Review

Meng Liu, Zhi-Wei Wei, Ai-Ping Luo, Wen-Cheng Xu* and Zhi-Chao Luo*

Recent progress on applications of 2D material-decorated microfiber photonic devices in pulse shaping and all-optical signal processing

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Abstract: Due to the exotic electronic and optical properties, two-dimensional (2D) materials, such as graphene, topological insulators, transition metal dichalcogenides, black phosphorus, MXenes, graphitic carbon nitride, metal-organic frameworks, and so on, have attracted enormous interest in the scientific communities dealing with electronics and photonics. Combining the 2D materials with the microfiber, the 2D material-decorated microfiber photonic devices could be assembled. They offer the advantages of a high nonlinear effect, all fiber structure, high damage threshold, and so on, which play important roles in fields of pulse shaping and all-optical signal processing. In this review, first, we introduce the fabrication methods of 2D material-decorated microfiber photonic devices. Then the pulse generation and the nonlinear soliton dynamics based on pulse shaping method in fiber lasers and all-optical signal processing based on 2D material-decorated microfiber photonic devices, such as optical modulator and wavelength converter, are summarized, respectively. Finally, the challenges and opportunities in the future development of 2D material-decorated

microfiber photonic devices are given. It is believed that 2D material-decorated microfiber photonic devices will develop rapidly and open new opportunities in the related fields.

Keywords: two-dimensional materials; microfiber; pulse shaping; all-optical signal processing.

1 Introduction

As the birth of two-dimensional (2D) materials, graphene was stripped from graphite by A. Geim and K. Novoselov in 2004 [1]. Owing to its novel physical properties, such as thermal transport, electronic transport, and mechanical properties, research on graphene has developed significantly [2–5]. Since then, a series of 2D materials have been successively isolated, including topological insulators (TIs) [6–12], transition metal dichalcogenides (TMDs) [13–21], black phosphorus (BP) [22–27], MXenes [28], graphitic carbon nitride ($g-C_3N_4$) [29–31], metal-organic frameworks [32–36], GeP [37], lead monoxide [38], tellurium [39, 40], selenium [41, 42], tin sulfide [43–45], tin monosulfide [46], $CH_3NH_3PbI_3$ perovskite [47, 48] bismuth quantum dots [49], titanium [50], and the other ones [51, 52]. Different from their bulk parental materials, the 2D materials exhibit exotic electronic and optical properties, providing exciting opportunities for nanoscale electronics and photonics.

Microfiber, drawn from conventional fibers, has excellent characteristics, such as high optical confinement, large portion of evanescent field, low optical loss, and full compatibility with optical systems [53–55]. Therefore, it has been widely applied in fields of miniature optical devices, optical sensing [56, 57], optical spectroscopy [58, 59], nonlinear optics [60–62], quantum optics, and atomic optics [63, 64]. Especially, due to the considerably large evanescent field, the microfiber when decorated with novel nanomaterials provides a convenient and efficient method for the interaction between light and materials.

*Corresponding authors: Wen-Cheng Xu and Zhi-Chao Luo,

Guangdong Provincial Key Laboratory of Nanophotonic Functional Materials and Devices and Guangzhou Key Laboratory for Special Fiber Photonic Devices and Applications, South China Normal University, Guangzhou 510006, China; and Guangdong Provincial Engineering Technology Research Center for Microstructured Functional Fibers and Devices, South China Normal University, Guangzhou 510006, China, e-mail: xuwc@scnu.edu.cn (W.-C. Xu); zcluo@scnu.edu.cn (Z.-C. Luo)

Meng Liu, Zhi-Wei Wei and Ai-Ping Luo: Guangdong Provincial Key Laboratory of Nanophotonic Functional Materials and Devices and Guangzhou Key Laboratory for Special Fiber Photonic Devices and Applications, South China Normal University, Guangzhou 510006, China; and Guangdong Provincial Engineering Technology Research Center for Microstructured Functional Fibers and Devices, South China Normal University, Guangzhou 510006, China. <https://orcid.org/0000-0002-2154-7385> (M. Liu)

Compared to the other types of 2D materials photonic devices [65–69], the 2D material-decorated microfiber photonic devices offer the advantages of long interaction length (highly nonlinear effect), all fiber structure, high damage threshold, and so on. Indeed, 2D material-decorated microfiber photonic devices play important roles in applications in fields of pulse shaping and all-optical signal processing.

On one hand, benefiting from the advantages of compactness, low loss, efficient diodes, high beam quality, excellent thermal management, and so forth, fiber lasers are extensively used in material processing, medicine, and sensing [70–75]. Among the fiber laser technologies, pulsed fiber lasers with ultrashort pulse width and ultrahigh peak power, achieved by the pulse shaping mechanism of Q-switching and mode-locking [72, 76, 77], have attracted much attention in recent years. The researchers are always motivated to explore new and better ways to generate shorter and shorter pulses, and improve the performance of pulsed fiber lasers [74]. A convenient and cost-effective way to achieve passive Q-switching/mode-locking pulses is to insert a saturable absorber (SA) into the laser cavity [78, 79]. Due to the advantages of large modulation depth, low saturation intensity, fast response time, and broadband operation, 2D material-based fast SAs, especially 2D material-decorated microfiber SAs, have achieved a lot of important results in the field of pulse shaping in the last decade [80–87]. In addition, due to the specially designed geometric structure, the 2D material-decorated microfiber SA with high nonlinearity and tailorable dispersion (microfiber) [88–90] would be beneficial for the exploration of soliton dynamics in ultrafast fiber lasers. On the other hand, all-optical signal processing, including signal regeneration and controlling light by light, plays a critical role in high-speed communication systems [91, 92], while 2D material-decorated microfiber photonic devices are desirable for the applications in all-optical signal processing, since they have exceptional nonlinear optical response, large third-order nonlinear index, and enhanced stability. So far, many reviews

classified by different kinds of 2D materials [93–96] or different applications of 2D materials [97–101] have been reported. Particularly, He et al. reviewed the emerging 2D materials beyond graphene for ultrashort pulse generation in fiber lasers [99], while Zhang et al. focused on the recent progress in 2D material-based SAs for all solid-state pulsed bulk lasers [100]. In addition, a more comprehensive one was reported by Guo et al. in 2019 [101]. However, an in-depth summary of 2D material-decorated microfiber photonic devices has yet to be conducted.

