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Q-Switched Raman Fiber Laser with Molybdenum Disulfide-Based Passive Saturable Absorber

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We demonstrate a Q-switched Raman fiber laser using molybdenum disulfide (MoS_2) as a saturable absorber (SA). The SA is assembled by depositing a mechanically exfoliated MoS_2 onto a fiber ferrule facet before it is matched with another clean ferrule via a connector. It is inserted in a Raman fiber laser cavity with a total cavity length of about 8 km to generate a Q-switching pulse train operating at 1560.2 nm. A 7.7-km-long dispersion compensating fiber with 584 ps·nm^{-1}km^{-1} of dispersion is used as a nonlinear gain medium. As the pump power is increased from 395 mW to 422 mW, the repetition rate of the Q-switching pulses can be increased from 132.7 to 137.4 kHz while the pulse width is concurrently decreased from 3.35 μs to 3.03 μs. The maximum pulse energy of 54.3 nJ is obtained at the maximum pump power of 422 mW. These results show that the mechanically exfoliated MoS_2 SA has a great potential to be used for pulse generation in Raman fiber laser systems.

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Stimulated Raman scattering (SRS) has been utilized to develop fiber lasers having wavelengths that are difficult to access directly with conventional gain media. In the SRS process, the amount of the Stokes frequency shift is intrinsically determined by the irradiated medium in which a quantum conversion increases proportionally with the complex part of the third-order nonlinear permittivity.[1] To date, various Raman fiber lasers (RFLs) have been fabricated and demonstrated by using germanosilicate or phosphosilicate glass fibers as Raman gain media. Most of the proposed lasers are operating with a cw mode with high output power. On the other hand, there is also growing interest in passively Q-switched fiber lasers due to their potential applications in LIDAR, remote sensing, communication and medicine.[2] Compared with the active technique, the passive approach is better in terms of simplicity, compactness, and flexibility of implementation.[3] The passive Q-switching generation can be realized by using either an artificial saturable absorber (nonlinear polarization rotation, nonlinear optical loop mirror) or real saturable absorber (SA) techniques.

To date, various real-SAs such as semiconductor SA mirrors (SESAMs), single wall carbon nanotubes (SWCNTs) and graphene saturable absorbers (SAs), have been exploited for realizing stable passive Q-switching. Compared with other passive techniques, graphene behaves as an excellent SA and its true potential in generating pulsed laser has been proved due to the combination of its unique optical and electronic properties.[4] The success of graphene has greatly encouraged scientific researchers to explore other graphene-like 2D nanomaterial for photonic applications.[5,6] Recently, topological insulators (TIs), a new class of nanomaterial characterized by an insulating bulk state and a gapless Dirac-type surface/edge,[7] have been attracting great interest in ultrafast photonics.[8] Taking advantage of the excellent saturable absorption of TIs, Luo *et al.* successfully experimentally demonstrated the generation of Q-switched pulses in ytterbium-doped fiber laser[9] and thulium-doped fiber laser[10] cavities operating at 1.06 μm and 2.0 μm, respectively.

Very recently, the saturable absorption of molybdenum disulfide (MoS_2), was also demonstrated by using the Z-scan technique at 800 nm.[11] By inserting the MoS_2 SA into an erbium-doped fiber laser (EDFL), a ∼710 fs pulse centered at 1569 nm wavelength with a repetition rate of 12.09 MHz was demonstrated.[12] In this Letter, we present a passively Q-switched RFL by a MoS_2-based SA using a 7.7-km-long dispersion compensating fiber (DCF) as the gain medium. The Q-switcher is assembled by depositing a mechanically exfoliated MoS_2 onto a fiber ferule facet before it is matched with another clean ferrule via a connector. With the multilayer MoS_2-based SA, the compact all-fiber laser emits stable Q-switched pulses with threshold pump power, central wavelength, minimum pulse duration, and maximum repetition rate of 395 mW, 1560.2 nm, 3.03 μm and 137.4 kHz, respectively. To the best of our knowledge, a Q-switched RFL operating in any wavelength regions by using a passive SA has never been demonstrated before. Most of the previous works are focused on carbon nanotubes and graphene nanomaterials by using a doped fiber as

