Q-switched Fiber Laser with MoS_2 Saturable Absorber

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Abstract: A MoS_2-based saturable absorber is fabricated using wet chemistry techniques. We use it to passively Q-switch a fiber laser at 1068 nm.

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1. Introduction

Two-dimensional (2D) crystals hold great potential for photonic applications due to their remarkable nonlinear optical and electronic properties. In particular, graphene has been extensively studied as a saturable absorber (SA) for short pulse generation [1, 2]. Recently, 2D crystals such as MoS_2 have also been shown to exhibit saturable absorption [3], high third-order nonlinear susceptibility [4] and ultrafast carrier dynamics [5, 6]. Such nonlinear optical properties highlight the material's promise as an ultrafast switch, importantly, with potential application at visible wavelengths due to a direct bandgap of ∼1.9 eV [3]. The characterization of saturable absorption in MoS_2 by Wang et al. [3] opens up new opportunities for short pulse generation that are, however, yet to be demonstrated.

Initial difficulties with the integration of graphene SAs into fiber laser cavities were overcome by solution processing and subsequent graphene-polymer composite preparation [1,2]. Indeed, liquid phase exfoliation (LPE) of bulk layered materials is now considered an important production route [7,8]. Here, we use such LPE techniques to produce liquid dispersions enriched with few layer MoS_2 flakes, which are then used to produce a free-standing MoS_2-polymer composite. This device is subsequently employed as a SA to generate Q-switched pulses in a fiber laser.

2. Material Fabrication

We prepare the MoS_2-polymer composite as follows. MoS_2 powder (120 mg) is mixed with 90 mg of sodium deoxycholate (SDC) in deionized (DI) water and ultrasonicated for 2 hours. The temperature of the dispersion is maintained constant during the ultrasonication via ice cooling (∼5°C). The resultant dispersion is centrifuged at 5 krpm for 1 hour in a Sorvall WX-100 ultracentrifuge with a TH-641 swinging bucket rotor. The exfoliated and dispersed MoS_2 flakes are characterized by optical absorption spectroscopy (OAS) and transmission electron microscopy (TEM). Fig.1a is a high resolution TEM image of an exfoliated few-layer MoS_2 flake. The concentration of dispersed MoS_2 flakes can be estimated using the Beer-Lambert Law [8] according to the relation $A = \alpha cl$, where A is the absorbance, l [m] is the light path length, c [g/L] the concentration of dispersed material and α [L g^{-1} m^{-1}] the absorption coefficient. We use α ∼3400L g^{-1} m^{-1} at 672 nm for MoS_2 [8]. The estimated concentration is ∼0.03 g/L. The top 4 mL of this dispersion is mixed with 2 mL of 15 wt% aqueous PVA solution. The mixture is then dried at ∼20°C to form a 30-40 μm free-standing composite film. Fig. 1b shows the transmission spectrum.

3. Laser Design and Characterization

We constructed an all-fiber ring cavity (Fig. 1c) including a ytterbium-doped fiber amplifier (YDFA), a polarization controller to adjust the net cavity birefrigence, a 10% output coupler and a chirped fiber Bragg grating (centered at 1069.9 nm with 4.26 nm 3-dB bandwidth) to provide a large net anomalous dispersion. The total cavity length was ∼10 m, with a net dispersion of ∼-30 ps^2. Our MoS_2 saturable absorber was included in the cavity by sandwiching a 1 mm × 1 mm piece of the MoS_2-polymer composite between two fiber ferrules.

At the lasing threshold, a continuous wave (CW) output was observed. Self-starting Q-switched pulsed operation was achieved by increasing the pump power. Initially, pulses were observed with 5.2 μs duration (full width at half maximum) at 58 kHz repetition rate. As typical of Q-switched lasers, the repetition rate increased and the pulse duration reduced with increasing pump power. We measured a maximum repetition rate of 105 kHz which corresponded to a minimum pulse duration of 2.2 μs. Typical Q-switched output characteristics, showing a 67 kHz pulse train of

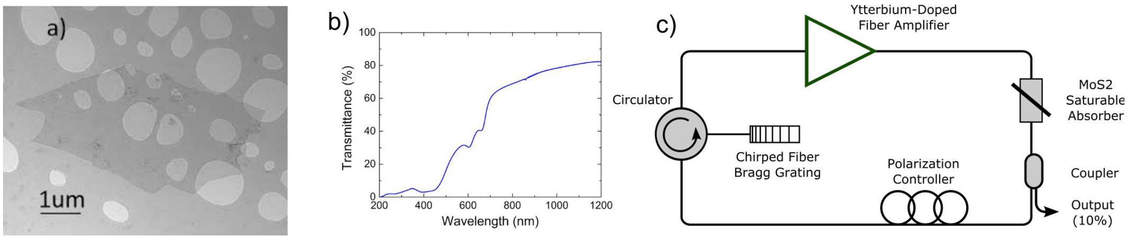

Fig. 1. (a) TEM image of an MoS_2 flake; (b) Transmission spectrum of MoS_2-polymer composite; (c) Laser cavity schematic.

