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SPECIAL TOPIC — Nanophotonics

MXene $Ti_3C_2T_x$ saturable absorber for pulsed laser at 1.3 μm*

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The excellent optical properties of MXene provide new opportunities for short-pulse lasers. A diode-pumped passively *Q*-switched laser at 1.3 μm wavelength with MXene $Ti_3C_2T_x$ as saturable absorber was achieved for the first time. The stable passively *Q*-switched laser has 454 ns pulse width and 162 kHz repetition rate at 4.5 W incident pumped power. The experimental results show that the MXene $Ti_3C_2T_x$ saturable absorber can be used as an optical modulator to generate short pulse lasers in a solid-state laser field.

Keywords: MXene $Ti_3C_2T_x$, passively *Q*-switched lasers, 1.3 μm, diode-pumped lasers

PACS: 42.70.Nq, 42.60.Gd, 42.55.Xi **DOI:** 10.1088/1674-1056/27/9/094214

1. Introduction

A diode-pumped 1.3 μm pulse laser has been applied in the fields of remote sensing, fiber optic communication, biomedicine, etc. When we look back through the development of laser technologies, we can see that novel materials play a crucial effect in the progress of science and technology. Especially, since graphene has been widely researched in the field of ultrafast laser and optical modulators, two-dimensional (2D) materials are attracting more and more attention of scientists.[1–5] In just a few short years, graphene oxide, topological insulators (TIs), transition metal dichalcogenides (TMDs), and black phosphorus (BP) were discovered in succession.[6–11] Due to their special electronic and optical properties, such as high optical damage threshold, ultrafast recovery time, and controllable modulation depth, they have been applied to the fiber lasers and solid-state lasers.[12–15] However, some 2D materials need to be further optimized, for example, black phosphorus is easily oxidized, and the fabrication process of TIs is complex. So the development of promising novel nonlinear optical materials, especially the 2D materials, is still a longstanding goal.

Recently, as a new member of the 2D materials, MXene has been researched gradually.[16–18] The A atomic layers of MAX phases are exfoliated to obtain MXene.[18] The general formula of MXene is $M_{n+1}X_nT_x$, where M is the transition metal, X is C and/or N, T is the surface terminations (hydroxyl, oxygen or fluorine), and n is 1, 2, or 3. At the same time, the MXene materials have the following outstanding advantages, including good conductivity, tunable bandgap, easy fabrication, broadband nonlinear optical response, and large nonlinear absorption coefficient.[14,19–28] MXene $Ti_3C_2T_x$ with great nonlinear optical characteristic has been successfully fabricated by Jiang *et al.*,[29] wherein the maximum nonlinear absorption coefficient (10^{-13} esu) is higher than that of other 2D materials, indicating a strong optical switch capability.[30,31] Moreover the zero-gap band structure of Ti_2C_3 ($E_g < 0.2$ eV of $Ti_3C_2T_x$) has broadband optical responsibility in the wavelength from visible light to near infrared light.[32,33] Also, $Ti_3C_2T_x$ has a layer structure like graphene, where the inter-layer distance is 0.98 nm.[34] The lower linear absorption of MXene $Ti_3C_2T_x$ ($\sim 1\%$/nm) reduces the loss compared to graphene (2.3% per atomic layer).[26,35] In addition, $Ti_3C_2T_x$ has electrical conductivities as high as 4.3×10^5 S/m that is several times higher than that of graphene.[23] The electronic band structure can be changed by controlling the terminations and transition metal layers.[36,37] The merits show that the MXene could be used to generate ultrashort pulse laser. So far, femosecond mode-locked fiber lasers with the MXene Ti_3CN saturable absorber were obtained in 2017,[38] and Jiang *et al.* reported a stable femtosecond fiber laser using MXene $Ti_3C_2T_x$ as saturable absorbers.[29] However, the pulse laser with MXene materials has not been reported in the solid-state laser field.

