Generation of Bright-Dark Soliton Pairs in Mode-Locked Fiber Laser Based on Molybdenum Diselenide

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ABSTRACT In this article, molybdenum diselenide (MoSe$_2$) was fabricated by chemical vapor deposition (CVD) with a modulation depth of about 7.3% and nonsaturable loss of about 30.6%. Bright-dark soliton pairs have been obtained in a thulium-holmium-doped fiber ring laser based on MoSe$_2$ as a saturable absorber (SA) for the first time, to the best of our knowledge. The results not only prove that MoSe$_2$ can be used as an excellent saturable absorber in the field of ultra-fast optics, but also provide a certain reference value for the future research on bright-dark soliton pairs based on two-dimensional materials.

INDEX TERMS Molybdenum diselenide, bright-dark soliton pairs, mode-locked fiber laser.

I. INTRODUCTION

Mode-locked fiber laser has been widely used in these fields of material processing, radar sensing, biomedical, scientific researches, and so on [1]. Under different operating conditions, mode-locked fiber laser can generate different types of solitons, such as traditional soliton [2], dissipative soliton [3], self-similar soliton [4], dark soliton [5], soliton rain [6], and soliton bunch [7]. What is more, there also exist bright-dark soliton pairs in the mode-locked fiber laser, which have a broad application prospect in the fields of spectroscopy, optical communication and soliton evolution. For the last few decades, bright-dark soliton pairs have been demonstrated theoretically though the nonlinear Schrödinger equation [8], [9] and have been realized experimentally in passively mode-locked fiber lasers [10]–[12]. Gao et al. have reported the study of graphene as a saturable absorber (SA) to obtain bright-dark soliton pairs, and they thought that the cross-phase modulation (XPM) was caused by different wavebands of bright pulse and dark pulse support the coexisting of the bright-dark soliton pair [15]. Recently, dual-wavelength bright-dark soliton pairs have also been observed in a fiber laser based on zirconium selenide (ZrSe$_2$) [16]. In view of complexity of features of TMDs, previous investigations on the bright-dark soliton pairs are still in the preliminary stage of exploration, and most of them are concentrated on 1.5 $\mu$m band, while the number of investigations on 2 $\mu$m band is relatively less. Therefore, it is crucial to explore new TMDs with decent performance to produce bright-dark soliton pairs.

As a member of TMDs, molybdenum diselenide (MoSe$_2$) has the advantages of narrower band gap, smaller line width and tunable exciton charging effect. The narrow bandgap of 1.1 eV (indirect), 1.5 eV (direct) and low optical absorption coefficient, these properties make MoSe$_2$ more suitable for wide-band saturated absorption and passive mode-locked fiber lasers than other sulfates [17], [18]. In particular, MoSe$_2$ also has a high third-order nonlinear refractive index ($10^{-11}$m$^2$/W) [19], which is much higher than topological insulator [20] and carbon nanotubes [21], this property demonstrated that bright and dark soliton pairs are orthogonal polarizations [14]. In 2018, Zhao et al. reported the study of the transition metal dichalcogenides (TMDs): ReS$_2$ as a saturable absorber (SA) to obtain bright-dark soliton pairs, they thought that the cross-phase modulation (XPM) was caused by different wavebands of bright pulse and dark pulse support the coexisting of the bright-dark soliton pair [15]. Recently, dual-wavelength bright-dark soliton pairs have also been observed in a fiber laser based on zirconium selenide (ZrSe$_2$) [16]. In view of complexity of features of TMDs, previous investigations on the bright-dark soliton pairs are still in the preliminary stage of exploration, and most of them are concentrated on 1.5 $\mu$m band, while the number of investigations on 2 $\mu$m band is relatively less. Therefore, it is crucial to explore new TMDs with decent performance to produce bright-dark soliton pairs.

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contributes to the generation of solitons. Relevant experiments have proved that the saturation absorption characteristics of MoSe$_2$ can obtain traditional soliton [22]–[24] or dissipative soliton [25]. So far, however, there have been no experimental reports on bright-dark soliton pairs based on MoSe$_2$-SA.

In this article, the bright-dark soliton pairs have been obtained in a thulium-holmium-doped fiber laser (THDFL) based on MoSe$_2$ as a SA. With the increase of pump power, the pulse shape of the bright-dark soliton pairs can be changed. The results show that MoSe$_2$ can be applied as an outstanding SA for the generation of bright-dark soliton pairs. In addition, our reports also provide some references for the future study of bright-dark soliton pairs based on two-dimensional materials.