In this review, we summarize recent progress of 2D material-decorated microfiber photonic devices in their fabrication and applications. We first briefly review the fabrication of 2D material-decorated microfiber photonic devices in Section 2. Then we highlight the recent works on pulse generation, soliton dynamics, and all-optical signal processing based on 2D material-decorated microfiber photonic devices in Sections 3, 4, and 5, respectively. Finally, we present the conclusion and related future opportunities in Section 6.

2 Devices fabrication

2.1 Microfiber fabrication

The microfiber has a structure comprising a narrow stretched filament (the taper waist), each end of which is linked to an unstretched fiber by a conical section (the taper transition region) (Figure 1A) [54]. There are several methodologies for the microfiber fabrication, such as drawing of glass fibers [103–112], drawing of bulk glass [113], drawing from polymer solutions [114–119], and so on. Among them, the flame-heated taper drawing, namely, flame-brushing technique, is the most common approach, which also has the better microfiber quality, mechanical strength, and low loss.

Figure 1B shows the typical experimental setup of a flame-brushing technique [102]. A bare standard single

Figure 1: Structure and fabrication of a microfiber.

(A) Microfiber structure. (B) Typical experimental setup for the flame-brushing scheme. Reproduced with permission [102]. Copyright 2012, IEEE Photonics Society.

mode fiber (SMF) was set on two fiber clamps, which were fixed on two motorized transition stages (MTSs). When the fiber was heated to a softening temperature, it was pulled by two high-precision MTSs controlled by a computer. Here, the flame sources could be oxygen-butane or oxygen-hydrogen torch flames, focused CO₂ laser [120], electric strip heaters [110, 121], alcohol burner [122], and so on. In order to monitor the process of fabricating microfibers, Mullaney et al. employed a range of optical techniques. Thermal imaging was used to optimize the alignment of the optical system; the transmission spectrum of the fiber was monitored to confirm that the tapers had the required optical properties and the strain induced in the fiber during tapering was monitored using in-line optical fiber Bragg gratings [123]. Generally, the fiber was tapered down so that its taper waist diameter became several to tens of microns.

The characteristics of microfibers, such as diameter, length, and insertion loss, have been fully investigated [124–127]. In order to control the microfiber waist diameter accurately, Xu et al. demonstrated a simple real-time method. A single-frequency laser is launched into the optical microfiber, and the transmitted power is used to estimate the diameter in real time during the fabrication. With this method, both the accuracy and precision of diameter control were within 5 nm for the diameter ranging from 800 to 1300 nm [124]. In addition, low insertion loss is mainly related to the control of the surface roughness and diameter uniformity. In the last decade, the microfibers with losses smaller than 0.001 dB/mm have been manufactured, which is sufficiently low for applications, by stabilizing the flame and using high purity gas [125]. During the fabrication, the air turbulence might also degenerate the microfiber quality, so it would be beneficial to fabricate the microfiber in enclosed space. As for the length of the microfiber, it determines the interaction length. Lee et al. proposed and demonstrated a novel tapering method of fabricating ultra-long microfibers. The technique comprises three steps for conventional flame-brushing and pulling, recalibration, and one-directional pulling. Using this method, the microfiber with 1.6 μm diameters, 500 mm uniform lengths with <66 nm diameter variances, and high transmittances of 91.5% is fabricated [126]. With the larger diameter of 5 μm , the microfiber length could be up to 165 cm [127]. As for the optimized length and diameter of the microfiber, it should be noted that the desired parameters of the microfiber, such as length and diameter, are totally different depending on the applications. For example, the diameter should be smaller in the harmonic mode-locking (HML) fiber lasers since it could potentially provide a larger nonlinear effect. However, the insertion loss would increase when

the diameter is small, so the diameter should be larger in the femtosecond pulsed fiber laser where low cavity loss is necessary.

2.2 2D material-decorated microfiber photonic device fabrication

There are two main methods to fabricate the 2D material-decorated microfiber photonic devices. First, using the light gradient force induced by the strong evanescent field, the 2D materials could be deposited on the waist of the microfiber. Second, the prepared 2D material film/flake was transferred to cover/wrap/attach the waist of the microfiber artificially.

2.2.1 Deposition method

As the most used method, the experimental setup of a 2D materials-deposited microfiber device is shown in Figure 2A [122]. The prepared microfiber was stuck on a glass slide. When injecting the visible light, the scattering evanescent field of the microfiber could be observed (Figure 2B). The light source was an amplified spontaneous emission (ASE) light source, which was amplified by an erbium-doped fiber amplifier to obtain a stronger evanescent field. A computer-interfaced microscope with a CCD camera was used to monitor the deposition process. First, the 2D material acetone solution was dropped onto the glass slide which covered the microfiber. Then the ASE light source was turned on, and the optical deposition process started. The optical gradient force induced by the evanescent field of the microfiber could deposit the 2D materials onto the microfiber, which can trap 2D materials gradually with an action similar to optical tweezers. Note that the deposition quality, such as uniformity and length, could be optimized through controlling the light power and deposition time. The deposition could be stopped by turning off the light source. The remaining 2D material solution was taken out by an injector. Finally, the fabricated 2D material-decorated microfiber device was evaporated at room temperature (Figure 2C). As we know, too strong interactions between the 2D material and the evanescent field might induce optical damage to the 2D material and microfiber. Then the microfiber with a larger diameter would be beneficial for reducing the interaction effect and insertion loss. It should also be noted that photonic devices are hard to achieve uniform material thickness since the deposition process is difficult to control precisely.