In this paper, the diode-pumped passively *Q*-switched

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pulses operating at the 1.3 μm region are generated by using the MXene $Ti_3C_2T_x$ saturable absorber for the first time. The minimum pulse duration and the maximum repetition rate are 454 ns and 163 kHz, respectively. It indicates that the MXene $Ti_3C_2T_x$ saturable absorber can be applied in laser technologies.

2. MXene $Ti_3C_2T_x$ preparation and characterization

The MXene $Ti_3C_2T_x$ solution is firstly fabricated by the acid etching process. The final MXene solution is dripped on a quartz substrate. The substrate is rotated on the spinner with a slow speed to disperse uniformly the solution and dried at room temperature. Figure 1(a) shows the MXene sample. A scanning electron microscopy (SEM) image of the 2D material is shown to characterize the surface form in Fig. 1(b). We can see that the MXene $Ti_3C_2T_x$ has a layer structure like graphene. A balanced twin-detector measurement technique is used to research the nonlinear saturable absorption of the sample. The laser source is a homemade acousto-optic Q-switched laser with 1.3 μm center wavelength, 250 ns pulse duration, and 5 kHz repetition rate. The nonlinear curve is shown in Fig. 1(c). The results are fitted with the saturable absorber model, given by[39]

$$T(I) = 1 - \varphi_0 \exp(-I/I_{\text{sat}}) - \varphi_{\text{ns}},$$

where $T(I)$, φ_0, I_{sat}, I, and φ_{ns} are the transmittance, modulation depth, saturation optical intensity, incident optical intensity, and nonsaturable loss, respectively. The modulation depth and saturation optical intensity are calculated to be $\sim 16\%$ and ~ 256 μJ/cm^2, respectively. The high nonsaturable loss can mainly be attributed to the Fresnel reflection loss (8%) for both sides of the pure quartz and the scattering of the saturable absorber.

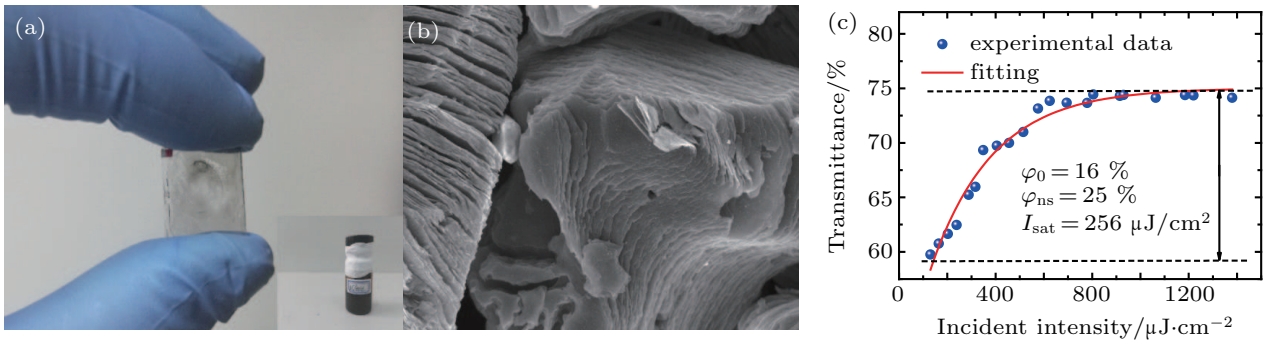


Fig. 1. (color online) (a) MXene $Ti_3C_2T_x$ sample. (b) SEM image. (c) Transmittance versus incident optical intensity.

3. Experimental setup

Figure 2 shows the schematic diagram of the passively Q-switched laser with MXene saturable absorber. A fiber-coupled laser diode emitted at the center wavelength of 803 nm acted as the pump source. The pumped beam with 200 μm radius is focused on the gain medium by the 1:1 coupled systems. The YVO_4/Nd:YVO_4/YVO_4 composite crystal is wrapped with indium foil and held in the copper block maintained at 15 °C using a water-cooled system. The size of the composite crystal is 4 mm×4 mm×(2+8+2) mm. Two end surfaces of the crystal are unparallel with a 2° tilt angle, which weaken the etalon effect. The experiment adopts a concave-flat cavity with the cavity length of about 36 mm. The concave surface of M1 ($R = 300$ mm) has high-reflection coated at 1.3 μm. M2 ($R = \infty$) with 4% transmittance for 1.3 μm acts as the output coupler, and the spot size calculated by the $ABCD$ matrix is 150 μm at the position of M2.