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a gain medium.[13–16] Most of the previous RFLs are also focused on cw operation.[17,18]

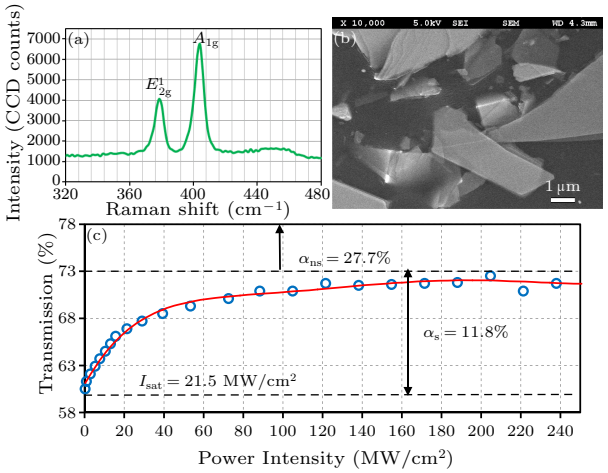

Fig. 1. Material characteristics for the exfoliated MoS_2: (a) Raman spectrum, (b) FESEM image, and (c) nonlinear transmission profile.

In this work, the MoS_2 SA was prepared by the mechanical exfoliation method, which has been widely used in graphene-based ultrafast fiber laser applications.[19,20] Mechanical exfoliation is advantageous mainly due to its simplicity and reliability, where the entire fabrication process is free from complicated chemical procedures and costly instruments. Relatively thin flakes were peeled off a large block of commercially available MoS_2 crystal using scotch tape. Then, we repeatedly pressed the flakes stuck on the scotch tape so that the MoS_2 flakes became thin enough to transmit light with high efficiency. Then we transferred the thinned flakes onto a fiber ferule facet before it was matched with another clean ferrule via a connector. The Raman spectrum of the exfoliated MoS_2 was measured by using a Renishaw's Raman analyzer with an excitation wavelength of 532 nm and laser power of 5 mW. This is one of the most widely exploited nondestructive methods for characterizing the vibrational modes and hence the structure of nanomaterial. Figure 1(a) shows the generated Raman spectrum, which exhibits two Raman characteristic bands at 404 cm^{-1} and 378 cm^{-1},[21,22] corresponding to the A_{1g} and E^1_{2g} modes, respectively. It should be noted that the peak frequency difference between the in-plane (E^1_{2g}) and out-of-plane (A_{1g}) vibration modes can be used to identify the number of MoS_2 layers. The frequency difference of the MoS_2 sample is 26 cm^{-1}, corresponding to a layer number of 2–5.[23] Figure 1(b) shows the FESEM image of the exfoliated MoS_2, which indicates the size of the flakes to be about $2 \times 5\,\mu m^2$.

Nonlinear optical properties are important criteria to determine the ability of each material to be applied as an SA. Figure 1(c) depicts nonlinear transmission profile which was measured by launching the 1550 nm mode-locked laser light into the SA's sample in twin-detector measurement configuration. The power intensities against transmission are fitted according to a simple two-level SA model.[24] With a modulation depth (α_s) of 11.8 %, saturation intensity (I_{sat}) of 21.5 MW/cm^2, and nonsaturable absorption (α_{ns}) of 27.7 %, it is confirmed that this MoS_2 has sufficient ability to be used as an SA.