Figure 2: 2D material-decorated microfiber photonic device fabrication using the deposition method.

(A) Experimental setup. (B) Evanescent field of a microfiber observed by visible light. (C) Microscopy image of the fabricated microfiber-based TISA. Reproduced with permission [122]. Copyright 2013, The Optical Society.

2.2.2 Covering/wrapping/attaching method

In addition to the deposition method, 2D materials also could be covered, wrapped, or attached onto the microfiber. As mentioned above, it is hard to achieve high surface quality of photonic devices by the deposited method, but it could be avoided by the covering/wrapping/attaching method. The uniform 2D material film could be easier to achieve. The fabrication of the 2D material-covered/attached microfiber is a little simple. Figure 3B and C show typical schematics of the 2D material-covered/attached microfiber [128, 129]. The 2D

materials were prepared as a film, which was transferred onto the microfiber surface for the covering method. For the attaching method, the microfiber was attached onto the 2D material film. The 2D material-wrapped microfiber is a bit complex [130]. Figure 3A shows the structure of a graphene-wrapped microfiber. The fabrication process is as follows. First, an adhesive tape with a selected graphene flake was draped over a microfiber. Then the adhesive tape was removed and only graphene was left on the microfiber. A nanosecond pulse laser beam through a fiber tip was next employed to cut the graphene to a 10- μm width alongside the microfiber. Finally, when the

Figure 3: 2D material-decorated microfiber photonic device fabrication using the covering/wrapping/attaching method.

(A) Graphene-wrapped microfiber. Reproduced with permission [128]. Copyright 2014 American Chemical Society. (B) Graphene-covered microfiber. Reproduced with permission [129]. Copyright 2014, The Optical Society. (C) Microfiber-attached graphene. Reproduced with permission [130]. Copyright 2013, The Optical Society.

microfiber was lifted from the glass slide, the graphene spontaneously wrapped around the microfiber to form a graphene-wrapped microfiber.

2.3 Advantages of 2D material-decorated microfiber photonic devices

So far, there are various methods to fabricate 2D material-based photonic devices for different applications, such as sandwiching 2D material-polyvinyl alcohol (PVA) nanocomposite film between fiber connector ends [80], injecting 2D materials into photonic-crystal fibers (PCFs) [131], and coating 2D materials on the surfaces of a D-shaped fiber [132]. Among them, the 2D material-PVA nanocomposite film is the most convenient and low-cost method, which also shows good thermal stability. However, the low damage threshold and short interaction length are the main drawbacks. Moreover, the physically touching scheme can cause the distortion and/or damage to the 2D materials. The PCF-filled photonic devices own a strong light-matter interaction but exhibit relatively larger insertion loss and distortion of regional guidance mode; the D-shaped fiber-based photonic devices overcome the optical power-induced thermal damage and guarantee a strong nonlinear effect from 2D material due to the long lateral interaction length, but flat material thickness and low polarization-dependent loss are not easy to achieve. Similar to the D-shaped fiber-based photonic devices, the microfiber-based photonic devices possess the advantages of high threshold value and long interaction length. Moreover, by controlling the fabrication details of a microfiber, the polarization-dependent loss could be very low and a uniform material thickness could be realized in 2D material-covered, -wrapped, or -attached microfiber photonic devices.

3 2D material-decorated microfiber photonic devices on pulse generation in fiber lasers

Pulsed fiber lasers have been demonstrated to be an excellent source for micromachining, imaging, and communication, which motivates the researchers in the field of laser technology to explore new and better ways to generate shorter pulses, and improve the performance of a mode-locked fiber laser. On the other hand, a new operating wavelength of a fiber laser is another hot topic [133–138]. By doping different trivalent rare earth ions, such as

ytterbium, erbium, and thulium into the glass hosts, we can obtain different lasing wavelengths [139–141]. Meanwhile, it has been demonstrated that 2D material-based SAs possess an excellent characteristic of a wide spectral range, from the ultraviolet to the mid-infrared [142–144]. Thus, 2D material-based SAs are beneficial for the development of convenient, reliable, and low-cost mode-locked fiber lasers for different operating wavelengths.

In this section, the research history and recent achievements of fiber lasers based on 2D material-decorated microfiber SAs in different wavelength regimes (1.0, 1.5, 2.0 μm) are briefly reviewed.

3.1 Pulse generation at 1.0 μm

As we know, Yb-doped fiber lasers operating in the wavelength region centered around 1.0 μm are one of the most effective high-power fiber lasers, which can be attributed to the broad gain bandwidth, broad absorption band, low laser threshold, high gain efficiency, and high gain of a Yb-doped silica fiber [72, 145]. Moreover, the Yb-doped fiber lasers operate in the all-normal dispersion regime emitting the dissipative solitons, which are different from the conventional solitons observed in the anomalous dispersion regime [146, 147]. For the integration of 2D materials, sandwich structures are most commonly used in fiber lasers [67, 148–153]. Inserting the sandwiched 2D material-based SAs into the Yb-doped fiber lasers, high-quality mode-locked pulses can be obtained, beyond doubt, but the low optical damage is a bottleneck in these types of SA-related optical applications, especially, toward the high-power laser regime [150, 151, 154–156]. In this regard, the 2D material-decorated microfiber can provide a higher optical damage threshold and longer interaction length due to the specific geometry design.

