



# Ultrashort pulse generation in mode-locked erbium-doped fiber lasers with tungsten disulfide saturable absorber

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## ABSTRACT

Tungsten disulfide (WS<sub>2</sub>), as one of typical transition metal dichalcogenides with the characteristics of strong nonlinear polarization and wide bandgap, has been widely used in such fields as biology and optoelectronics. With the magnetron sputtering technique, the saturable absorber (SA) is prepared by depositing WS<sub>2</sub> and Au film on the tapered fiber. The heat elimination and damage threshold can be improved for the WS<sub>2</sub> SA with evanescent field interaction. Besides, the Au film is deposited on the surface of the WS<sub>2</sub> film to improve their reliability and avoid being oxidized. The fabricated SA has a modulation depth of 14.79%. With this SA, we obtain a relatively stable mode-locked fiber laser with the pulse duration of 288 fs, the repetition rate of 41.4 MHz and the signal to noise ratio of 58 dB.

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## 1. Introduction

Compared with solid-state lasers, fiber lasers have the advantages of easier integration and lower cost [1,2]. In fiber lasers, saturable absorbers (SAs) have been considered to be the effective method to achieve the passive mode-locking with wide spectral bandwidth and narrow pulse width. Besides, comparatively large nonlinear phase shift can be obtained without increasing the cavity length, which results in a higher repetition rate [3–5].

For saturable absorption materials used in SAs, graphene has attracted wide attention, and has been used to realize the passively Q-switching and mode-locking in fiber lasers [6–11]. Its property of broadband absorption makes it enable to be used in the wide spectral band. But, in generally, its modulation depth is approximately 1% [12–14]. Extremely high electron mobility [15–26] is another merit of graphene, however, its on-off ratio is often lower than 10, so it can only be used in some high-frequency devices. Other two dimensional (2D) materials mainly consist of topological insulator (TIs), transition metal dichalcogenides (TMDs), and black phosphorus (BPs). The BPs is a type of direct bandgap semiconductor, its forbidden band width is about 0.3–1.5 eV [27–30]. This value lies between the zero bandgap graphene and the larger bandgap TMDs. Its biggest feature is the anisotropic character,

but the electron mobility is less than that of graphene, and on-off ratio is less than that of TMDs [27,28]. The type of the energy band structure of TIs is insulator, and the energy gap exists at the Fermi level. But the surface of TIs has Dirac-like electronic states which can pass through the bandgap. TIs have large nonlinear effect and modulation depth (more than 70% at 1570 nm [31]), while their electron relaxation time is shorter than 300 fs, which indicates that it is a relatively slow saturable absorbent material compared to graphene. Besides, it can be easily damaged in the application of ultrafast optics due to its low damage threshold [32–43]. For TMDs, they have the higher nonlinear optical property, on-off ratio and a relatively large band gap. With the decrease of the number of layers, the indirect band gap can become the direct band gap [44–52].

So far, researches have used some methods to insert SAs into the cavity of lasers. The transmissive structure has been used in the early experiment: WS<sub>2</sub> was transferred onto the polyvinyl alcohol (PVA) sheet, which is inserted between two flanges [48–51]. But the insertion loss is increased to some extent, and the pulse duration is usually picosecond. Besides, it can be easily damaged because of the low threshold. Another method is WS<sub>2</sub> solution is deposited onto the surface of the tapered fiber [53,54]. This method can not guarantee the solution be deposited on the

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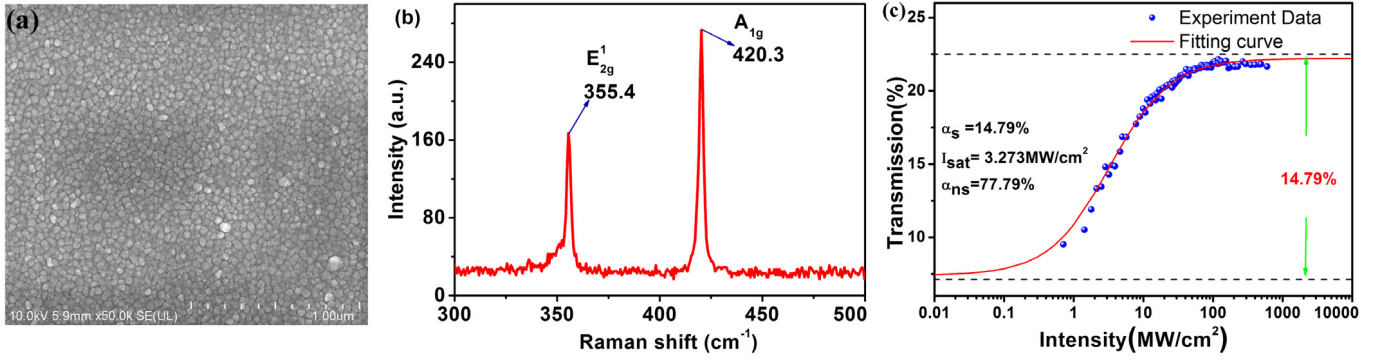


