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TOPICAL REVIEW— Nanophotonics

Two-dimensional materials-decorated microfiber devices for pulse generation and shaping in fiber lasers*

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Two-dimensional (2D) materials have been regarded as a promising nonlinear optical medium for fabricating versatile optical and optoelectronic devices. Among the various photonic applications, the employment of 2D materials as nonlinear optical devices such as saturable absorbers for ultrashort pulse generation and shaping in ultrafast lasers is one of the most striking aspects in recent years. In this paper, we review the recent progress of 2D materials based pulse generation and soliton shaping in ultrafast fiber lasers, and particularly in the context of 2D materials-decorated microfiber photonic devices. The fabrication of 2D materials-decorated microfiber photonic devices, high performance mode-locked pulse generation, and the nonlinear soliton dynamics based on pulse shaping method are discussed. Finally, the challenges and the perspective of the 2D materials-based photonic devices as well as their applications are also discussed.

Keywords: two-dimensional materials, microfiber, soliton dynamics, fiber lasers

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1. Introduction

Ultrafast lasers capable of generating ultrashort pulses play an important role in a wide range of fields ranging from fundamental science to industrial purposes,[1–3] enabling rapid development of ultrafast science and technology.[1,4,5] An ultrashort pulse can be routinely generated from fiber lasers by the principle of passive mode locking technology.[6–9] A straightforward way to achieve the passive mode-locking operation is to insert a nonlinear optical element, also known as saturable absorbers (SA) into the laser cavity.[7] With the great advances made both in laser and fiber technologies, the performance of the ultrafast fiber lasers could be comparable with the solid-state lasers. Generally, the pulses emitted from fiber lasers can be regarded as optical solitons after achieving the passive mode locking operation. Due to the high peak power of the mode-locked pulse, the soliton pulse circulating along the laser cavity will exhibit some interesting nonlinear dynamics by the combination of the intracavity nonlinear effect and the cavity parameter selections. Therefore, in addition to being an ultrashort pulse source, an ultrafast fiber laser is also actually a nonlinear optical system which provides a good platform for investigating various soliton dynamics and nonlinear phenomena.[10] Indeed, by tuning the cavity parameters such as nonlinearity, birefringence, and dispersion, many soliton nonlinear phenomena and dynamics can be observed in fiber lasers, i.e., soliton explosions,[11–15] dissipative soliton resonance,[16–20] multi-soliton patterns,[21–23] vector solitons,[24–28] and dark solitons.[29,30] These discovered soliton dynamics further demonstrated that the fiber lasers are indeed valuable for fundamental research. In fact, in a fiber laser cavity, the investigation of soliton nonlinear dynamics generally needs the saturable absorption effect, nonlinearity controlling, and dispersion engineering. Therefore, if we suppose that a single photonic device simultaneously provides both functions of the saturable absorption and nonlinearity controlling, it would be useful for the investigation of soliton nonlinear phenomena in ultrafast fiber lasers.

On the other hand, since two-dimensional (2D) materials were first discovered in 2004,[31] the interest for fabricating high-performance, next-generation optical and optoelectronic devices based on 2D materials has been greatly stimulated.[32–35] Among the various photonic applications, the use of 2D materials as broadband and cost-effective saturable absorbers (SAs) has become one of the most intriguing topics in recent years.[36,37] Graphene, as a representative 2D material, has been discovered to possess excellent nonlinear optical properties, such as wavelength-independent saturable absorption, ultrafast nonlinear optical response, and a

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large nonlinear refractive index.[38–40] Therefore, the nonlinear optical properties of graphene make it suitable for the ultrashort pulse generation and shaping in fiber lasers.[41] For instance, relying on the nonlinear saturable absorption ability, various high-performance ultrafast lasers operating at different wavebands based on graphene photonic devices have been reported.[36,42–49] Inspired by the successful story of graphene, graphene-like 2D layered materials, i.e., transition metal dichalcogenides (TMDs),[50–60] topological insulators,[61–76] black phosphorus,[77–85] antimonene,[86,87] and MXene,[88,89] were rapidly developed and have also been demonstrated as good candidates of SAs (or nonlinear optical switches) for ultrashort pulse generation with similar features, i.e., saturable absorption and large nonlinear refractive index,[77,88–90] and with distinctive advantages of a tunable bandgap and optical loss. Therefore, 2D materials can find potential applications in fabricating compact highly nonlinear, saturable absorption photonic devices.[67,91–96] Generally, the fabrication of 2D materials-based SAs can be realized by depositing the 2D materials onto the fiber core,[59] chemical vapor deposition,[49,97–99] and spraying approaches.[100] However, by using these methods, the interaction length between the 2D materials and propagation light is short. In this case, although the fabricated 2D materials-based photonic devices provide the saturable absorption effect, the tuning of the highly nonlinear effect which is beneficial for the investigation of soliton nonlinear dynamics will be limited.