II. PREPARATION AND CHARACTERIZATION OF THE SA

To prepare more efficient, complete, and flat MoSe$_2$ films, the CVD method was chosen. Specifically, in order to protect the integrity of MoSe$_2$ film, a layer of polymethyl methacrylate (PMMA) colloid was coated on the surface of MoSe$_2$ film, and the MoSe$_2$-PMMA film was transferred to the end face of the fiber adapter with tweezers. The PMMA layer was dissolved by the acetone solution to obtain MoSe$_2$ films. The Raman spectrum of MoSe$_2$ film detected by Raman spectrometer (Horiba HR-800) is shown in Fig. 1(a). The MoSe$_2$ film exhibits three characteristic Raman bands at 239 cm$^{-1}$, 284.3 cm$^{-1}$ and 450.1 cm$^{-1}$, which correspond to the A$_{1g}$, E$_{2g}$ and C modes, respectively. For peak C, the reason of davydov splitting [26]. From Fig. 1(b), it can be seen that the thickness was about 7 nm, corresponding to 10-layer MoSe$_2$.

The inset is the morphology of MoSe$_2$ observed by an atomic force microscope (AFM). A few layers of MoSe$_2$ films can withstand a higher power damage threshold and prevent MoSe$_2$ films from being damaged by high-intensity laser during the experiment. The nonlinear transmission of MoSe$_2$-SA was measured by using a mode-locked THFL with the pulse width of 18 ps, the central wavelength of 1925.76 nm and the output power of 38 mW. The double-arm balance detection method was adopted to record the light transmission of MoSe$_2$-SA under different pump powers. The measurements and fitting results of nonlinear optical characteristics of MoSe$_2$-SA are shown in Fig. 1(c). The modulation depth ($\Delta\alpha$) and nonsaturable loss ($\alpha_{ns}$) were measured to be $\sim$7.3% and $\sim$30.6%, respectively.

III. EXPERIMENTAL SETUP

The experimental schematic configuration of a thulium-holmium-doped fiber laser based on MoSe$_2$-SA is shown in Fig. 2. To achieve a more compact mode-locked structure, a ring cavity structure was adopted. A laser diode with maximum pumping power of 1 W at 1550 nm was used as the pump source. A wavelength division multiplexer (WDM) with a wavelength of 980/1550 nm was used for coupling the laser from the pump source into the laser cavity. The polarization independent isolator (ISO) was used to ensure unidirectional operation in the ring fiber laser and prevent the reflected laser from breaking the WDM. An extruded polarization controller (PC) was used to adjust the polarization state in the cavity. A 70:30 optical coupler (OC) was connected at the rear to obtain a 30% laser output. The optical spectrum of the laser was monitored by a spectrometric analyzer (Omni-λ750i, Zolix). The 3 GHz radiofrequency (RF) spectrum analyzer (FSL3, Ro-hde&Schwarz) and 1 GHz oscilloscope (Wave Runner 610Zi) were combined with a photodetector (ET-5000F, EOT) to monitor the spectrum and time-domain waveform. MoSe$_2$-SA was connected by sandwiching the MoSe$_2$ films between two fiber optic connectors (FC/APC) with a flange in the middle and integrated.
into the laser cavity. In addition, the total cavity length was \( \sim 91.5 \) m, including 2.5 m thulium-holmium-doped fiber (THDF, Coractive TH512), about 89 m single-mode fiber (SMF-28e) and 1.5 cm tapered fiber. The waist of the tapered fiber was about 10 \( \mu \)m, and the addition of SMF and tapered fiber can improve the high nonlinearity in the cavity, which was more conducive to the generation of solitons.

IV. RESULTS AND DISCUSSION

A. BRIGHT SOLITON OPERATION

The performance of the fiber laser without MoSe\(_2\)-SA has been studied for the first time. By adjusting the pump power and PC, during the entire measurement, neither the mode-locked state nor dual-wavelength operation were observed. After adding MoSe\(_2\)-SA into the cavity, the bright soliton can be observed by increasing the pump power to 350 mW and properly adjusting the PC. The single pulse profile of the bright soliton is shown in Fig. 3(a), the inset is the pulse train. The interval of the pulse train was 454.5 ns, which was consistent with the round-trip time of the cavity. The optical spectrum is shown in Fig. 3(b). It can be discovered that the central wavelength was 1983.6 nm and the full width at half maximum (FWHM) was 4.22 nm. In addition, there is no obvious kelly sideband in the optical spectrum. This phenomenon may be attributed to the spectral filtering effect which was caused by the combination of the polarization of the PC and the birefringence of the long SMF.