Fig. 1. (a) SEM characteristic of the fiber-taper WS<sub>2</sub> SA; (b) Raman spectra of the fiber-taper WS<sub>2</sub> SA; (c) Nonlinear saturable absorption of the fiber-taper WS<sub>2</sub> SA. The modulation depth is about 14.79%, the saturation intensity is 3.273 MW/cm<sup>2</sup>, and the nonsaturable loss is about 77.79%.

tapered fiber surface uniformly, and the long-term exposure in the air can cause 2D materials be oxidized easily. In our experiment, with the magnetron sputtering technique, the SA is fabricated by depositing the WS<sub>2</sub> on the tapered fiber. The Au film are coated on WS<sub>2</sub> films to avoid being oxidized. Due to the high nonlinearity of the fiber-taper WS<sub>2</sub> SA, the pulse duration has been effectively narrowed in fiber lasers, and is measured to be 288 fs.

## 2. Characterization of the fiber-taper WS<sub>2</sub> SA

The diameter of the tapered fiber is about 20 μm, and the length of the fused zone is 3 mm. The smaller the tapered fiber diameter of the fused zone is, the greater the evanescent field strength will become. Thus, changing the tapered fiber diameter of the fused zone for the WS<sub>2</sub> SA can control the nonlinearity. We conduct the scanning electron microscope (SEM) of the SA as shown in Fig. 1(a), which confirms that the fused zone of the tapered fiber is indeed covered WS<sub>2</sub> uniformly.

For a more detailed understanding of the properties of the WS<sub>2</sub> materials used in the experiment, we measured the Raman spectra of the WS<sub>2</sub> material. The Raman spectrum is a scattering spectrum, which is based on the Raman scattering effect and analyzes the scattering spectrum different from the incident light frequency to obtain the molecular vibration and rotation information. In Fig. 1(b), we can see that the Raman peaks of WS<sub>2</sub> are located at 355.4 cm<sup>-1</sup> and 420.3 cm<sup>-1</sup>, which belong to E<sub>2g</sub><sup>1</sup> and A<sub>1g</sub> vibration modes respectively. E<sub>2g</sub><sup>1</sup> belongs to in-plane vibration mode, A<sub>1g</sub> belongs to out-of-plane vibration mode. With the balanced twin-detector method, the experimental datas of the modulation depth have been obtained. In Fig. 1(c), we fitted the curve by the two-level model,

$$T = 1 - \left( \frac{\alpha_s}{1 + \frac{I}{I_{sat}}} + \alpha_{ns} \right), \quad (1)$$

where  $T$  is the transmittance,  $\alpha_s$  is the saturable loss,  $\alpha_{ns}$  is the non-saturable loss,  $I$  is the input intensity, and  $I_{sat}$  is the saturation intensity. The fitted values of the modulation depth  $\alpha_s$  of the SA is 14.79%, the saturation strength is 3.273 MW/cm<sup>2</sup>, and the non-saturable loss  $\alpha_{ns}$  is 77.79%.

## 3. Experimental setup and results of passively mode-locked EDF lasers based on the fiber-taper WS<sub>2</sub> SA

WS<sub>2</sub> is used as the saturable absorption materials for the SA in the all fiber ring cavity lasers with erbium-doped fiber as gain medium. As shown in the Fig. 2, the ring cavity is composed with the laser diode (LD), wavelength division multiplex (WDM), erbium-doped fiber (EDF, Liekki 110-4/125), optical coupler (OC), polarization controller (PC), polarization dependent isolator (ISO) and WS<sub>2</sub> SA. The LD we used is a semiconductor laser with a center wavelength of 976 nm and the maximum pump power of 630 mW. The pump light is coupled into the

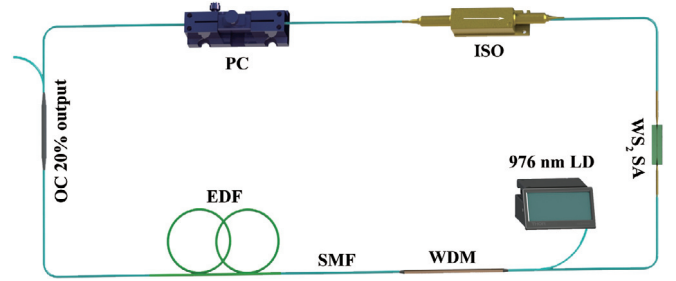


Fig. 2. Schematic diagram of all-fiber mode-locked laser based on the fiber-taper WS<sub>2</sub> SA. LD is the laser diode; WDM is the wavelength division multiplexer; EDF is the erbium-doped fiber; OC is the optical coupler; PC is the polarization controller; ISO is the isolator.

ring cavity by the WDM with the leading fiber of SMF28. EDF forms the inversion between upper and lower energy levels after the absorption of pump light, which results in the spontaneous emission to achieve amplification. The proportion of OC we used in experiment is 80:20, so we can output the mode-locked pulse by OC. The isolator is connected to the PC to guarantee the single-direction operation. PC changes the polarization state of transmitted light by changing the deformation of the fiber, which facilitates the realization of mode-locked pulses. Our mode-locked pulses are measured at the 20% output of OC.