As we know, due to its unique propagation features, optical microfiber is also deemed a great platform for constructing versatile photonic devices.[101–112] The first low-loss optical waveguiding in microfibers with diameters below the wavelength of the guided light was demonstrated by Tong and colleagues in 2003,[113] which opened up great opportunities for designing smart and compact fiber photonic devices. Recently, it has been demonstrated that the 2D materials could be coated onto the microfiber by the optical deposition method,[114,115] where the deposition amount of 2D materials could be tuned by roughly adjusting the deposition time. Therefore, the interaction length between the 2D materials and propagation light could be greatly enhanced owing to the evanescent field interaction along the microfiber. Moreover, the microfiber itself also possesses highly optical nonlinearity which is dependent on the fiber diameter.[116] Therefore, in this case, the saturable absorption effect could be used for passive mode locking while the highly nonlinear effect is favorable for investigating soliton dynamics.

In this review, we briefly summarize the recent progress in 2D materials-based SAs for ultrafast fiber lasers, particularly in the context of a 2D materials-decorated microfiber device for pulse generation and soliton shaping. We will discuss the fabrication method of 2D materials-decorated microfiber photonic devices and their applications for ultrashort pulse generation firstly, then the soliton nonlinear dynamics based on such photonic devices will be introduced. Finally, we conclude this work with the challenges and the outlook for 2D materials-based photonic devices in ultrafast optics applications.

2. Photonic device fabrication

Firstly, we need to fabricate a microfiber so as to deposit the 2D materials onto it.[117] Briefly, the bare part of the single mode fiber (SMF) is heated by an alcohol burner and stretched carefully at the same time. With this process, the waist diameter of the SMF can be tapered down to several microns, where the insertion loss and the evanescent field intensity can be both in a reasonable range. The microfiber can be transferred to a glass slide for the purpose of stable operation. After the fabrication of the microfiber, visible light is launched into it to observe the intensity of the scattering evanescent field, as shown in Fig. 1(b). Generally, 2D materials-deposited microfiber devices are fabricated by depositing the 2D materials onto a microfiber. The optical gradient force to deposit the 2D materials onto the microfiber is induced by the evanescent field of the microfiber, which can trap 2D materials gradually with an action similar to optical tweezers.

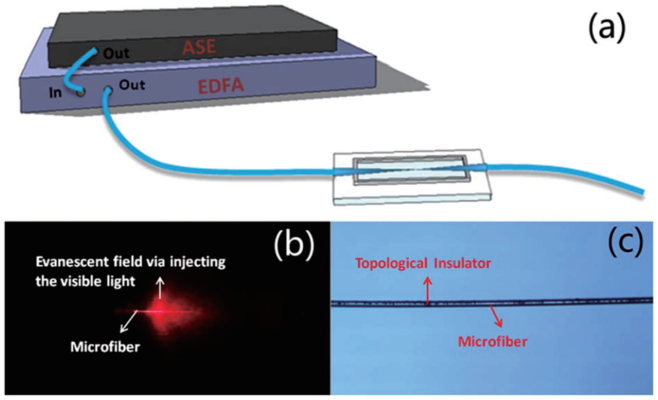


Fig. 1. (color online) (a) Experimental setup for the fabrication of a microfiber-based TISA; (b) evanescent field of microfiber observed by visible light; (c) microscopy image of fabricated microfiber-based TISA. Selected from Ref. [93].

The experimental setup shown in Fig. 1(a) is commonly used to execute the optical deposition. Here, the pumping laser can be a 980 nm laser diode or other laser source at different wavebands. If the output power of the laser source is not enough, an optical amplifier can be introduced to boost the pumping laser power. The process of optical deposition can be understood as follows. When the light source is injected into the microfiber, a fraction of the injected light will propagate as the evanescent field around the microfiber. The 2D materials are trapped gradually onto the microfiber by the optical gradient force induced by the evanescent field of the microfiber.