Graphene was demonstrated to be an effective SA for Yb-doped fiber lasers, which has also been promoted to a graphene-decorated microfiber for the applications in Yb-doped fiber lasers [157–160]. In 2012, Luo et al. designed a graphene-decorated microfiber device with the characteristics of both saturable absorption and polarizing effect [157]. Inserting the graphene-decorated microfiber SA into an Yb-doped fiber laser, the stable triple-wavelength dissipative soliton operation around 1035 nm, with a pulse energy of 6.4 nJ and a pulse duration of 74.6 ps, can be achieved simultaneously. By depositing graphene onto the microfiber, the dual-wavelength rectangular pulse, multiple vector solitons, and the all-optical Q-switcher in Yb-doped fiber lasers were demonstrated subsequently [158–160]. As for other 2D materials, Du et al. reported the

first example of a molybdenum disulfide (MoS_2)-enabled wave-guiding photonic device [161]. In this case, the MoS_2 -decorated microfiber had excellent characteristics, such as saturable absorption, endurance of high-power laser excitation (up to 1 W), and polarization sensitive. By employing the MoS_2 -decorated microfiber SA in an

Yb-doped fiber laser, we can observe high-power stable dissipative solitons at 1042.6 nm with a pulse duration of 656 ps and a repetition rate of 6.74 MHz (Figure 4). In addition, BPs are also deposited onto the microfiber for pulse generation in Yb-doped fiber lasers [162, 163]. Table 1 summarizes the performances of pulsed Yb-doped fiber

Figure 4: Yb-doped mode-locked fiber laser with a MoS_2 -decorated microfiber SA.

(A) Experimental setup. (B) Optical spectra of the generated dissipative solitons under different pump powers. (C) Wide-band oscilloscope tracings. (D) Individual pulse profile. (E) Radio frequency spectral profile (inset: the wideband RF spectrum). Reproduced under the terms of a Creative Commons Attribution 4.0 International License [161]. Copyright 2014, Springer Nature.

Table 1: Summary of pulsed fiber lasers with 2D material-decorated microfiber photonic devices.

Characteristics of 2D material-decorated microfiber photonic devices							Laser performance		Ref.
2D material	Integration method	Diameter (μm)	Modulation depth (%)	Nonsaturable loss (%)	Saturation intensity (MW/cm ²)	λ (nm)	Frep (MHz)	τ (ps)	
Graphene	Deposited	3.5	1.9	—	—	1031.43/1034.94/1038.43	0.5515	74.6	[157]
Graphene	Deposited	6	—	—	—	1061.8/1068.8	1.78	4.41–4.23	[158]
Graphene	Deposited	—	—	—	—	1068.09	3.19	35.8	[159]
Graphene	Covered	7	—	—	—	1060	30.32–101.29 kHz	2.61–5.21 μs	[160]
MoS ₂	Deposited	—	10.47	—	—	1042.6	6.74	656	[161]
BP	Covered	—	1.94	73	1.21	1064	26–76 kHz	5.5–2.0 μs	[162]
rGO	Wrapped	6	5.75	54.1	—	1560	7.47	18	[164]
Graphene	Covered	12	12.88	—	—	1545.5–1550	27	14	[165]
Graphene	Deposited	6	—	—	—	1559	312.5	0.679	[166]
Graphene	Covered	—	1.77–0.9	—	—	1555	—	0.765	[167]
Graphene	Covered	7.5	—	—	—	1565	33	0.494	[168]
Graphene	Covered	12	12.88	84	—	1550	22.34–111.7	2.32–9.24	[169]
Graphene	Deposited	11	—	—	—	1559.74/1560.54	100 GHz	1.63	[170]
Graphene	Wrapped	6	4.37	95.27	1.51 GW/cm ²	1531.3	1.89	1.21	[171]
Graphene	Deposited	20.5	3.4	50.4	—	1559	366	7	[172]
Graphene	Deposited on Microfiber knot	5	—	—	—	1044.8	162 GHz	6.17	[173]
		—	—	—	—	1550	106.7 GHz	9.37	
Graphene	Deposited	4.8	1.5	—	—	1530/1531.5/1533/1534.5	8.034	8.8	[174]
Graphene	Deposited	8	1.5	23	—	1532	7.35	—	[175]
Graphene	Deposited	3.2	1.5	—	—	1539.6	10.36–41.8 kHz	3.89 μs	[102]
		4.3	—	—	—	1557.56	3.33	15.7	
Graphene	Wrapped	16	4.9	8.58	25.34	1550.328	17.83	30.71	[176]
Graphene	Deposited	6	6.8	3.6	—	1530.38	2.67	—	[177]
Bi ₂ Se ₃	Deposited	1.8	1.82	68.6	—	1560.88	3.125 GHz	1.754	[178]
Bi ₁ Te ₃	Deposited	12	1.7	69.9	—	1558.5	2.04 GHz	2.49	[122]
Bi ₂ Te ₃	Deposited	54	6.2	20	28	1564.1	2.95 GHz	0.92	[179]
Bi ₂ Te ₃	Deposited	20	30	40	—	1543.2	2.6–12 kHz	50–9.5 μs	[180]
Bi ₂ Te ₃	Deposited	—	—	—	—	1560	11.4	9 ns	[181]
Bi ₂ Te ₃	Deposited	23.8	4.8	73.4	—	1564	390	1.34	[182]
Bi ₂ Te ₃	Deposited	20	16.3	38.1	—	1559.4/1557.7	239/388	1.3	[183]
Bi ₂ Se ₃	Deposited	8	5.57	68.69	—	1529.96	—	—	[184]
Bi ₂ Se ₃	Deposited	9	2.11	47.1	—	1531.4	5.03	—	[185]
Sb ₂ Te ₃	Deposited	10	1.5	64.9	—	1562.82	607.2	—	[186]
In ₂ Se ₃	Deposited	17	4.5	21.9	7.3	1565	40.9	0.276	[187]
		—	6.9	28.8	10.6	1932	15.8	1.02	
MoS ₂	Deposited	9	1.8	51.1	—	1558.7	5.05	—	[188]