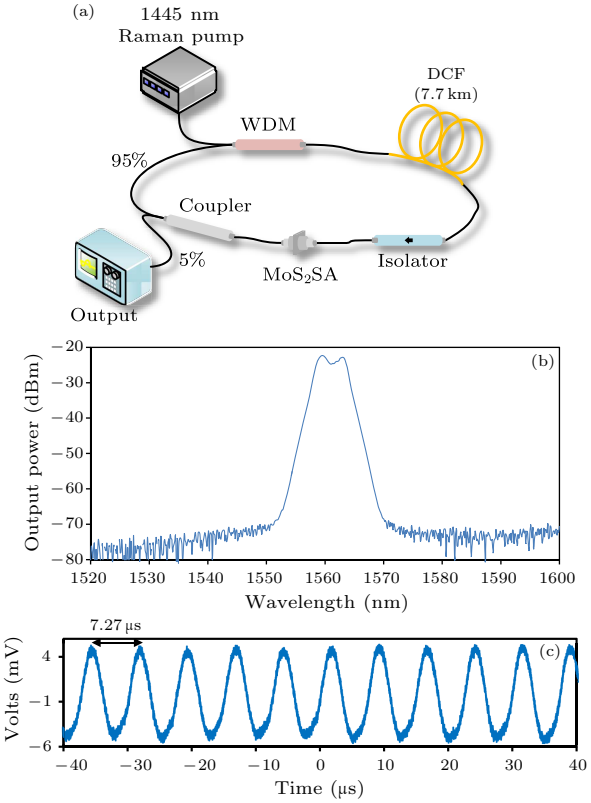

Fig. 2. (a) The proposed Q-switched RFL with a ring cavity configuration. (b) Output spectrum of RFL at 422 mW pump power. (c) Typical oscilloscope trace at the pump power of 422 mW.

The assembled all-fiber SA is then inserted in the RFL cavity for Q-switching experiment as shown in Fig. 2(a). It uses a 7.7-km-long dispersion compensating fiber (DCF) with 584 ps·nm^{-1}km^{-1} of dispersion as a nonlinear gain medium. The DCF was pumped by a 1455 nm laser via a 1455/1550 nm wavelength division multiplexer (WDM). The DCF was pumped by a 1455 nm fiber laser via a 1455/1550 nm wavelength division multiplexer (WDM). This S-band fiber laser has a linewidth of about 2 nm with the maximum output power of 20 W. It has a side-mode suppression ratio of about 17 dB at operating wavelength of 1455 nm. The isolator is incorporated in the setup to ensure the unidirectional operation of the laser and also to suppress the Brillouin backscattering which induces pulse instability. The signal was coupled out by using a 5/95 output coupler which keeps 95% of the light oscillating in the ring cavity. The output laser was tapped from a 5 % port of the coupler for both spectral and tempo-

ral diagnostics. The spectral characteristic was measured by using an optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm while the temporal characteristics were measured by using a 500 MHz oscilloscope and a 7.8 GHz rf spectrum analyzer via a 1.2 GHz photodetector. The total cavity length of the ring laser is around 8 km. Figure 2(b) shows the output spectrum of the Q-switched RFL at the pump power of 422 mW. It indicates that the laser operates at 1560.2 nm with 3 dB spectral bandwidth of 5.9 nm. It is also observed that the RFL generates a stable pulse train with an increasing repetition rate as the pump power is increased from 395 mW to 422 mW. Figure 2(c) shows the typical pulse train at the pump power of 422 mW. It is observed that the pulse train has the period of 7.27 μs without noticeable timing jitter, which corresponds to a pulse repetition rate of 137.4 kHz. To verify that the MoS_2 SA was responsible for the Q-switching pulse generation for the laser, the FC fiber ferrule filled with MoS_2 film was replaced with a clean ferrule. In this case, we observe no Q-switching pulse on the oscilloscope at any pump powers, which confirms the Q-switching operation was attributed to the MoS_2 SA.

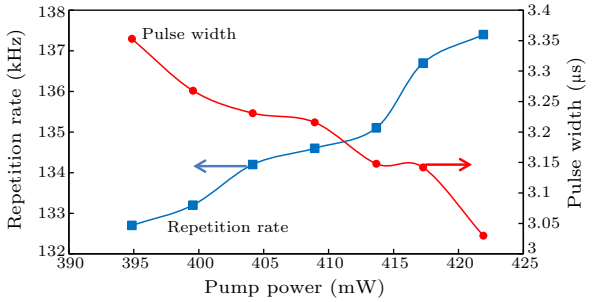

Fig. 3. Repetition rate and pulse width at various pump powers.