Turn on the light source and place a drop of a 2D material solution on the microfiber waist to start the deposition process. If possible, the microscope can be employed to observe the whole deposition process *in situ*. One advantage of using microscope is that the deposition amount of 2D material can be controlled by adjusting the light power and deposition time. According to our experimental experiences, when the deposition length of the 2D material reaches about ~ 0.1 mm to 1.2 mm, the light source needs to be turned off to prevent too much insertion loss. Next the residual solution is taken out by an injector and the 2D material will still stick to the microfiber by Van der Waals forces. After evaporating at room temperature, the fabrication of the 2D material-decorated microfiber device is completed, as shown in Fig. 1(c). Note that, in addition to the optical deposition method, a pulsed laser deposition (PLD) system was also proposed to fabricate the 2D material-decorated microfiber, which enables a more uniform deposition in comparison to optical deposition.[118]

3. Applications for ultrafast fiber lasers

As we know, the incorporation of a SA into the laser cavity will enable the fiber laser to deliver mode-locked pulses if the cavity parameters are properly set.[7] The pulse features emitted by the fiber lasers could be influenced by the characteristics of SAs such as the modulation depth, nonsaturable loss, and response time.[119] So far, ultrafast fiber lasers have been demonstrated with a variety of 2D materials, which is initiated by the successful fabrication of graphene SA.[36,37] The duration of a mode locked pulse obtained based on 2D materials SA ranges from the picosecond to femtosecond level,[44,97,120–122] partially depending on the fiber dispersion distribution in the laser cavity and the performance of the SAs.

When focusing on the 2D materials-decorated microfiber SAs, the evanescent field interaction between the propagation light and the 2D materials is utilized. In this regard, the specific geometry of such devices offers a high optical damage threshold and high third-order nonlinearity. Therefore, the high optical damage threshold can be used to avoid the breakdown of the SAs, while the highly nonlinear effect can be employed for investigating the soliton dynamics in fiber lasers. In the following, we will briefly review the recent progress in these two aspects by the use of 2D materials-decorated microfiber SAs.

3.1. Generation of mode-locked pulse

The deposition of nanomaterials onto the microfiber as SA was proposed by the group led by Yamashita,[123,124] although the saturable absorption nanomaterials used in those works are carbon nanotubes. The results indicated that other 2D materials could also be deposited onto the microfiber as SAs for ultrafast photonics application. The graphene-decorated microfiber (side-polished fiber) SA for a mode-locked fiber laser was demonstrated in 2010.[125] Because only part of the propagation light interacts with the graphene, the graphene-decorated microfiber SA possesses the advantages such as endurance of higher optical power and quick cooling down. Relying on these advantages, they obtained the mode-locked pulse with the intracavity power up to 21.41 dBm without any thermal damage to the graphene. After that, apart from the demonstration of these microfiber-based SAs in fiber lasers at different wavebands,[126,127] versatile 2D-materials such as TMDs,[59,128–130] few-layer black phosphorus (BP),[79] Mxene[88] decorated microfiber SAs were proposed and demonstrated, which are mainly focused on the optimization of the pulse duration and output optical power of mode locking operation. For example, it has been demonstrated that the fiber laser delivered the 67 fs mode-locked pulse train with a tungsten disulfide (WS_2) microfiber SA,[129] in which a hybrid mode locking regime, that is, the combination of NPR and WS_2 microfiber SA, was proposed to obtain an ultrashort pulse. As shown in Fig. 2, the 3-dB spectral bandwidth of the mode-locked pulse is up to 114 nm, corresponding to the pulse duration of 67 fs. Then, taking advantage of enduring high optical power, Yan *et al.* also demonstrated that the fiber laser could even produce the mode-locked pulse with an average output power of 68.3 mW based on the MoS_2 deposited microfiber SA, which corresponds to an intracavity optical power of ~ 200 mW.[131] Recently, the nonlinear optical properties of few-layered BP have become a hot topic due to their saturable absorption ability for ultrafast fiber lasers.[77–85] However, one of the drawbacks of few-layered BPs is that the lack of stability in air and ease of oxidation, which prevents BPs towards its further exploration. In fact, the oxidation of BPs in air might be accelerated by thermal effect induced by the high power illumination. In this case, the microfiber-based few-layered BP SA was proposed to alleviate the thermal effect induced performance degradation of BPs.[79] Indeed, the fiber laser mode-locked by the microfiber-based few-layered BP SA shows relatively stable operation for 10 h, as shown in Figs. 3 and 4. Moreover, a self-starting mode-locked operation could be achieved in the fiber laser for several days. On the other hand, the vector features of solitons in the fiber lasers mode-locked by 2D materials were reported[132,133] because of no evident polarization dependent loss in 2D materials-based SAs. Note that several multiwavelength mode-locked fiber lasers using 2D material deposited microfiber photonic devices were also demonstrated, where the operation regimes could be either in the dissipative soliton and dissipative soliton resonance.[134,135]

