$MoTe_2$ Saturable Absorber With High Modulation Depth for Erbium-Doped Fiber Laser

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***Abstract*—Transition metal dichalcogenides have recently been considered the candidates for saturable absorption materials due to their advantages in both electronic and optoelectronic. Compared with MoS_2 and WS_2, $MoTe_2$ exhibits smaller bandgap. As a result, $MoTe_2$ owns inherent advantages in the near-infrared applications. In this paper, the $MoTe_2$ saturable absorber (SA) were prepared by the magnetron sputtering deposition method. Owing to the enhanced light-materials interaction between $MoTe_2$ and evanescent field from the microfiber, the modulation depth of the $MoTe_2$ SA was up to 26.97%. By assembling the $MoTe_2$ SA into the erbium-doped fiber laser, the mode-locked fiber laser at 1.5 μm was demonstrated. The pulse duration of 111.9 fs was proved to be the shortest in the fiber lasers based on transition metal dichalcogenides. Moreover, the mode-locked fiber laser maintains the long-term stability. Our results suggest that the proposed $MoTe_2$ SA is promising for the ultrashort pulse generation and stable system operation.**

***Index Terms*—Fiber lasers, mode-locked laser, nonlinear optical materials, saturable absorbers.**

I. Introduction

ULTRAFAST fiber lasers have attracted much attention over the recent decades owing to their extensive applications in medicine, manufacturing, communication and fundamental sciences [1]–[4]. SAs as the key optical devices of fiber lasers, have been the research focus in ultrafast optics. After the elimination of dyes, the semiconductor saturable absorber mirrors (SESAMs) have become popular SAs in passively Q-switched and/or mode-locked lasers [5]. However, the narrow operating bandwidth, complex manufacturing process, low damage threshold and high cost limit the further development of SESAMs [6]–[9]. Lately, the first experimental observation of graphene aroused the research upsurge of two-dimensional (2D) materials and the laser development has been injected with new vitality [6]–[14].

So far, there are some mature materials to select from, which include not only the commonly used graphene, topological insulator and black phosphorus, but also some new materials with excellent performance [15]–[20]. Among them, transition metal dichalcogenides (TMDs) have recently emerged as the potential candidates due to their superior properties in both electronic and optoelectronic [21]–[23]. The indirect bandgap of TMDs in bulk weaken the light-matter interaction, while the direct bandgap of few-layer TMDs enhance light activity. It has demonstrated that layered TMDs exhibit remarkable thickness-dependent electronic and optical properties [24], [25], which lead to the ultrafast nonlinear optical absorption and high carrier mobility. As two high performance saturable absorption materials, which are comparable to graphene, molybdenum disulfide (MoS_2) and tungsten disulfide (WS_2) have been extensively studied [26]–[29]. It has reported that the increase of chalcogenide atom mass (from S to Se to Te) will reduce the band gap of corresponding material [30]. As a result, $MoTe_2$ exhibits smaller direct bandgap of 1.10 eV in monolayer and indirect bandgap of 1 eV in bulk compared with commonly studied MoS_2 and WS_2 [31]. The smaller bandgap of $MoTe_2$ promotes it a promising candidate for near or near-infrared wavelength regime.

In addition to the material itself, the structure is also a significant part affecting the characteristics of SA. According to the previous research, some commonly used structures of SAs mainly include: mirrors [32]–[34], sandwiches [35]–[38] and micro-fiber structures [39]–[41]. The mirror structure relies heavily on the tight vertical contact between the fiber connector and the mirror, which is difficult and unstable. In sandwich structure, the material is sandwiched between two fiber connectors matched by adapter. This structure is not conducive to heat dissipation. In contrast, the micro-fiber structure is effective and easy to implement. On the one hand, the light-matter interaction is realized by the evanescent field of the light beam, which avoid the heat accumulation [42]. On the other hand, the proper selection of the waist diameter and the effective length will enhance the nonlinearity of the whole SA. As we know, the small tapered diameter and long effective length are able to enhance the nonlinearity of SAs [43], [44]. Therefore, the micro-fiber structure is considered to be the most suitable structure in the experiment.