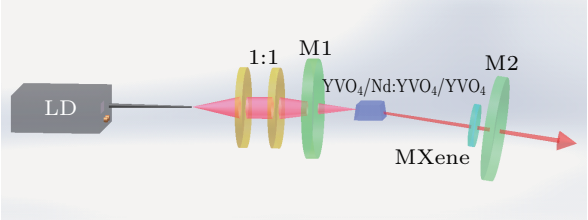


Fig. 2. (color online) Schematic diagram of Q-switched laser based on the MXene saturable absorber.

4. Experimental results and discussion

Through carefully regulating and optimizing the cavity, a continuous-wave operation was in an optimal state. Then the saturable absorber was inserted into the cavity and placed near the output coupler. A stable Q-switched operation was achieved by carefully adjusting the saturable absorber. At the same time, in order to characterize the pulse laser, the average output power was measured by a power meter (30 A-SH-V1, Israel). The digital oscilloscope (Tektronix DPO 4104, USA) and photoelectric detector (EOT, ET-3000) were used to record the pulse width and repetition rate with the increase of the incident pump power.

Figure 3(a) shows the average output power, which in-

creases with increasing incident pump power. The maximum average output power and threshold power are 30 mW and 4.2 W, respectively. At the same time, the emission spectrum of the Q-switched laser is measured by an optical spectrum analyzer (Avaspec-3648-USB2). The peak wavelength is 1.3 μm at 4.5 W incident pump power as shown in the inset of Fig. 3. As shown in Fig. 4, the pulse width decreases with the increase of the incident pump power. The shortest pulse width is measured to be about 454 ns, corresponding to a 162 kHz repetition rate. According to the measured parameters, the single pulse energy and peak power are calculated. The single pulse energy is about 0.2 μJ. With increasing incident pump power from 4.25 W to 4.5 W, the peak power varies from 265 mW to 406 mW, as shown in Fig. 5.

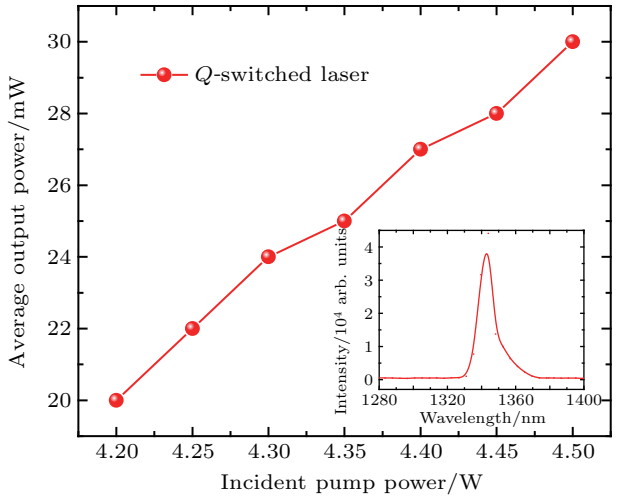


Fig. 3. (color online) (a) Average output power versus incident pump power. Inset: Emission spectrum in passively Q-switched operation.

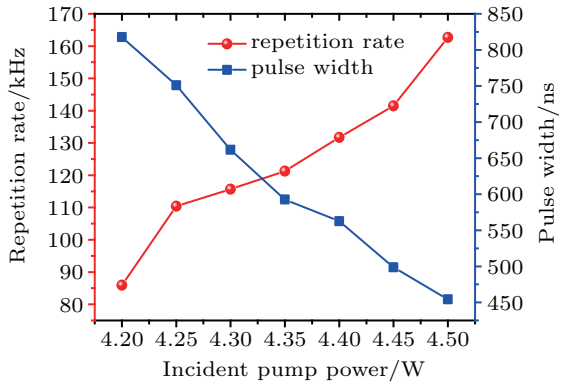


Fig. 4. (color online) Pulse width and repetition rate versus incident pump power.

