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Versatile soliton emission from a WS_2 mode-locked fiber laser

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ABSTRACT

Recently, few-layer tungsten disulfide (WS_2), as a shining 2D material, has been discovered to possess both the saturable absorption ability and large nonlinear refractive index. Here, we demonstrate versatile soliton pulses in a passively mode-locked fiber laser with a WS_2-deposited microfiber. The few-layer WS_2 is prepared by the liquid-phase exfoliation method and transferred onto a microfiber by the optical deposition method. Study found, the WS_2-deposited microfiber can operate simultaneously as a mode-locker and a high-nonlinear device. In experiment, by further inserting the WS_2 device into the fiber laser, besides the dual-wavelength soliton, noise-like soliton pulse, conventional soliton and its harmonic form are obtained by properly adjusting the pump strength and the polarization states. For the dual-wavelength soliton pulses and noise-like pulse, the maximum output power of 14.2 mW and pulse energy of 4.74 nJ is obtained, respectively. In addition, we also achieve the maximum harmonic number (135) of conventional soliton, corresponding to a repetition rate of ~497.5 MHz. Our study shows clearly that WS_2-deposited microfiber can be as a high-nonlinear photonic device for studying a plenty of nonlinear soliton phenomena.

1. Introduction

Since firstly demonstrated in 1986, mode-locked fiber lasers have gained great attentions owing to their potential applications in the fields of micromachine, sensing, optical metrology and biomedicine [1]. An important goal of the mode-locked fiber lasers is to achieve soliton operation. It provides an excellent framework for understanding complex nonlinear phenomena and stimulates novel cavity designs. Reciprocally, the mode-locked fiber laser serves as an ideal platform for testing the concept of solitons and revealing their versatile dynamics. By properly selecting the laser cavity parameters, various kinds of soliton pulses including conventional soliton, similariton [2], dissipative soliton [3], and noise-like soliton pulse [4], have been demonstrated in the lasers. Among them, the highly cavity nonlinearity plays an important role in the formation and evolution of soliton pulses [5–14]. Generally, to obtain high nonlinearity in the cavity it can be achieved by improving the pump power or inserting a length of highly nonlinear fiber. For example, Vazquez-Zuniga et al. obtained the noise-like pulses in a passively mode-locked fiber laser with a 12-m highly nonlinear fiber [15]. However, it greatly increases the cost and difficulty. Thus, it is urgent to seek the highly nonlinear photonic device.

Recently, 2D nanomaterials, namely graphene [16–20], topological insulators (TIs) [21–23], transition metal dichalcogenides (TMDCs) [24–28], and black phosphorus (BPs) [29,30], have gained great attention in physics, chemistry and material fields due to their potential applications. Among them, few-layer WS_2, as one of TMDCs, has been widely used for constructing mode-locked [31–39] or Q-switched [40–45] fiber lasers at the wavelength range of 0.6–2 μm due to their broadband saturable absorption and pulse-shaping ability. Interestingly, besides saturable absorption, few-layer WS_2 exhibits a huge Kerr refractive index with a value of 10^{-11} m^2/W due to the comprehensive contribution of both bound-electronic and free-carrier nonlinearities [38], which is one order of magnitude greater than that of graphene and favorable for versatile soliton pulse generation but not fully explored yet. Moreover, few study concerns the dual-property of the WS_2 device, namely, saturable absorption and high-nonlinearity, which relates to the real part and imaginary part of third-order nonlinear refractive index of few-layer WS_2, respectively. Thus, a question arises naturally: is it possible to generate the versatile soliton pulses in a fiber laser with few-layer WS_2? The exploration of this question will help us to understand the nonlinear optical property of few-layer WS_2 and design the novel lasers.

Here, we experimentally demonstrated the versatile soliton pulses in a passively mode-locked fiber laser with a WS_2-based microfiber. The WS_2 device can be as both a mode-locker and a high-nonlinear medium simultaneously. By utilizing the dual optical properties of

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the WS_2 photonic device, dual-wavelength soliton, noise-like pulse, conventional soliton and its harmonic form are obtained by properly adjusting the pump strength and the polarization state in the cavity. This work provides an example of the WS_2-deposited microfiber could both be as both a mode-locker and an excellent high-nonlinear medium for versatile soliton formation.

2. Preparation, characterization of microfiber-based WS_2 device

The high-quality WS_2 nanosheets as-used in this experiment were prepared through the liquid-phase exfoliation method [31]. The concentration of WS_2 nanosheets in the solvent is about 0.1 mg/ml, as shown in the inset of Fig. 1(a). Firstly, we transfer the WS_2 solution onto a sheet of quartz glass and dry at the room temperature so as to character its property. Then, the crystalline structure of the WS_2 material was characterized by using Raman system at 514 nm. Fig. 1(a) shows the Raman spectrum of the WS_2 nanosheets in the range of 280–480 cm^{-1}. It can be clearly seen that there are two typical Raman peaks located at ~352.6 and ~418.1 cm^{-1}, corresponding to in-plane vibrational mode E^1_{2g} and out-plane vibrational mode A_{1g} of S–W–S lattice vibration, respectively. Next, we characterized its morphological properties with a scanning electron microscopy (SEM) and atomic force microscope (AFM), as shown in Fig. 1(b) and (c), respectively, which reveal that the WS_2 material exhibits sheet-like structure with wide distribution.