In this paper, the $MoTe_2$ SA was fabricated by the magnetron sputtering deposition (MSD) method. Owing to the enhanced

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light-materials interaction between $MoTe_2$ and evanescent field from the microfiber, the modulation depth of the $MoTe_2$ SA is up to 26.97%, which is higher than that of the $MoTe_2$ SA with sandwich structure [31]. The passively mode-locked fiber laser employed with the prepared $MoTe_2$ SA was successfully implemented at 1.5 μm regime. The average output power and signal-to-noise ratio (SNR) of proposed fiber laser were 23.4 mW and 92.5 dB, respectively. The corresponding pulse duration was 111.9 fs. Compared with previous reports, the 111.9 fs pulse duration is the shortest among TMDs-based fiber lasers. Moreover, the mode-locked system maintains the long-term stability. This great progress in pulse duration and stability proves that the proposed $MoTe_2$ SA has great application prospects in realizing stable ultrafast lasers.

II. Experimental Results

A. Fabrication and Characterization of the $MoTe_2$ SA

The $MoTe_2$ SA was fabricated by the MSD method, the production process of the $MoTe_2$ SA is briefly described as follows. Before the manufacture, $MoTe_2$ target and tapered fiber were prepared in advance. To enhance light-materials interaction and strengthen nonlinearity of SA, the tapered fiber with small tapered diameter and long effective length is preferred. The tapered diameter and effective length of selected tapered fiber were 15 μm and 1 cm. The purity of $MoTe_2$ was 99.99%. During production, the tapered fiber was fixed in the vacuum chamber. By employing vacuum pump, the pressure of vacuum chamber was pulled to 3×10^{-3} Pa. After the bombardment of ionized Ar, $MoTe_2$ plasma plume were inspired from the target. Then, inspired $MoTe_2$ plasma plume were uniformly deposited on the outer wall of the tapered fiber. The fiber rotates at a uniform speed to ensure the uniformity of the film during the production.

The scanning electron microscope (SEM) is generally considered to be a convenient and efficient way to characterize the surface state of materials. As shown in Fig. 1(a), the arrangement of materials was uniform and regular according to the surface morphology of materials. From the lateral surface of $MoTe_2$ indicated in Fig. 1(b), the thickness of $MoTe_2$ film was 99.2 nm. The detailed elemental composition and corresponding bonding types were detected accurately by X-ray photoelectron spectroscopy (XPS). From the spectra of Mo in Fig. 2(a), two prominent peaks represented by solid lines locate at 228.5 eV and 231.8 eV. According to previous reports [45], the peak appears at 228.5 eV is attributed to Mo $3d_{5/2}$ and the peak appears at 231.8 eV is attributed to Mo $3d_{3/2}$. Two weak peaks of 233 eV and 236.1 eV represented by dotted lines are assigned to Mo-O bonds. Similarly, the spectra of Te is given in Fig. 2(b). The peak at 573.1 eV corresponds to Te $3d_{5/2}$, and the peak at 583.6 eV corresponds to Te $3d_{3/2}$. The weak peaks at 577 eV and 587.3 eV are assigned to Te-O bonds. The two Mo-O and Te-O impurity mentioned above indicate that $MoTe_2$ is slightly oxidized. We speculate that this weak oxidation phenomenon may originate from the edge of the material, and the effect on the experiment is negligible.