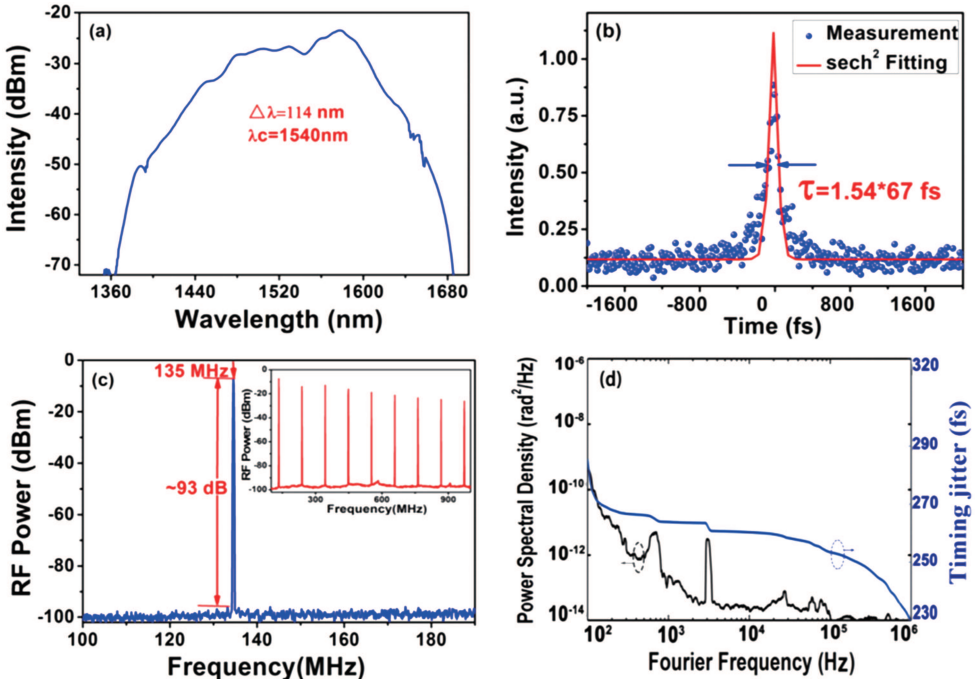


Fig. 2. (color online) Experimental results of the passively mode-locked EDF laser with fiber-taper WS_2 SA. (a) Optical spectrum. (b) Autocorrelation trace with 67 fs pulse duration. (c) Radio frequency (RF) spectrum. (d) Phase noise measurement at 135 MHz. Selected from Ref. [129].

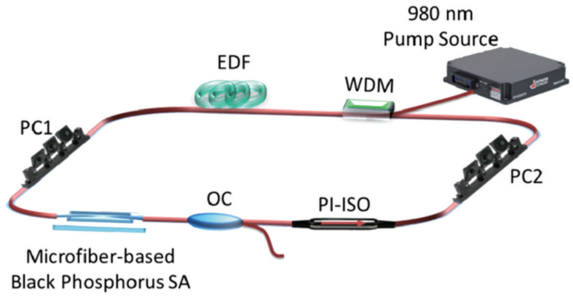


Fig. 3. (color online) Schematic of the microfiber-based BP SA mode-locked fiber laser. Selected from Ref. [79].

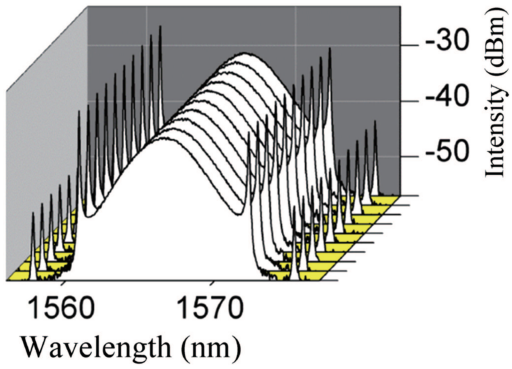


Fig. 4. (color online) Repeatedly recorded mode-locked spectrum at a 1-h interval. Selected from Ref. [79].

