump combiner. A 4-m double-clad Tm-doped single-mode fiber (TDF, IXFiber) is used as the gain medium; it has core/cladding diameters of 10/125 μm, numerical apertures (NAs) of 0.16/0.46, and an absorption of 5 dB/m at 789 nm. A polarization controller (PC) is employed to adjust the cavity polarization, and an isolator (ISO) is used to ensure unidirectional operation. A 30-m-long standard single-mode fiber (SMF) is connected to an optical coupler (OC) with 30% output. In addition, the MoS_2 SA is coupled to the cavity by a circulator. The fiber Bragg grating (FBG) has a central wavelength of 2010.15 nm, a 3-dB bandwidth of 0.38 nm, and a reflectivity of 94%, and is used as an external mirror of the ring cavity. The 1-m-long unpumped Tm/Ho-codoped fiber (THDF, Coractive TH512) is spliced between the MoS_2 SA and the FBG. The THDF has core/cladding diameters of 9/125 μm and a core NA of 0.16. The laser output performance was monitored by an optical spectrum analyzer (Yokogawa AQ6375B), a 1 GHz oscilloscope (Lecroy WaveRunner 610Zi) via a 12.5 GHz photodetector (EOT ET-5000F), and a 3 GHz radio-frequency (RF) spectrum analyzer (Rohde & Schwarz FSL3).

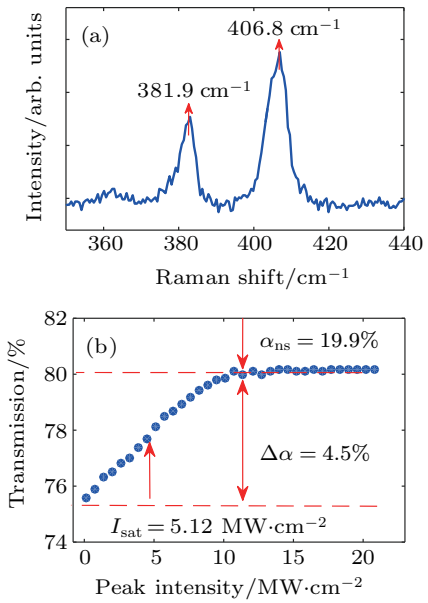


Fig. 1. (color online) Characterization of MoS_2: (a) Raman spectrum, (b) transmission of the MoS_2 film.

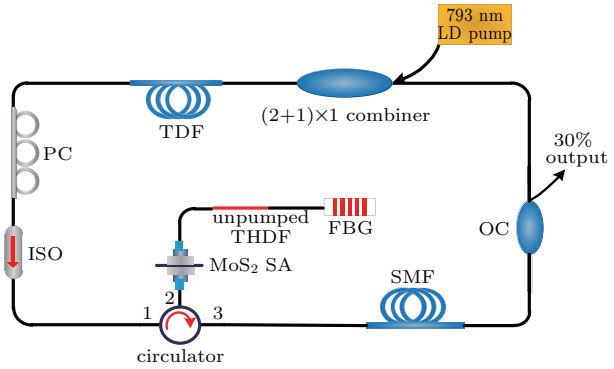


Fig. 2. (color online) Experimental setup of the MoS_2 mode-locked Tm-doped fiber laser.

3. Experimental results and discussion

Continuous wave (CW) operation of the laser started at a pump power of ~ 1.04 W. A stable pulse train could be achieved by adjusting the PC slightly when the pump power was increased to 1.10 W. A nanosecond-scale pulse train and single pulse envelope of the mode-locked fiber laser at a pump power of 1.45 W are shown in Fig. 3(a). The period of the pulse train is 268.0 ns; this corresponds to a fundamental repetition rate of ~ 3.73 MHz, which is consistent with the cavity round-trip time.[25] The pulse repetition rate and pulse width versus pump power are summarized in Fig. 3(b). We found experimentally that the pulse repetition rate remained constant with increasing or decreasing pump power. For pump powers of 1.10, 1.15, 1.2, 1.25, 1.3, 1.35, 1.4, and 1.45 W, pulse widths of 64.7, 59.5, 51.6, 45.2, 35.6, 29.0, 25.0, and 13.8 ns, respectively, were observed. The decrease in pulse width with increasing pump power is due to the effect of nonlinear absorption by the MoS_2 SA. A similar result was reported in Ref. [22]. As the pump power was increased further beyond

1.46 W, the stable mode-locked operation became unstable owing to competition between the mode-locked operation and CW operation.[19] Moreover, when the pump power was reduced to 1.45 W, the pulse train remained stable. Further, no transient effect was observed on the oscilloscope of the pulse train with a wide time span.