Table 1 (continued)

Characteristics of 2D material-decorated microfiber photonic devices										Ref.
2D material	Integration method	Diameter (μm)	Modulation depth (%)	Nonsaturable loss (%)	Saturation intensity (MW/cm²)	λ (nm)	Freq (MHz)	τ (ps)		
MoS ₂	Wrapped	7	4.4	95	8 GW/cm²	1595	1.3152	2.4	[189]	
MoS ₂	Deposited	14	1.77	46.4	–	1556	340	1.9	[190]	
MoS ₂	Deposited	11	2.82	57.34	–	1558	2.5 GHz	3	[191]	
WS ₂	Deposited	20	1	6.2	–	1568.55/1569	2.14	11	[192]	
WS ₂	Deposited	22	6.5	–	370	1558.5/1566	8.83	0.605/0.585	[193]	
WS ₂	Deposited	10	0.6	78	–	1561	24.93	0.369	[194]	
WS ₂	Deposited	18	8	22	–	1558.5	19.58	0.675	[66]	
WS ₂	Deposited	12	35.1	57.9	22.8	1540	135	0.067	[195]	
WS ₂	Wrapped	1.6	0.9	29.8	0.2 GW/cm²	1562.4	220.3 kHz	20–130 ns	[196]	
WSe ₂	Wrapped	11	54.5	18	–	1556.42	14.02	0.477	[197]	
		–	1.83	90.5	–	1886.22	11.36	1.18		
MoTe ₂	Deposited	20	25.5	20	–	1559.57	26.6	0.229	[198]	
		–	22.1	23	–	1934.85	15.37	1.3		
TiS ₂	Deposited	25	8.3	–	1.2 mW	1563.3	22.7	0.812	[199]	
PtSe ₂	Covered	7.5	1.11–4.9	~70–80	0.34–1.23 GW/cm²	1563	23.3	1.02	[200]	
HfS ₂	Deposited	12	15.7	20.6	8	1561.8	21.45	0.2217	[201]	
BP	Wrapped	9	16	24	6.8	1542.4/1543.2	3–18.5 kHz	10–40 μs	[202]	
BP	Deposited	10	6.91	37	4.5 mW	1532–1570	4.69	0.94	[203]	
BP	Deposited	~7	12.5	32.5	27.9	1064.4	16.77	51	[163]	
		–	10	41	8.3	1576.1	34.27	0.4037		
BPQDS	Deposited	12	9	7.5	1.5	1562.8	10.36	0.271	[204]	
Se	Deposited	8.2	2.13	~72	–	1555.67	13.68	3.1	[41]	
PbO	Deposited	–	–	–	–	1030.9	18.81	5.47	[37]	
		8	4.1	27.5	13.8 GW/cm²	1557.68	14.5	0.65		
GO	Deposited	6.4	–	–	–	2032	20–45 kHz	3.8–9 μs	[205]	
Graphene	Covered	8	19	67	–	1880–1940	19.7	1.9	[206]	
WTe ₂	Deposited	20	31.0	34.3	7.6	1915.5	18.72	1.25	[207]	
WSe ₂	Deposited	6	1.83	87	3.7	1863.96	11.36	1.16	[208]	
MoTe ₂	Deposited	15	5.7	70	8.3	1930.22	14.353	0.952	[69]	
BP	Deposited	14	40.2	55.9	7.12	1948	12.5–28.1 kHz	15.1–5.6 μs	[209]	

lasers based on graphene, MoS₂, BP, and PbO. It can be seen that for these lasers, the pulse widths are in the range of 4.23 ps [158] to 656 ps [161], which is much larger than that in 1.5 or 2.0 μm fiber lasers due to the larger chirp in the all-normal dispersion regime. In addition, generally mode-locked pulses with a fundamental repetition rate are obtained, lower than 20 MHz.

3.2 Pulse generation at 1.5 μm

Although Yb-doped fiber lasers are still considered to be the most promising high-power fiber lasers, their operating wavelength is restricted to around 1–1.1 μm , limiting the applications in other wave bands, such as eye-safe wavelength ranges. Er-doped fiber lasers, since the operating wavelength at 1.5 μm falls within the low-loss window of optical fibers that facilitates long-haul optical communications, have received much attention [210–213]. Moreover, due to the anomalous dispersion provided by an SMF in the 1.5 μm wavelength band, Er-doped fiber lasers can directly emit shorter pulses compared to dissipative solitons with the large chirp in Yb-doped fiber lasers [214, 215]. In fact, 2D material-decorated microfiber SAs have been widely used in Er-doped fiber lasers to generate ultrashort pulses [66, 102, 122, 163–204, 216–224].