As mentioned above, 2D materials-decorated microfiber photonic devices possess high third-order nonlinearity.[40,92,136] On the other hand, the repetition rate is a key parameter of mode-locked fiber lasers. Recently, four-wave-mixing (FWM) mode locking was proposed to achieve ultrahigh repetition rate pulses up to several hundreds of GHz in fiber lasers.[137,138] Therefore, it is expected that the 2D materials-decorated microfiber photonic devices can be used to efficiently generate the FWM effect, and thus will find potential applications in FWM mode locking of fiber lasers. Indeed, by incorporation of a graphene-deposited microfiber

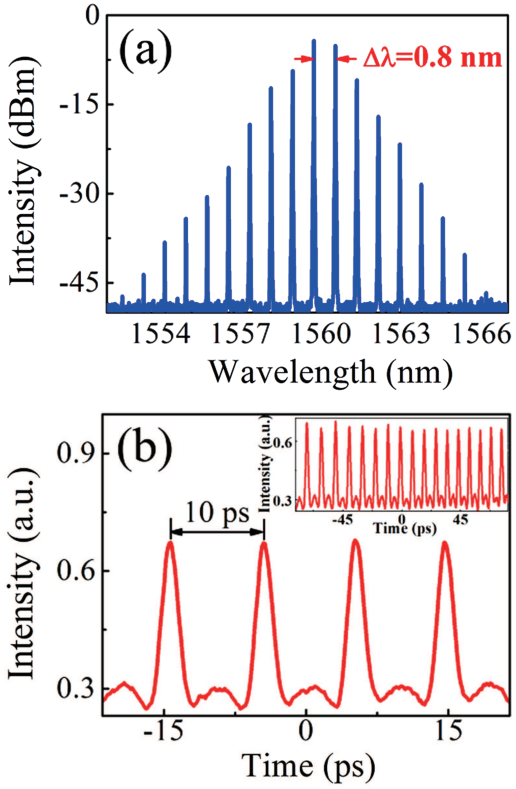


Fig. 5. (color online) DFWM mode-locked operation: (a) spectrum, (b) autocorrelation trace. Selected from Ref. [139].

photonic device and an F–P filter in a fiber laser, the mode-locked pulse train with a 100 GHz repetition rate was easily obtained by virtue of the FWM mode locking mechanism, as shown in Fig. 5.[139] Here, the F–P filter was used to select the lasing wavelengths, while the graphene device was employed to induce the FWM effect. Very recently, the graphene deposited microfiber knot as the broadband resonator was also employed to achieve the ultrahigh repetition rate pulse in both the 1.06 μm and 1.55 μm wavebands.[140]

3.2. Soliton shaping and nonlinear dynamics

Generally, the pulses delivered from the fiber lasers can be regarded as optical solitons. The stable propagation of solitons in fiber lasers needs to balance the fiber dispersion and the intracavity nonlinearity. However, when the balance is disturbed, for example, for higher nonlinearity, the mode-locked solitons in fiber lasers will show many interesting nonlinear behaviors. As mentioned above, provided that a single photonic device can simultaneously provide both the saturable absorption and high nonlinearity, it would be also beneficial for observing various soliton nonlinear dynamics in fiber lasers. Therefore, one would naturally consider the employment of 2D-materials-decorated microfiber photonic devices to investigate soliton nonlinear phenomena in ultrafast fiber lasers.

3.2.1. Harmonic mode locking operation

As we know, when the nonlinearity of a laser cavity is high, a direct phenomenon is that the mode-locked soliton will break into multiple pulses with equal intervals, which is also called harmonic mode locking state.[141–143] The repetition rate of a fiber laser can be increased with the harmonic mode-locking operation by simply adjusting the pump power. As the 2D materials-decorated microfiber photonic devices exhibit highly nonlinear effects, one would expect that the HML operation can be readily obtained by the 2D material deposited microfiber. As an example, we fabricated a microfiber with a diameter down to 12 μm, and the microfiber was covered by a few-layered topological insulator (TI, Bi_2Te_3).[93] At a low pump power, single soliton operation could be achieved. However, due to the high nonlinearity of the TI decorated microfiber photonic device, multi-soliton operation could be always obtained at a higher pump power and the pulse repetition rate was sensitive to the pump power. Harmonic mode locking was achieved by properly rotating the PCs. Finally, the fiber laser could operate at the pulse repetition rate of 2.04 GHz under a pump power of 126 mW, corresponding to the 418th harmonic of the fundamental repetition frequency, as depicted in Fig. 6. The pulsed laser deposition (PLD) method was also used to fabricate the microfiber-based TI SA. Using the fabricated SA, a stable femtosecond harmonic soliton pulse generation with repetition rate of 2.95 GHz was obtained.[144] In addition to the microfiber scheme, 2D materials such as graphene[145] and $MoSe_2$[146] deposited side-polished fiber devices as SAs were also proposed to enhance the interaction length through the evanescent field. By employing the 2D materials deposited side-polished fiber SAs, high-performance harmonic mode locking was demonstrated in passively mode-locked fiber lasers. Moreover, by virtue of simultaneously excellent SA effect and high nonlinearity of 2D materials-deposited microfiber devices, a robust dual-wavelength harmonic mode locking fiber laser was demonstrated.[67] The repetition rates at two wavelengths are different from each other. This is because the nonlinear effects experienced by the two sets of harmonic mode locked pulses are different.