B. BRIGHT-DARK SOLITON PAIRS OPERATION

By increasing the pump power to 550 mW and adjusting the PC carefully, the bright soliton can be switched to the bright-dark soliton pairs. The reason for switching between solitons is the combined action of laser total gain, total loss, dispersion value and various nonlinear effects [5]. The single pulse profile of a typical bright-dark soliton pair is shown in Fig. 4(a), the inset is the pulse train. In the continuous wave background, the pulse intensity of the bright soliton and the dark soliton was almost the same. When the pump power was 850 mW, an interesting phenomenon was discovered.

The pulse width and amplitude of bright soliton and dark soliton were no longer the same. The pulse width of the bright soliton was 4.3 ns and the dark soliton was 3.8 ns. The single pulse profile of the bright-dark soliton pairs is shown in Fig. 4(b), this phenomenon attributed to the gain of the cavity and the nonlinear effect was similar to these articles [13], [27]. In order to further investigate the relationship between bright soliton and dark soliton, the bright-dark soliton pairs could be separated by adjusting an external cavity PC. Previous results implied that the bright soliton and the dark soliton were related to the polarization [14], [15]. This sequence of bright soliton and dark soliton is shown in Fig. 4(c). The corresponding optical spectra of the bright soliton, dark soliton and bright-dark soliton pairs are shown in Fig. 4(d). Two spectral peaks were located at 1981.5 nm and 1982.3 nm respectively. The bright soliton and the dark soliton were located at different wavebands, which may cause the XPM effect in the fiber. Due to the XPM effect, different wavebands of dark soliton and bright soliton could be coupled in a system and propagated in the same medium [28]. Generally speaking, the generation of temporal optical solitons is related to refractive nonlinearity and dispersion. In our experiments, MoSe\(_2\) can support the generation of third-order nonlinear effects because of its high third-order refractive index. Initial mode-locked pulse was generated due to the saturation absorption capacity of MoSe\(_2\), and then the pulse was.
while the XPM supported the coexistence of bright-dark soliton pairs in the same medium [29].

The laser performance under different pump powers has also been investigated. The pump power was increased by 0.1 W each time. The evolution of the pulse profile of bright-dark soliton pairs with the increase of pump powers is shown in Fig. 5(a). The amplitude and pulse width of the bright soliton changed greatly. The optical spectra under different pump powers are shown in Fig. 5(b). The optical spectrum was still dual-wavelength, but the intensity increased gradually. The relation between average output power, pulse energy and pump power is shown in Fig. 5(c). With the increase of pump power, the maximum pulse energy reached 2.31 nJ. There was an obvious linear relationship between

FIGURE 4. Performance of bright-dark soliton pairs: (a) Single pulse of bright-dark soliton pairs at a pump power of 550 mW. Inset: pulse train; (b) Single pulse of bright-dark soliton pairs at a pump power of 850 mW. Inset: pulse train; (c) Bright soliton and dark soliton; (d) Corresponding output spectra of bright soliton, dark soliton and bright-dark soliton pairs.

FIGURE 5. Performance of bright-dark soliton pairs under different pump powers: (a) Pulse distribution of bright-dark soliton pairs under different pump powers; (b) Spectral distribution of bright-dark soliton pairs under different pump powers; (c) Relationship between average output power and pulse energy and pump power.
average output power and pump power. Under the maximum pump power of 1 W, the maximum average output power was 5.1 mW, while the slope efficiency was only 1.1%. The low efficiency may be caused by the large loss of connection and transmission in the cavity. In future research, the parameters of the resonator will be further optimized, which are expected to improve the laser efficiency.

The XPM supports the coexistence of bright soliton and dark soliton. For the bright-dark soliton pair operation, we find that the pulse shape can be changed with the increase of pump power. To the best of our knowledge, this is the first report of bright-dark soliton pairs based on MoSe$_2$-SA. Our results have proved that MoSe$_2$ can be used as an excellent SA for the generation of bright-dark soliton pairs. To improve the laser efficiency, we will further reduce the cavity loss by optimizing the cavity length or depositing MoSe$_2$ on the tapered optical fiber in our future work.

V. CONCLUSION

In summary, bright-dark soliton pairs have been obtained in a Thulium-holmium-doped fiber ring laser based on MoSe$_2$-SA. The saturation absorption capacity of MoSe$_2$ is attributed to the formation of bright soliton and dark soliton.

Good or bad stability is the criterion to judge whether the bright-dark soliton pairs can be used or not. The RF spectrum was monitored by a spectrum analyzer, as shown in Fig. 6(a).

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