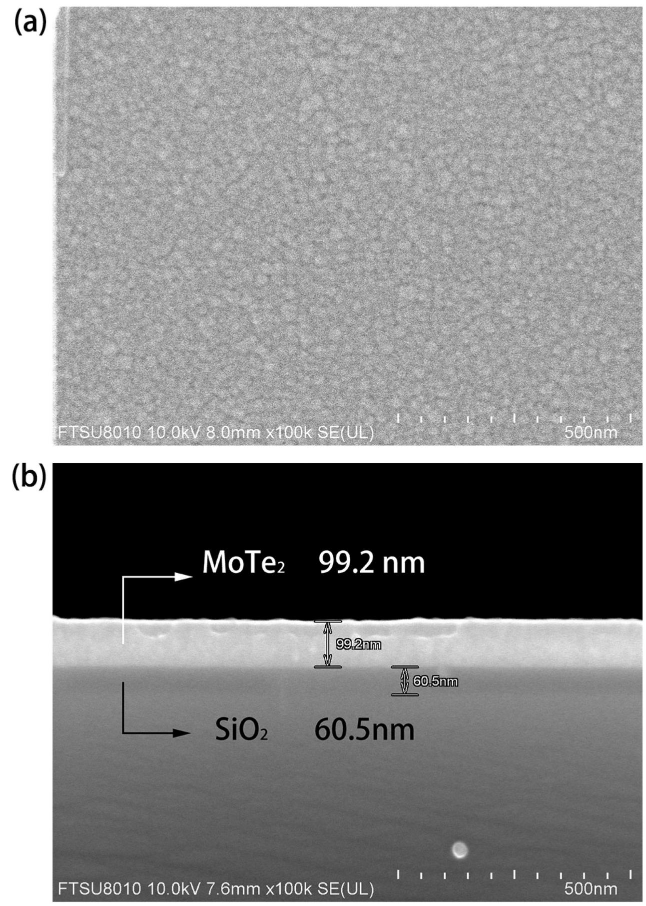

Fig. 1. SEM of the $MoTe_2$ SA. (a) The surface morphology; (b) The thickness of $MoTe_2$ indicated by lateral surface.

The nonlinear optical absorption property of the $MoTe_2$ SA were studied by means of the balanced twin detector measurement technology. The pulse duration of the erbium-doped mode-locked fiber laser employed in the experiment was 600 fs, the corresponding fundamental frequency was 120 MHz. The data were well fitted by the formula

$$\alpha(I) = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns}$$

As it presented in Fig. 3, the modulation depth of as-prepared $MoTe_2$ SA is up to 26.97%. The calculated optical to optical efficiency of this SA is 44%.

B. Experimental Setup of Mode-Locked Fiber Laser Based on the $MoTe_2$ SA

The optical nonlinearity of the prepared microfiber-based $MoTe_2$ SA is further investigated by means of a classical all fiber cavity, and the schematic diagram is shown in Fig. 4. The mature commercial laser diode (LD) operates at 980 nm with the maximum power of 630 mW was adopted as the pump source. The wavelength division multiplexing (WDM, 980/1550 nm) was responsible for pumping light into the ring cavity. As the gain medium, erbium-doped fiber (EDF) was used to enhance

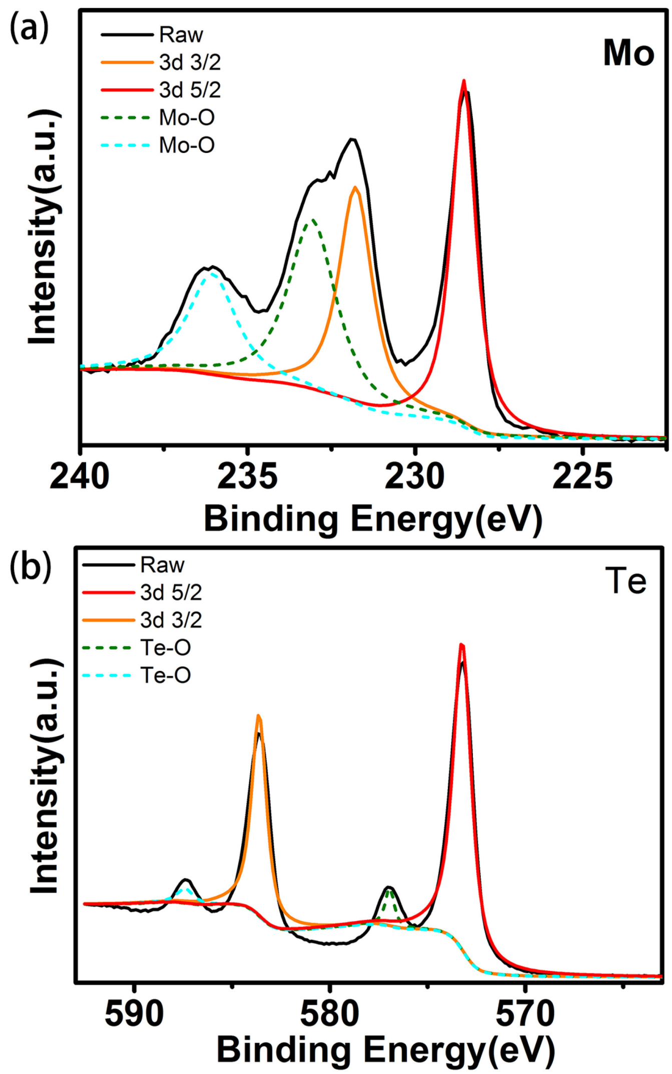

Fig. 2. The XPS of $MoTe_2$ SA (a) XPS spectra of Mo; (b) XPS spectra of Te.