The interaction between graphene and the evanescent light field is capable of passive mode-locking in an Er-doped fiber laser, which was first proposed by Song et al. [225]. In this case, the graphene was decorated onto a side-polished fiber and the mode-locked pulse was obtained with the intracavity power up to 21.41 dBm without any thermal damage to the graphene. The higher optical damage threshold of such photonic devices greatly motivated the research of 2D material-decorated microfiber SAs. After that, the graphene-decorated microfiber was used to achieve the operation of multiwavelength [174], wavelength-tunable [165, 176], and pulse duration-tunable [167–169, 176] in Er-doped mode-locked fiber

lasers. Apart from graphene, many other 2D materials, such as TIs, TMDs, BP, and gold nanorod, possess the characteristic of saturable absorption, indicating that they can be deposited onto the microfiber as SAs for ultrafast photonics applications. Indeed, versatile 2D material-decorated microfiber SAs were proposed and demonstrated, focusing on the optimization of the pulse duration and output optical power of mode-locking operation [163, 178, 179, 181–183, 185–188, 190–197, 199, 200, 202–204, 216, 221–224]. Recently, emitting 67 fs mode-locked pulses in an Er-doped fiber laser based on the hybrid mode-locking mechanism of NPE and tungsten disulfide (WS₂) microfiber SA has been demonstrated [195]. The influences of the WS₂ microfiber SA in the mode-locked fiber laser were demonstrated, such as narrowing the pulse width and reducing the mode-locked threshold by contrastive experiments. Few-layer BPs, due to the similar structure as graphene and thickness-dependent direct band gap, have attracted much attention [226–230]. However, a major obstacle for the practical applications of few-layer BPs comes from their instabilities of laser-induced optical damage. By coupling few-layer BPs with the microfiber evanescent field, the performance degradation of BPs induced by the thermal effect can be alleviated. Thus, the mode-locked fiber laser based on a BP-decorated microfiber SA was proposed [203] and exhibited relatively stable operation for 10 h (Figure 5). The 1.5 μm waveband pulsed fiber lasers based on 2D material-decorated microfiber SAs are summarized in Table 1. On the generation of an ultrashort pulse, the TMDs and BP show more advantages and most of the corresponding pulse widths are shorter than 1 ps. The minimum pulse width is 67 fs in a fiber laser based on WS₂ [195].

To achieve ultrahigh-repetition-rate pulses (up to 100 GHz) in fiber lasers, the dissipative four-wave-mixing (DFWM) mode-locking technique is a promising method, which requires multiwavelength selective components and highly nonlinear elements with proper dispersion parameters existing in cavity [231, 232]. Due to the high

Figure 5: Er-doped mode-locked fiber laser with a BP-decorated microfiber SA.

(A) Microscopic image of the fabricated microfiber-based BP SA. (B) Experimental setup. (C) Repeatedly recorded mode-locked spectrum at a 1-h interval. Reproduced with permission [203]. Copyright 2015, The Optical Society.

third-order nonlinearity of 2D material-decorated microfiber photonic devices, they have potential applications to achieve DFWM mode-locking. Recently, graphene-decorated microfiber photonic devices combined with the F-P filter were employed in fiber lasers to achieve ultrahigh-repetition-rate pulses with a 100 GHz repetition rate by virtue of the FWM mode-locking mechanism [170]. In addition, the graphene-deposited broadband microfiber knot resonator was used to achieve ultrahigh-repetition-rate pulses in both the 1.06- and 1.55- μm wavebands (Figure 6) [173].

3.3 Pulse generation at 2.0 μm

Thulium-doped fiber lasers, operating at an eye-safe wavelength of 2 μm , have a wide range of potential applications in fields such as material processing, long-range light detection and ranging, free space optical communication, nonlinear frequency conversion, and laser surgery [233–235]. To date, various 2D materials possessing intensity-dependent transmittance properties were employed as SAs to construct ultrafast mode-locked fiber lasers at different wavebands, even at the mid-infrared region [152, 236]. To gain high-energy pulses in Tm-doped fiber lasers, Q-switching and mode-locking are the two main methods. In theory, if a material possesses saturable absorption, it can be used not only as a mode-locker but also as a Q-switcher. For example, a high-energy Q-switched double-clad Tm-doped fiber laser based on a graphene-decorated microfiber SA was demonstrated in 2013, in which Q-switched pulses with a single pulse energy of 6.71 μJ (corresponding to an average power of 302 mW) at a wavelength of 2032 nm were observed [205]. In addition, Wang et al. reported a passively Q-switched Tm-doped fiber laser using a BP-decorated microfiber SA for the first time [209]. On the other hand, the generation

of high-energy soliton pulses needs an excellent SA with high power tolerance and large modulation depth. MoTe_2 , one of the members of TMDs, has a smaller direct band gap of about 1.1 eV, which makes it more suitable as an SA in near-infrared wavelength fiber lasers [237]. In 2018, Wang et al. fabricated a MoTe_2 -decorated microfiber SA using the magnetron-sputtering deposition method [198]. The MoTe_2 -decorated microfiber SA was incorporated in an Er-doped fiber laser and a Tm-doped fiber laser. In 2.0 μm wavelength regime, the generated soliton pulses had a single pulse energy of 13.8 nJ with pulse duration of 1.3 ps, corresponding to an average power of 212 mW, which is the highest pulse energy and output power reported Tm-doped mode-locked fiber lasers based on 2D material SAs (Figure 7). Other 2D material-decorated microfiber SAs were also widely used in Tm-doped mode-locked fiber lasers [69, 197, 187, 206–208, 238]. Compared to Er-doped mode-locked fiber lasers based on 2D material-decorated microfiber SAs, Tm-doped fiber lasers are less concerned, indicating that more investigations are needed to be conducted in the 2.0 μm waveband. It can be seen from Table 1 that the pulse widths of these fiber lasers are ~ 1 ps. In addition, both the modulation depths and nonsaturable absorptions of 2D material-decorated microfiber SAs in 2.0 μm seem to be larger than the general level of other wavebands.