The temporal pulse profile and pulse trains on different time scales are shown in Fig. 6. The pulse profile is asymmetric with a fast rising time and a slow falling time. Because of saturable absorption of the 2D material, once it reaches the saturation state, the rising edge rapidly sets up. Moreover, the photon density of the intracavity will reduce. So the phenomenon is observed. If the incident pump power is increased further, the Q-switched pulse train becomes unstable, and damage with a burning formed dot is observed on the end surface of the saturable absorber at ~ 5 W incident pump power.

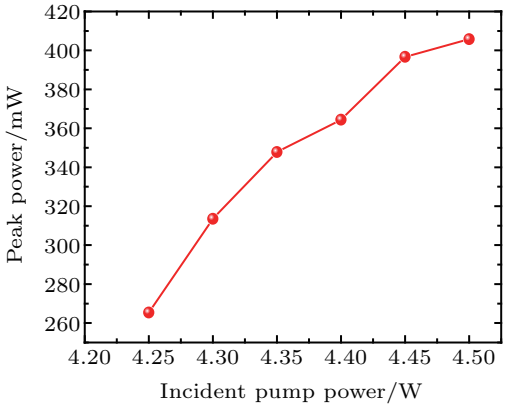


Fig. 5. (color online) Peak power versus incident pump power.

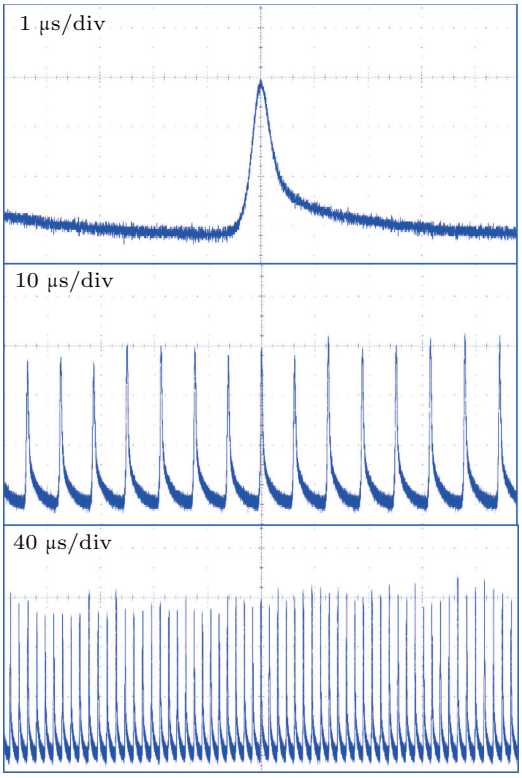


Fig. 6. (color online) Pulse train and temporal pulse profile at 4.5 W incident pump power on two different time scales.

For passively Q-switched laser operation, the pulse width is given by[40,41] $\tau = (3.52 \times T_R)/\Delta T$, where T_R is the cavity round-trip timing, ΔT represents the modulation depth, and τ is the pulse width. The pulse width is inversely proportional to the modulation depth. Increasing the modulation depth is beneficial to impress the pulse width. From the above, optimizing the saturable absorber is helpful to generate better pulse characteristics.

5. Conclusion

We have experimentally demonstrated a diode-pumped passively Q-switched operation with MXene $Ti_3C_2T_x$ to generate short pulse lasers. The YVO_4/Nd:YVO_4/YVO_4 laser at 1.3 μm is realized with 30 mW maximum average output power. The pulse width is as short as 454 ns and the repetition rate is 162 kHz. As far as we know, MXene $Ti_3C_2T_x$ is firstly used in the field of solid-state lasers. Considering the excellent characteristics of MXene, such as the broadband nonlinear optical response, it is a potential saturable absorber for solid-state lasers of various wavelengths.

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