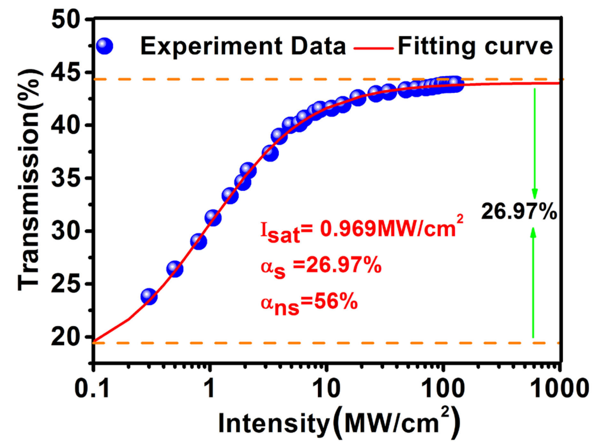

Fig. 3. The nonlinear response of the $MoTe_2$ SA.

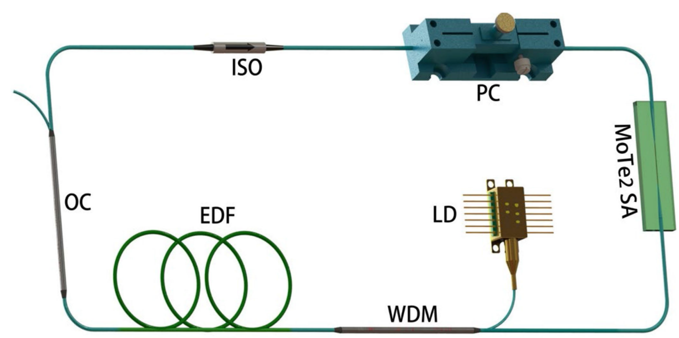

Fig. 4. The experimental scheme of the $MoTe_2$-based fiber laser.

the light. To guarantee the unidirectional laser transmission, the isolator (ISO) was used to prevent the backpropagation of light. To change the polarization state of the intra-cavity beam and optimize the operation state of the laser, the polarization controller (PC) was employed. The 20:80 optical coupler (OC) was served as the output media, the 20% of light in the cavity was extracted for measurement and monitoring. With the help of commonly used experimental detection devices, such as optical spectrum analyzer (Yokogawa AQ6370C), signal & spectrum analyzer (FSW 26, Rohde & Schwarz) and oscilloscope (Tektronix DPO3054), experimental data and real-time status were recorded in time.

The threshold of the mode-locked operation is 270 mW. The interval of mode-locked pulses is 10.4 ns as shown in Fig. 5(a). The long time spectrum of the mode-locked operation is revealed in Fig. 5(b), which indicates that the laser operates steadily at 1561 nm and the corresponding 3 dB bandwidth is 24.9 nm. The RF spectrum with the span and resolution of 20 kHz and 10 Hz is shown in Fig. 5(c), which indicates the fundamental repetition rate and SNR are 96.323 MHz and 92.5 dB. Furthermore, the broadband RF spectrum with a range of 800 MHz is given in illustrations. The uniform downward trend reflects the good stability of mode-locked operation. Fig. 5(d) shows the smooth autocorrelation trace of obtained mode-locked pulses. The pulse duration is given as 111.9 fs after the appropriate fitting with $sech^2$ profile. The corresponding time-bandwidth product of mode-locked system is 0.3428, which indicates that the mode-locked pulses are slightly chirped. The damage threshold of the $MoTe_2$ SA is about 61.7 mJ/cm^2.

The variation trend of output power with pump power is revealed in Fig. 6(a). When the pump power increases evenly, the output power also increases at a uniform rate. Even when the maximum power is reached, the trend is also changing along the line, which indicates that the $MoTe_2$ SA can withstand higher power under stable working conditions. The maximum output power is 23.4 mW. The long term power stability monitoring is shown in Fig. 6(b). After eight hours of monitoring in laboratory environment, the output power jitter is only 0.10432, which indicates that the mode-locked system implemented has remarkable stability. Fig. 6(c) measure the timing jitter of the fiber laser. The timing jitter of 200 fs further proves the mode-locked state of the system is very stable.