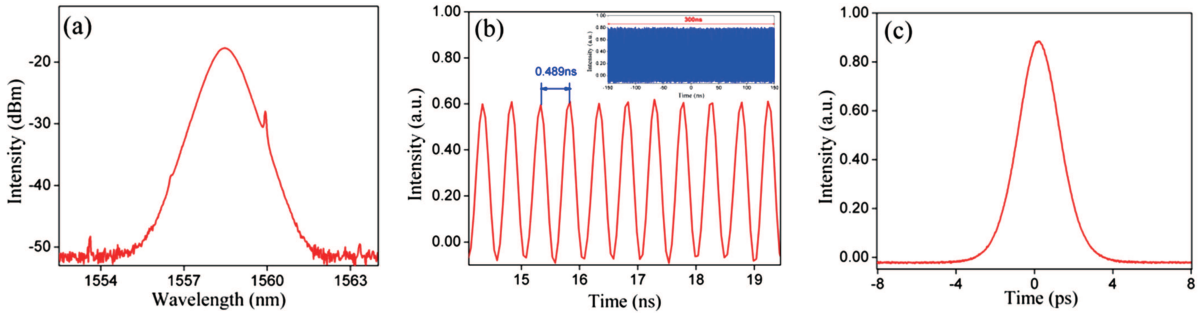


Fig. 6. (color online) HML operation at the repetition rate of 2.04 GHz. (a) Mode-locked spectrum; (b) recorded pulse-train; inset, pulse train with 300 ns span; (c) corresponding autocorrelation trace. Selected from Ref. [93].

3.2.2. Soliton molecules

When the fiber laser operates in the multi-soliton regime, the solitons will interact with each other in the laser cavity and exbihit versatile multi-soliton dynamics.[147–149] In addition to the harmonic mode locking operation, another interesting multi-soliton dynamic is the formation of soliton molecules.[150–153] The soliton molecule consists of multiple solitons with a small time interval, which generally possesses the fixed phase relationship among these solitons.[150–153] Recent results also demonstrated that the solitons inside the molecules could have evolving phase delay when propagating along the laser cavity.[154,155] For 2D material deposited microfiber photonic devices, we should stress that, apart from the saturable absorption effect, they also show highly opti-

cal nonlinearity. In this case, the highly optical nonlinearity is beneficial for the optical soliton splitting or pulse breaking into some optical waves. After the pulse is broken into some optical waves, the 2D material deposited microfiber photonic devices (real SAs) facilitate the efficient reshaping of the broken optical waves into multiple solitons comparing to the artificial saturable absorbers such as NPR and NALM. As the soliton molecule is also a type of multi-soliton dynamic, the insertion of 2D material deposited microfiber photonic devices would be favorable for the generation of soliton molecules in fiber lasers. By introducing a highly nonlinear 2D materials-deposited microfiber photonic device, soliton molecules were easily obtained in both the Er-doped fiber laser at 1.55 μm[156] and Yb-doped fiber laser at 1.06 μm.[157] In particular, taking advantage of the nonlinear optical properties of the graphene-decorated microfiber, the multi-soliton could be reshaped and form the so called structural soliton molecule,[95] where the individual solitons (soliton atoms) inside the soliton molecules show different characteristics such as peak intensities, durations, and ultra-narrow pulse separations, as shown in Figs. 7 and 8. Moreover, owing to the relatively high nonlinearity for strong soliton shaping, the multiple soliton molecules have also been observed in fiber lasers.[158] The investigation of multiple soliton molecules could further enhance the understanding of the physical mechanism of soliton molecules in nonlinear optical systems.

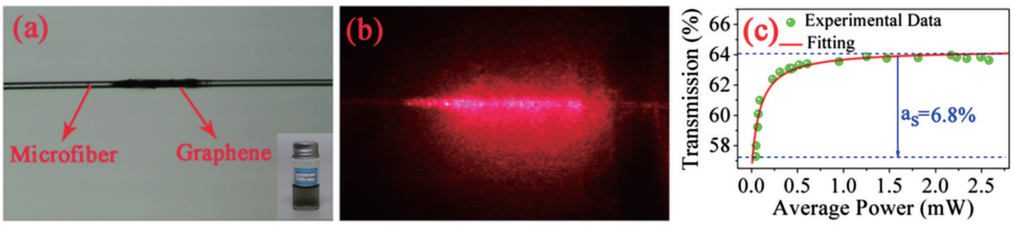


Fig. 7. (color online) (a) Microscopy image of microfiber-based GSA; (b) scattering evanescent field of the microfiber; (c) saturable absorption curve and the corresponding fitting curve. Selected from Ref. [95].