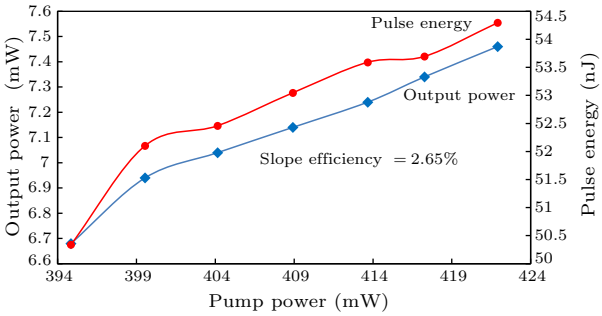

Fig. 4. Average output power and single pulse energy at various pump powers.

The pulse repetition rate and pulse width of the proposed Q-switched RFL are investigated as a function of the pump power. The results are plotted in Fig. 3, showing that the repetition rate of the Q-switching pulses can be increased from 132.7 to 137.4 kHz as the power of the pump is varied from 395 mW to 422 mW. Concurrently, the pulse width decreases from 3.35 μs to 3.03 μs. The pulse width could be decreased further by shortening the laser cavity length. In addition, the average output power and the corresponding single-pulse energy of the laser are also investigated at various pump powers. The results are plotted in Fig. 4. It shows that both the average output power and the pulse energy increase with the input pump power. The maximum average output power of the Q-switched laser is 7.46 mW while the slope efficiency is calculated to be around 2.65%. The slope efficiency is relatively low due to the high cavity loss and un-optimized gain medium length. The efficiency could be improved by using a gain medium with a higher nonlinearity, thus the total cavity length can be shortened. The maximum pulse energy of 54.3 nJ is obtained at the maximum pump power of 422 mW.

Figure 5 shows the corresponding rf spectrum at multi-mode pump power of 395 mW. As illustrated in Fig. 5, the fundamental repetition rate of the laser is obtained at 132.7 kHz with a signal-to-noise ratio of 42 dB. This indicates that the Q-switching operation is very stable. Agreeing to the Fourier transform, the peak of fundamental repetition rate gradually decreases until the third harmonic, and disappears. Throughout the experiment, we can confirm that no mode-beating frequency is present. This Q-switching performance could be further improved by optimizing the cavity design and the MoS_2 SA parameters such as modulation depth and insertion loss.

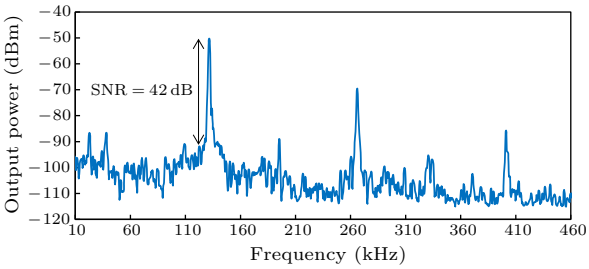

Fig. 5. The rf spectrum at pump power of 395 mW.

In summary, we have successfully demonstrated a Q-switched RFL using a MoS_2 SA as a Q-switcher. The Q-all-fiber switcher device is prepared by depositing a mechanically exfoliated MoS_2 onto a fiber ferrule facet before it is matched with another clean ferrule via a connector. The RFL cavity used a DCF as a nonlinear gain medium with a total cavity length of about 8 km. The SA is incorporated in the ring cavity to generate a Q-switching pulse train operating at 1560.2 nm. As the pump power is increased from 395 mW to 422 mW, the repetition rate increases from 132.7 to 137.4 kHz while the pulse width decreases from 3.35 to 3.03 μs. The highest pulse energy of 54.3 nJ is achieved at the pump power of 422 mW. These results show that MoS_2 is a new potential SA material for pulsed laser applications.

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