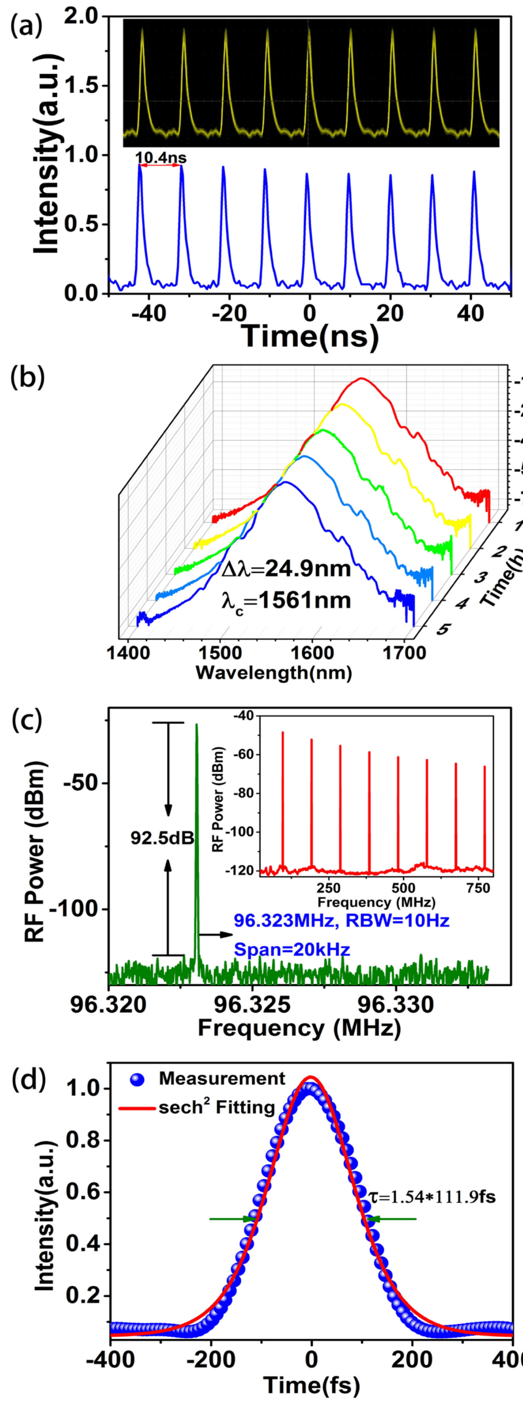

Fig. 5. (a) The sequence of mode-locked operation; (b) The spectral; (c) The RF spectrum; (d) The autocorrelation trace.