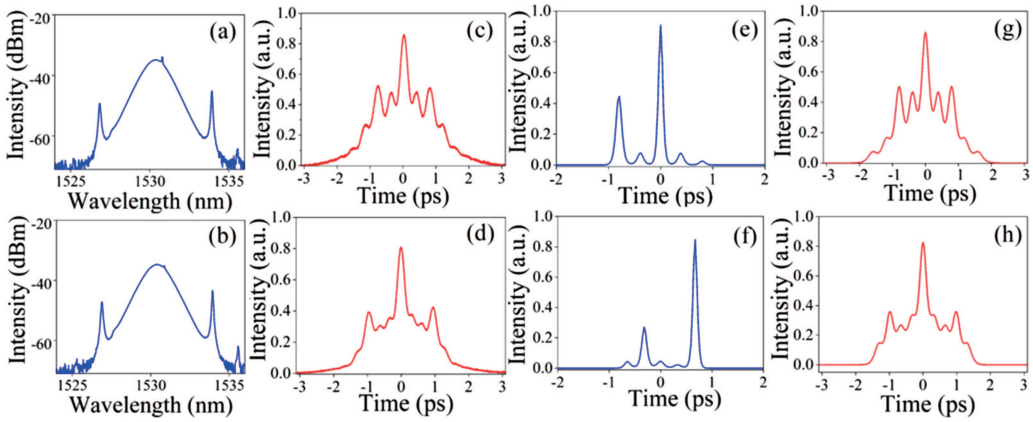


Fig. 8. (color online) Structural soliton molecules: (a) and (b) mode-locked spectra; (c) and (d) the measured autocorrelation traces; (e) and (f) the theoretically plotted pulse profiles; (g) and (h) the recovered autocorrelation traces. Selected from Ref. [95].

3.2.3. Rogue wave generation

After achieving multi-soliton operation, the solitons can move towards each other owing to the different group velocities. Therefore, on the oscilloscope traces we can see the formation of soliton rain,[159,160] soliton flow,[159,160] and chaotic soliton bunches,[149,161] which could be referred to as dynamical multi-soliton patterns. Because of the relative movement among these generated solitons, soliton collisions are observed under these operation regimes. It has been demonstrated that chaotic soliton collisions might induce the generation of rogue waves.[161,162] Therefore, one way to generate rogue waves is to obtain random soliton collisions in fiber lasers. In fact, the concept of rogue waves was initially from the area of oceanography, and then the investigation of rogue wave was also turned into the field of nonlinear optics, which are called optical rogue waves. The generation of optical rogue waves is a nonlinear process in optical systems, possessing unique characteristics such as extremely high amplitude, unpredictability, and small probability.

On the other hand, the observation of dynamical multi-soliton patterns including chaotic soliton collisions needs a higher pump power to ensure the highly nonlinear effect experienced by the solitons in the laser cavity.[163–165] Therefore, the incorporation of a highly nonlinear 2D materials-decorated microfiber photonic device could relax the requirement of pump power level for observing the dynamical multi-

soliton patterns.[156,158] Indeed, the fiber laser could easily operate in chaotic multi-soliton bunches accompanying soliton collisions if a 2D material-decorated microfiber photonic device was employed.[96,166] The evolution of a chaotic multi-soliton bunch over several cavity roundtrips and the peak pulse intensity histogram of chaotic multi-pulse bunch are depicted in Figs. 9 and 10. Here, the highest pulse amplitude is about 4 times that of the significant wave height (SWH), demonstrating that a rogue wave has been observed under this operation regime.[96] Note that the envelope of the chaotic multi-pulse bunch could be up to tens of nanoseconds. Therefore, the rogue waves were generated by long-range chaotic multi-pulse interactions.[96] Moreover, by carefully designing the laser cavity, we also demonstrated the generation of rogue waves induced by short-range chaotic pulse interactions within the time scale of picoseconds in mode-locked fiber lasers by utilizing 2D-materials deposited microfiber SAs.[166]

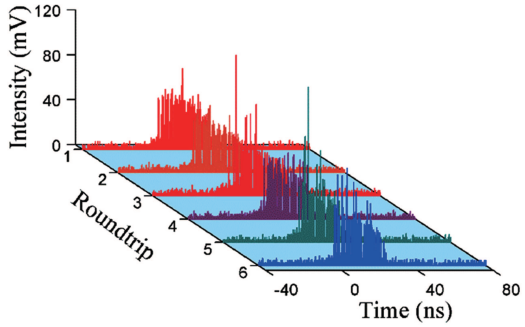


Fig. 9. (color online) Evolution of chaotic multi-pulse bunch over several cavity round-trips. Selected from Ref. [96].