4 2D material-decorated microfiber photonic devices on soliton dynamics investigation in fiber lasers

Generally, mode-locking pulses are initiated from the intense fluctuations of the noise background and evolve

Figure 6: DFWM mode-locking operation in the Er-doped fiber laser.

(A) Microscopy image of the graphene-deposited microfiber knot resonator. (B) Repeatedly recorded mode-locked spectrum at a 5-min interval. (C) Autocorrelation trace of filter-driven four-wave mixing mode-locking operation in the Er-doped fiber laser based on the graphene-deposited microfiber knot resonator. Reproduced with permission [173]. Copyright 2018, The Optical Society.

Figure 7: Er- or Tm-doped fiber laser with a MoTe₂-decorated microfiber SA.

(A) Experimental setup. (B) Relationship between the pump power and the laser output power. (C) Optical spectrum with the bandwidth of 3.2 nm. (D) Radio frequency spectrum at a fundamental frequency of 15.37 MHz (inset: the wideband RF spectrum). (E) Autocorrelation trace for the output pulse (inset: autocorrelation trace with a large range of 50 ps). Reproduced with permission [198]. Copyright 2018, The Optical Society.

into shorter pulses by employing the intensity-dependent transmittance properties of SAs [74, 76, 77]. The mode-locked pulses can be regarded as optical solitons,

whose formation strongly relies on the balance between dispersion and nonlinearity, even for dissipative solitons [239, 240]. Thus, the nonlinearity is necessary for

mode-locking. However, excessive nonlinearity in cavity leads to pulse destabilization and distortion, resulting in the occurrence of multiple pulses, which is an obstacle for performance improvement of a high-energy pulse fiber laser. We hope that nonlinearity is just enough to obtain ultrashort pulses, and no more. However, from the perspective of nonlinear soliton dynamics, nonlinearity should be embraced [239, 241]. Enough nonlinearity can excite various dissipative structures and self-organization effect in mode-locked fiber lasers, which enables mode-locked fiber lasers to become an ideal platform to explore nonlinear soliton dynamics [239]. Alternately, the investigation of nonlinear soliton dynamics will accelerate the performance improvement of mode-locked fiber lasers. Thus, providing a photonic device with saturable absorption and high nonlinearity would be beneficial for investigating nonlinear soliton dynamics in fiber lasers, and 2D material-decorated SAs are powerful candidates for such applications.

4.1 HML operation

According to the soliton area theorem, if the nonlinearity in cavity is large enough, the single soliton will split into multi-solitons due to the peak power limiting effect. Then, the multi-solitons will be distributed at equal intervals caused by long-range interactions between multi-solitons, mediated by the acoustic-wave effect, non-soliton components, and the gain depletion and recovery mechanism, which is called HML [242–244]. HML operation provides a simple way to enable a fiber laser to scale the pulse repetition rate to the GHz regime without reducing the laser cavity length. By the advantage of the high nonlinearity of a 2D material-decorated microfiber, HML operation could be easily obtained [66, 122, 166, 172, 178, 179, 182, 183, 186, 190–192, 218]. As an example, few-layered TI (Bi_2Te_3) was deposited onto a microfiber with a waist diameter of down to $12\text{ }\mu\text{m}$ [122]. Multi-soliton operation can be achieved in a higher pump power with the help of high nonlinearity of a TI-decorated microfiber SA, and the pulse repetition rate was sensitive to the pump power. When the pump power was increased to 126 mW, the HML operation with a pulse repetition rate of 2.04 GHz was obtained, corresponding to the 418th HML state. Subsequently, Yan et al. fabricated a microfiber-based TI SA by utilizing the pulsed laser deposition method [179]. Similarly, they also obtained HML operation by increasing the pump power and adjusting the intracavity polarization state, where the order of HML operation also gradually increased with the increase of the pump power. In addition, by adjusting

the intracavity polarization state at the maximum pump power, the order of HML operation further increased. Finally, they obtained stable HML operation with the repetition rate up to 2.95 GHz and output powers beyond 45 mW. The laser performances at 2.23 and 2.95 GHz are presented in Figure 8. Moreover, by employing the TI-decorated microfiber as a dual-function photonic device with the saturable absorption and highly nonlinear effects, a dual-wavelength HML fiber laser was demonstrated [183]. In this case, the dual-wavelength pulse-trains possess different HML orders due to the different cavity nonlinear effects experienced by the two lasing wavelengths.

4.2 Soliton molecules

As we know, coherent interactions between several optical solitons coexisting in the cavity result in bound states, which is also termed soliton molecules [245–247]. The evolution of soliton molecules, one of the most striking nonlinear dissipative phenomena, has been numerically predicted to be stationary, periodic, and chaotic [248, 249]. Especially, by virtue of the dispersive Fourier transformation (DFT) technique, the internal motion of soliton molecules was directly revealed [250, 251]. On the other hand, the intracavity nonlinear effect is vital to the evolution and dynamics of soliton molecules. For 2D material-decorated microfiber photonic devices, it can provide highly optical nonlinearity to support a variety of soliton molecules within the laser cavity with relatively low pump power. By introducing a highly nonlinear 2D material-deposited microfiber photonic device, soliton molecules were observed experimentally not only in anomalous-dispersion fiber lasers [177, 184, 186, 188, 190, 219, 252, 253] but also in normal dispersion ones [254]. Due to the relatively high nonlinearity provided by the 2D material-deposited microfiber photonic device, the soliton would radiate excessive energy to resist the accumulated cavity nonlinearity, and multi-solitons would be reshaped from the radiative waves. Multiple soliton molecules, soliton molecule bunch, and harmonic soliton molecules are also observed owing to the strong soliton shaping [186, 188, 253]. Generally, the pulse separation and the phase difference between pulses are the two main parameters to characterize the soliton molecules. By employing 2D material-deposited microfiber SAs in fiber lasers, it has been demonstrated that the pulse separation can be changed by simply adjusting the polarization controller, in which the loosely bound states can be attributed to the long-range pulse-to-pulse interactions [219, 252]. Moreover, Liu et al. observed the soliton molecules with low-contrast fringes

Figure 8: HML operation obtained in a fiber laser with a TI-decorated microfiber SA.