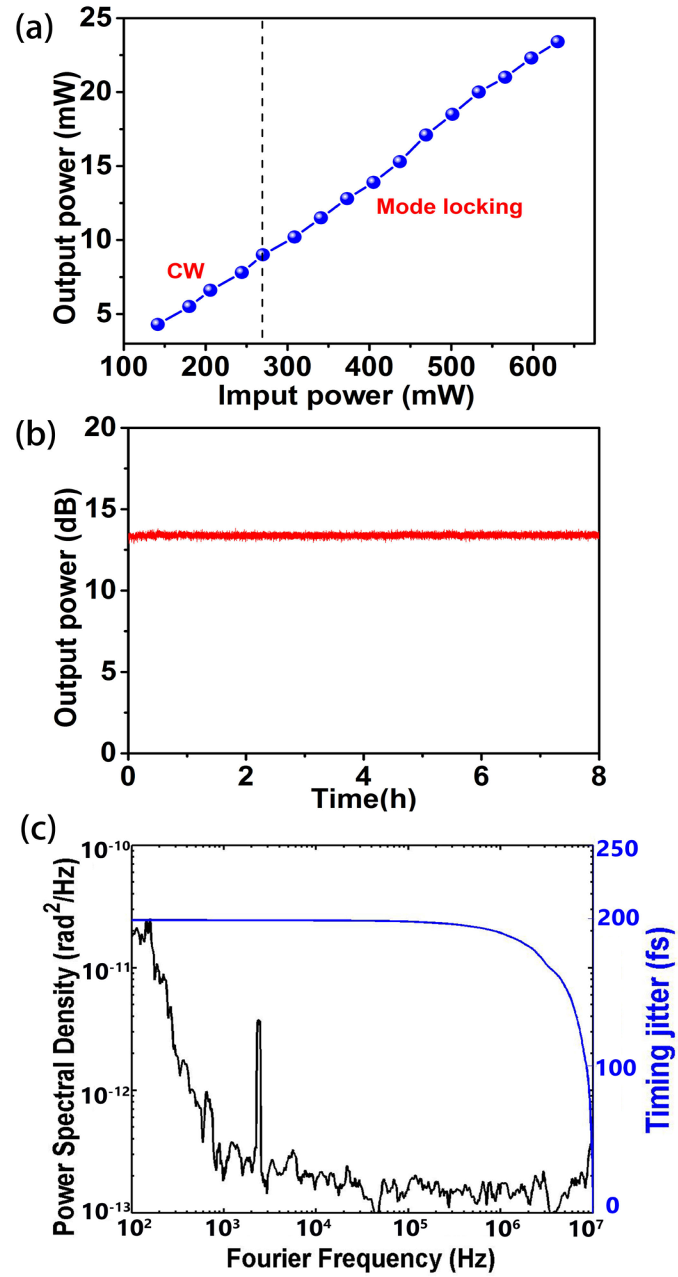

Fig. 6. (a) The variation trend of output power with pump power; (b) The long term power stability monitoring; (c) Phase noise measurement.

III. Discussion

When the microfiber-based $MoTe_2$ SA is removed, the mode-locked pulses can no longer be observed, which indicates that the $MoTe_2$ SA plays an essential role in mode-locking operation. In addition, we note that the pulse duration of this mode-locked based on the $MoTe_2$ SA is superior. To speak volumes for this point, the performance of lasers based on different materials have been compared in Table I. As shown in Table I, besides

TABLE I
CONTRASTS OF MODE-LOCKED FIBER LASERS WITH DIFFERENT 2D MATERIALS

Materials	MD (%)	$\lambda_0/\Delta\lambda$(nm)	τ(fs)	SNR(dB)	Refs.
Graphene	11	1545/48	88	65	47
BPs	8.1	1571.45/2.9	946	70	48
Bi_2Se_3	5.2	1600/7.9	360	56	49
WS_2	7.8	1560/6.75	395	64	33
MoS_2	0.2	1560/20.5	200	84	50
$MoTe_2$	1.8	1561/2.4	1200	>50	30
$MoTe_2$	0.7	1559.3/1.06	2460	62	51
$MoTe_2$	26.97	1561/24.9	111.9	92.5	This work

the carbon-based materials, the pulse duration of 111.9 fs in this paper is the shortest. We attribute the generation of short pulses to the large modulation depth of the $MoTe_2$ SA. Because the large modulation depth is good for ultrashort pulses.

On the one hand, the tapered fiber allows a long light-matter interaction length. In commonly used sandwich structures, the interaction length of light and material is limited by the thickness of the material, often in the nanoscale. However, in tapered fibers, it can be extend to centimeter-scale by means of evanescent field effect. This sufficient reaction of light and material enable the $MoTe_2$ material to fully exhibit its nonlinearity. On the other hand, the diameter of tapered fiber can also affect the nonlinearity of SA. According to previous studies [46], SAs owning small waist diameter tend to show larger modulation depth. Therefore, we attribute the high modulation depth of SA to the tapered fiber structure. In other words, the tapered structure plays an important role in optimizing the performance of mode-locked fiber laser.

In addition, from the long-term output power monitoring and the time jitter of laser, the proposed system exhibits superior stability. In our opinion, it is related to the short cavity length of proposed laser. Based on the traditional ring cavity, the repetition frequency of the laser is as high as 96.323 MHz, which indicates that there are almost no surplus fibers in the cavity except for the necessary optical fibers connecting devices. This choice reduces the unnecessary interference in the cavity and makes the laser compact and stable. All the results indicate that the proposed $MoTe_2$ SA not only has great potential in achieving ultrashort pulses, but also performs well in achieving the stable system.

IV. Conclusion

In conclusion, the mode-locked EDF laser has been successfully implemented based on the $MoTe_2$ SA. The $MoTe_2$ SA has been fabricated by the MSD method. The selected microfiber has owned small tapered diameter and long effective length, which allowed a long light-matter interaction length and enhanced the nonlinearity of the $MoTe_2$ SA. As a result, the modulation depth of the $MoTe_2$ SA is up to 26.97%. The output power and SNR of the proposed EDF laser are 23.4 mW and 92.5 dB, respectively. The long time stability of the mode-locked system has also been impressive. Most notably, the pulse duration of 111.9 fs obtained in the experiment is the shortest among the TMDs fiber lasers. In addition, from the long-term output power monitoring and the time jitter of the fiber laser, the proposed system has exhibited superior stability. All the results indicate that the proposed $MoTe_2$ SA has good performance as an ultrafast photonic device.

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