2.7 μs pulses are shown in Fig. 2. The average output power was 0.46 mW, corresponding to a pulse energy of 6.9 nJ. Measurement of the output radio frequency (RF) spectrum (Fig. 2d) showed a peak-to-pedestal ratio of 48 dB. Here, the laser operated at 1068.2 nm with 0.07 nm 3-dB bandwidth (Fig. 2c); although the central wavelength was determined by the grating reflection band, we were also able to achieve stable Q-switching at 1028 nm using a different grating.

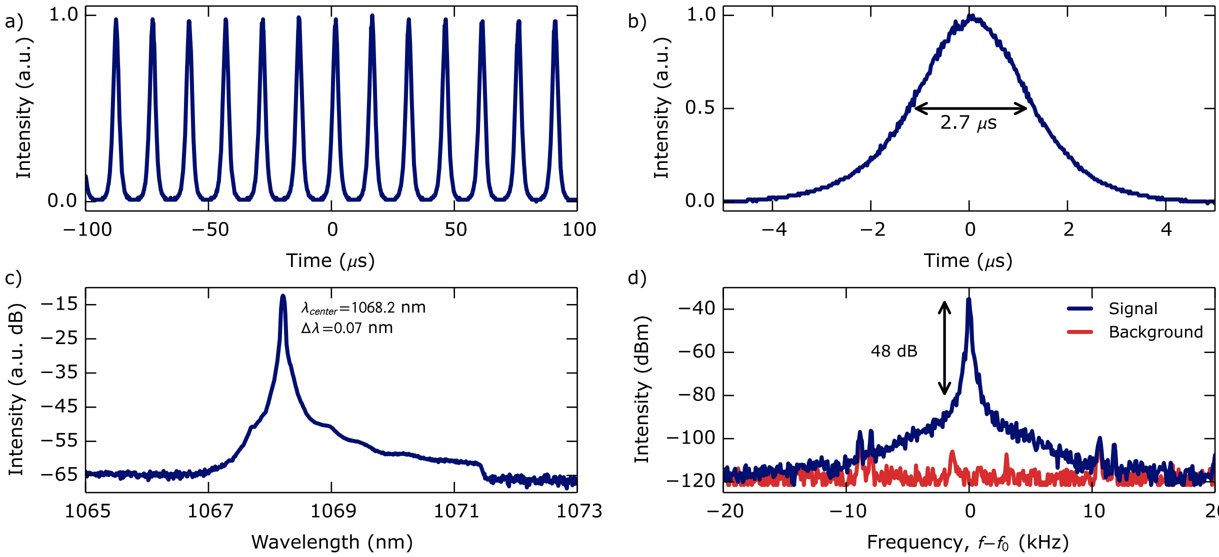

Fig. 2. Q-switched laser characteristics: (a) pulse train; (b) pulse profile; (c) optical spectrum; (d) RF spectrum, f_0=67 kHz.

4. Conclusion and Outlook

We have fabricated an MoS_2-polymer saturable absorber and demonstrated the first pulsed laser using this 2D material, operating in the Q-switched regime. Characterization of the saturable absorber will also be discussed and optimization of the MoS_2 composite for achieving mode-locked operation is a topic of ongoing work.

References

1. Z. Sun et al., "Graphene Mode-Locked Ultrafast Laser," ACS Nano **4**, 803 (2010).
2. T. Hasan et al., "Nanotube-Polymer Composites for Ultrafast Photonics," Advanced Materials **21**, 3874 (2009).
3. K. Wang et al., "Ultrafast Saturable Absorption of Two-Dimensional MoS_2 Nanosheets," ACS Nano **7**, 9260-9267 (2013).
4. R. Wang et al., "Third-Harmonic Generation in Ultrathin Films of MoS_2," ACS Applied Materials & Interfaces, **6**, 314 (2014).
5. H. Shi et al., "Exciton Dynamics in Suspended Monolayer and Few-Layer MoS_2 2D Crystals," ACS Nano, **7**, 1072 (2013).
6. R. Wang et al., "Ultrafast and spatially resolved studies of charge carriers in atomically thin molybdenum disulfide," Physical Review B, **86**, 045406 (2012).
7. F. Bonaccorso et al., "Production and processing of graphene and 2d crystals," Materials Today **15**, 564 (2013).
8. J. N. Coleman et al. "Two-Dimensional Nanosheets Produced by Liquid Exfoliation of Layered Materials," Science **331**, 568 (2011).