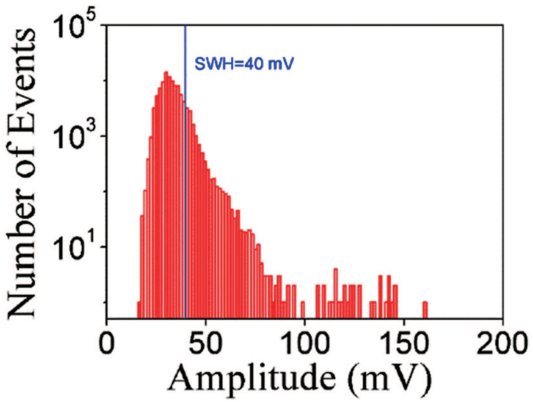


Fig. 10. (color online) Intensity histogram on log scale of chaotic multi-pulse bunch. Selected from Ref. [96].

4. Conclusion and perspectives

Over the past decade, 2D materials-based photonic devices have been intensively investigated and a great deal of progress has been made in this field. The on-going research results show that more and more types of 2D materials as well as their nonlinear optical properties will be discovered. The unique features of 2D materials will open new opportunities for fabrication of novel photonic devices, such as high performance SAs for ultrashort pulse generation in lasers. However, the difference of 2D materials in the nonlinear optical performance needs to be further resolved, in order to better apply them in the field of nonlinear optics with desirable requirements. For example, it has been demonstrated that few-layer MoS_2 possesses stronger saturable absorption response than graphene at a specific waveband.[167] Therefore, it is of interest to employ few-layer MoS_2 as SAs or optical switches for the ultrafast lasers operating in the corresponding waveband. Anyway, the rising photonics technology based on 2D materials, particularly the SAs based on 2D materials, indeed enables the fast development of ultrafast laser technologies because the 2D materials offer an effective but inexpensive way to fabricate high-performance SAs.

2D materials-decorated microfiber photonic devices indeed show interesting nonlinear properties for versatile photonic applications. Due to the different nonlinear properties of 2D materials, it is theoretically expected that there will be some difference in the nonlinear optical performance of different 2D materials-decorated microfiber devices. However, the evanescent field interaction between the 2D materials and the propagation light makes it difficult to measure the nonlinear properties of such microfiber devices precisely. Regarding applications in fiber lasers as briefly reviewed in this work, 2D materials-decorated microfiber photonic devices could be used as highly nonlinear elements in fiber lasers for investigating various soliton nonlinear dynamics and phenomena. In the lab environment, 2D materials-decorated microfiber devices could be used for months if they are protected carefully. However, we still need to take a step further to fabricate the robust 2D materials-decorated microfiber photonic devices. It is because microfiber photonic devices are frangible and easy to damage if there is no extra protection. Therefore, if the 2D materials-decorated microfiber can be packaged well, they will be more favorable for the practical applications. Note that non-uniform deposition of 2D materials onto the microfiber might introduce polarization dependent loss in such devices. In addition, the geometry of the microfiber as well as the smooth degree also influences the polarization dependent features of 2D materials-deposited microfiber photonic devices. On the other hand, the silicon waveguide could be designed to fabricate versatile photonic devices with different functions. It is expected that 2D materials can be integrated into the silicon waveguide photonic devices to further improve their performance. Moreover, owing to the high nonlinearity of 2D materials-decorated microfiber, recent achievements show that they can also be applied to all-optical signal processing, such as optical switchers, modulators, and wavelength convertors.[168–170] Finally, the careful design of a microfiber can engineer the dispersion and nonlinearity properties,[113] which is also favorable for

the investigation of nonlinear optical phenomena. It is hoped that more practical applications of 2D materials-decorated microfiber photonic devices in various fields can be developed in the near future.

In conclusion, ultrafast lasers based on 2D materials have become a hot topic and active research direction in the fields of nonlinear optics and laser technologies. In addition, we also expect to see more soliton nonlinear dynamics in fiber lasers by virtue of the unique characteristics of 2D materials-decorated microfiber photonic devices. With the rapid development of science and technology, we believe that more and more commercially available products based on 2D materials, which depends on the long-term stability and the large-scale manufacturing potential, will be released in future decades.

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