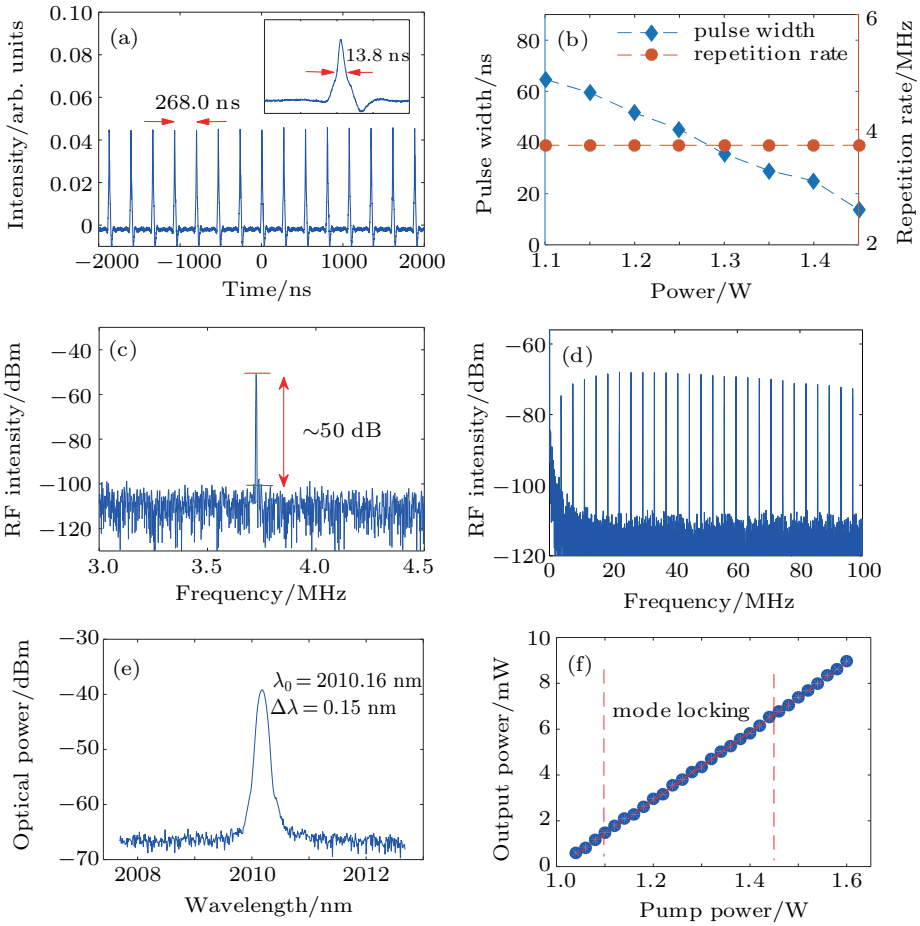


Fig. 3. (color online) Experimental results: (a) pulse train at a pump power of 1.45 W (inset: single pulse envelope), (b) repetition rate and pulse width versus pump power, (c) RF spectrum at 3.73 MHz repetition rate, (d) RF spectrum with a span of 100 MHz, (e) optical spectrum, and (f) average output power versus pump power.

It is worth mentioning that we first adopted the typical ring cavity configuration without the unpumped THDF. However, we observed unstable mode-locking behavior. Mode competition is an important factor affecting the stability of the laser. Mode competition will generally cause mode-hopping, which is commonly suppressed by adding an unpumped fiber to the laser cavity. Thus, to improve the stability of the fiber laser, we employed an extra 1-m-long unpumped THDF in the cavity. The measured absorption coefficient of the THDF is about 2.8 dB/m at 2010 nm, because the counterpropagating beams in the unpumped THDF form a standing wave that results in periodic spatial hole-burning, which can suppress the weaker mode and achieve lasting mode selection.[26] This effectively improves the stability of the mode-locked fiber laser. Because Tm-doped fiber lasers have a large gain bandwidth, the narrow-bandwidth FBG is employed as a wavelength selection component to select the frequency and reduce the effective gain bandwidth of the laser in order to suppress oscillation of the side mode.[27,28] It can be inferred that the nanosecond pulse width is due to the narrow-bandwidth FBG.

The stability and quality of the mode-locked pulses are evaluated using the RF spectrum. An RF spectrum with a 1-kHz-resolution bandwidth is shown in Fig. 3(c). The fundamental RF peak is located at 3.73 MHz, which corresponds to the fundamental repetition rate and is consistent with the cavity length of ~ 55 m; these are typical features of passive mode-locked operation. Further, the signal-to-noise ratio is ~ 50 dB, indicating high mode-locking stability. The wideband RF spectrum is shown in Fig. 3(d) at a resolution of 1 kHz over a span of 100 MHz. The wideband RF spectrum has no other frequency component except the fundamental and harmonic frequencies.

The optical spectrum of the mode-locked fiber laser at a pump power of 1.45 W is shown in Fig. 3(e). Because of the narrow-bandwidth FBG, the central wavelength is 2010.16 nm, and the 3-dB spectral bandwidth is 0.15 nm. Figure 3(f) shows the average laser output power versus the pump power. A stable mode-locked pulse is observed within a

350 mW pump power range. When the pump power is 1.45 W, the average output power is 7.56 mW, and the slope efficiency is 1.84%. The low slope efficiency is caused mainly by mode field mismatch between the double-clad Tm-doped fiber and the standard SMF, which results in a large splicing loss. Further, because of the limitations on existing experimental devices, we used an FBG with low reflectivity rather than higher or total reflectivity; consequently, some of the power is leaked. In addition, in this work, the maximum time–bandwidth product of the generated nanosecond pulses is 720.5, which is far beyond the sech^2 transformation limit of 0.315, indicating that the mode-locked pulses have a giant chirp.

4. Conclusion

In summary, a passively mode-locked Tm-doped fiber laser with nanosecond pulse width based on a MoS_2 SA was demonstrated. An unpumped THDF was used to achieve nanosecond mode-locked pulses, and the pulse train showed no transient effect or evidence of Q-switching. Owing to the effect of nonlinear absorption in the MoS_2 SA, the pulse width was decreased from 64.7 to 13.8 ns by increasing the pump power. The central wavelength and 3-dB spectral bandwidth were 2010.16 and 0.15 nm, respectively. Higher output power could be achieved by controlling the cavity losses. In the future, we will use appropriate equipment to measure the linear chirp directly.

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