In Fig. 3(a), we can see that we get a relatively neat lock sequence map, and our mode-locked state is relatively stable. The maximum output power of the fiber laser is 18.4 mW with the 630 mW pump power. The mode-locked state has a spectral width of 19 nm at 3 dB as we can see in Fig. 3(b), the evident Kelly sidebands on the spectrum can be clearly observed, which indicates that the mode-locked laser is operating in typical soliton regime [55,56]. The pulse duration measured with an autocorrelation instrument is 288 fs in Fig. 3(c). When the resolution is 10 Hz and the range is 10 kHz, we obtain the steady-state repetition rate of 41.4 MHz and the SNR is 58 dB as shown in Fig. 3(d).

## 4. Conclusions

Mode-locked EDF fiber lasers have been demonstrated at 1560 nm. By using the magnetron sputtering technique, WS<sub>2</sub> and Au film have been deposited on the tapered fiber to prepare the SAs with evanescent field interaction. The heat elimination and damage threshold of SAs can be improved. Also, the oxidation of WS<sub>2</sub> have been avoided with the Au film deposited on the surface of WS<sub>2</sub>. The stable mode-locked pulse has been obtained based on the WS<sub>2</sub> SA, whose modulation depth is 14.79%. For the output mode-locked pulses, the repetition rate is 41.4 MHz, the SNR is 58 dB, and the pulse duration is 288 fs. The results of this paper show that the WS<sub>2</sub> materials fabricated by using the magnetron sputtering technique can obtain a wider spectral width and a shorter pulse duration.

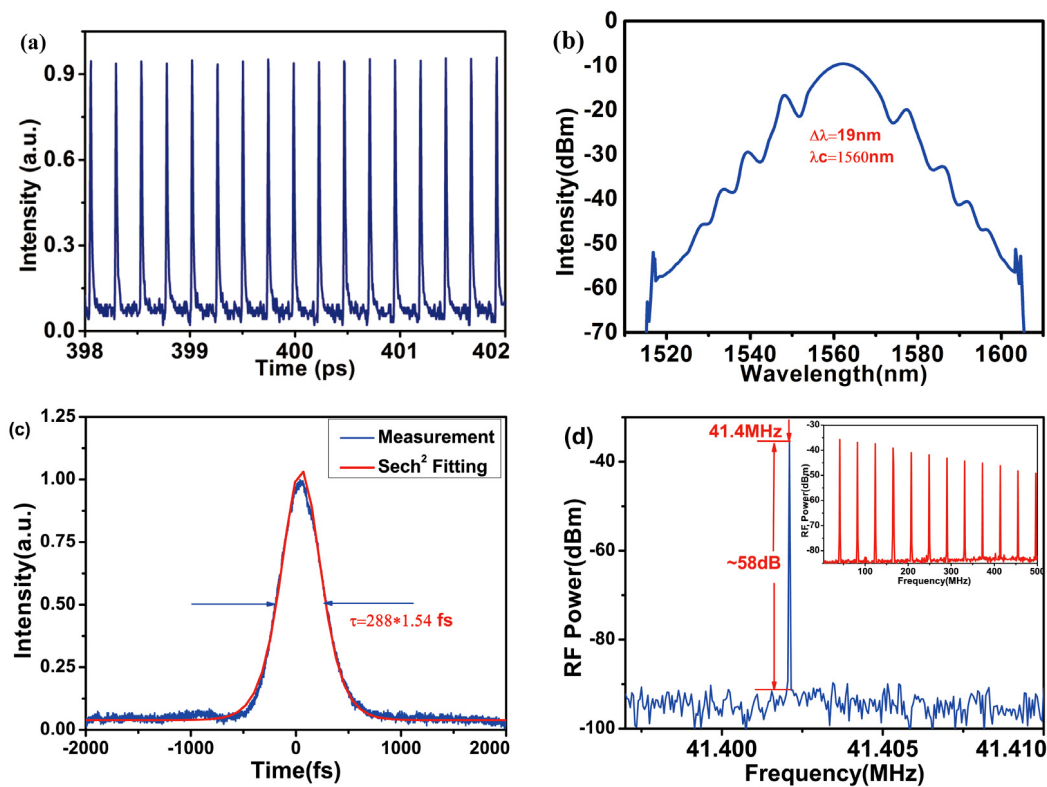


Fig. 3. Experimental results of the passively mode-locked laser based on the fiber-taper WS<sub>2</sub> SA. (a) Mode locked pulse sequence. (b) Optical spectrum of the generated pulses. The 3 dB spectral width is 19 nm at 1560 nm. (c) Intensity autocorrelation trace with 288 fs pulse duration. (d) Radio frequency (RF) spectrum with 58 dB SNR measured with 10 kHz RBW.

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