To realize the all-fiber laser and further enhance the nonlinearity in the laser cavity, we will transfer the few-layer WS_2 onto the waist of microfiber with the optical deposition method, forming a microfiber-based WS_2 device. The microfiber with the waist diameter of ~20 μm, was prepared by fused taper method, as shown in the inset of Fig. 2. The saturable absorption property of the WS_2 device plays an important role for the generation of soliton pulse. Seen clearly from the Fig. 2, its saturation intensity, modulation depth and nonsaturation loss is about 42.6 MW/cm^2, 1% and 6.2%, respectively, which measured by power-dependent transmission scheme [38]. The as-used pump source is a mode-locked fiber laser. Its central wavelength, pulse width and repetition rate are 1550 nm, 300 fs and 15 MHz. Additionally, we provided the total cavity loss of the WS_2 device is about 3 dB, which was measured with an optical power meter.

3. Experimental setup

The experimental scheme of the mode-locked fiber laser is shown in Fig. 3. The pump source is a fiber-pigtailed 980 nm laser diode (980-420-B-FA, LD) and transferred the energy to a piece of ~5 m Erbium-doped fiber (Core active L-900, EDF) with dispersion parameter of ~−16.3 ps/(km nm) via a 980/1550 wavelength-division multiplexer (WDM). The single mode fiber (SMF) varies 50 m and 90 m and its dispersion parameter is ~18 ps/(km nm). A 10% optical coupler (OC) is used to extract the laser output. A polarization-independent isolator (ISO) is used for unidirectional operation of the fiber laser and a polarization controller (PC) is used to adjust the polarization state in the cavity, respectively. To enhance the nonlinear effect in the cavity, the microfiber-based WS_2 device was spliced right after the PC. The pulse information and laser power obtained is measured by an optical spectrum analyzer (YOKOGAWA, AQ-6370C) with the resolution of 0.01 nm, a 1 GHz mixed oscilloscope (Tektronix MDO4054-6, 5 GHz/s) combined with a high-speed photo-detector (Thorlabs PDA, 10 GHz) and an optical power meter, respectively.

4. Results and discussions

Before carrying out this experiment, we firstly measured the operation characteristics of the laser without incorporating the WS_2 device. By adjusting the pump power from 0 to 420 mW and polarization states from 0° to 180°, there is no mode-locking generation, which excludes the possibility of NPR and the Fabry–Perot effect in the cavity.

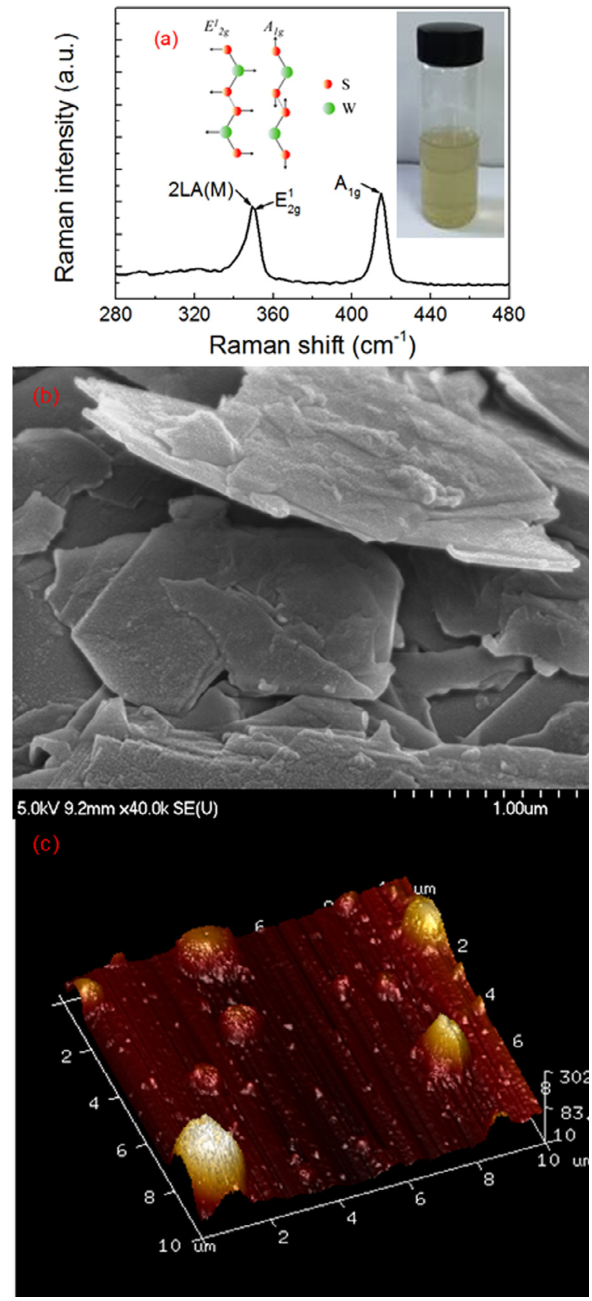

Fig. 1. Typical characteristics of the WS_2 nanosheets: (a) the Raman spectrum, inset: the photograph of WS_2 sample, (b) the SEM, and (c) the AFM.

Then, we inserted the WS_2-deposited microfiber into the laser cavity when the length of SMF is ~50 m, corresponding to the cavity dispersion parameter value of −1.09 ps^2. Initially, continue wave operation started at ~18 mW and the dual-wavelength mode-locking operation occurred at ~72 mW. Thereafter, the dual-wavelength soliton state can be achieved by properly adjusting the polarization states when the pump power continuously increased from 72 to 210 mW. Notably, the dual-wavelength soliton is developed from two CWs lasing, which indicates the existence of the cavity birefringence filter [46]. Normally, the filtering effect can be ignored in the weakly birefringent fiber lasers where the cavity birefringence induced artificial birefringence filter has a large bandwidth. However, the situation may be changed in our experiment. As mentioned above, if no WS_2 device exists, it will be no dual-wavelength lasing appears whatever adjust the pump power and polarization states in a wide range. Thus, the microfiber-based WS_2

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