(A) Nonlinear saturable transmission curve of a microfiber-based TI film SA. (B) Transmission spectrum measured at ~ 350 W of incident peak power. (C) and (D) Spectrum and autocorrelation trace for the case of 2.23 GHz. (E) and (F) Spectrum and autocorrelation trace for the case of 2.95 GHz. Reproduced with permission [179]. Copyright 2015, The Optical Society.

on the spectrum in a fiber laser with the WS_2 -deposited microfiber SA, which could be caused by unequal properties or loosened phase relationships between two bound pulses [253]. Apart from regular soliton molecules, the structural soliton molecules have also been demonstrated in a fiber laser based on the graphene-deposited microfiber SA, where the individual solitons (soliton atoms) inside the soliton molecules show different characteristics such as peak intensities, durations, and ultra-narrow pulse separations (Figure 9) [177].

4.3 Disordered multi-soliton patterns

Different from the soliton molecules with the fixed phase difference and pulse separation, multi-solitons also show

random distribution within the laser cavity. There are a variety of disordered multi-soliton patterns due to the random interaction among solitons, dispersive waves, and continuous waves, such as soliton bunches (soliton clusters) [185, 224], soliton rains [255, 256], soliton flow [255, 256], and noise-like pulses [257, 258]. Since the multi-soliton patterns present more physical features, it would be meaningful and interesting to investigate the multi-soliton operation in passively mode-locked fiber lasers. In addition, the investigation of disordered multi-soliton dynamics would help us better understand and control the interactions among multi-solitons over large temporal extensions, opening the ways to the manipulation of large-scale multi-soliton compounds. Again, the observation of various multi-soliton patterns needs a higher pump power to ensure the highly nonlinear effect

Figure 9: Structural soliton molecules generated in a fiber laser with a microfiber-based graphene SA.

(A) Microscopy image of the microfiber-based graphene SA. (B) Scattering evanescent field of the microfiber. (C) Saturable absorption curve and the corresponding fitting curve. (D) and (H) Mode-locked spectra. (E) and (I) Measured autocorrelation traces. (F) and (J) Theoretically plotted pulse profiles. (G) and (K) Recovered autocorrelation traces. Reproduced with permission [177]. Copyright 2014, The Optical Society.

experienced by the solitons in the laser cavity. Therefore, the incorporation of a highly nonlinear 2D material-decorated microfiber photonic device could relax the requirement of a pump power level for observing the disordered multi-soliton patterns.

Soliton bunches are a stable and tight packet grouped by several or dozens of soliton pulses, but the bunched pulses are unstable and even chaotic. Versatile 2D materials such as graphene, TI, MoS_2 , gold nanorod, and WS_2 -decorated microfiber SAs are incorporated into the laser cavity to generate soliton bunches [185, 188, 204, 219, 220]. In a passively mode-locked fiber laser with a graphene SA on a microfiber, the soliton self-organization and pulsation were observed [220]. It was found that the formation of equidistant soliton bunches can be attributed to the optomechanical interaction in the optical fiber. Particularly, by virtue of the DFT technique, the spectral evolution of pulsating solitons in the anomalous dispersion regime was first revealed (Figure 10).

Soliton rains describe an intriguingly dissipative phenomenon that several isolated solitons rise from noisy background spontaneously and drift toward a condensed phase [255, 256]. Conversely, soliton flow

describes a phenomenon that several isolated solitons spontaneously flow out of a stable condensed phase and eventually disappear in the noisy background [255, 256]. Soliton rains and soliton flow are intermediate regimes where an intense interaction occurs between soliton pulses and continuous waves. The investigation of soliton rains and soliton flow is meaningful for a better understanding of mode-locking nonlinear dynamics. In fact, soliton rains and soliton flow are frequently observed in fiber lasers with 2D material-decorated microfiber SAs [184, 188, 204, 220, 223]. In 2015, Luo et al. observed soliton flow in a fiber laser with a few-layer MoS_2 -deposited microfiber photonic device (Figure 11) [188]. As can be clearly seen here, the drifting solitons spontaneously flow out of the condensed phase and eventually vanish in the noisy background. The continuous wave component on the spectrum indicates that it plays an important role in the interactions among multiple solitons, which is favorable for the generation of soliton flow in fiber lasers.

A noise-like pulse is another type of disordered multi-pulse pattern. Although a seemingly regular pulse train is observed by an oscilloscope, each pulse is actually

Figure 10: Pulsating soliton bunch generated in a fiber laser with a graphene SA on a microfiber.

(A) and (B) Shot to shot spectra of the one-soliton and dual-soliton bunch, respectively. (C) Single-shot spectra at round trips A (red) and B (green) in (A). (D) Single-shot spectra at round trips C (red) and D (green) in (B). Averages (blue) of 9762 consecutive single-shot spectra in both cases are also shown in (C) and (D), respectively. Reproduced with permission [220]. Copyright 2018, The Optical Society.

Figure 11: Soliton flow generated in a fiber laser with a MoS₂-deposited microfiber SA.

(A) Experimental setup. (B) Spectrum. (C) Pulse train. Reproduced with permission [188]. Copyright 2015, The Optical Society.

a locally chaotic multi-pulse wave packet. Noise-like pulses are typically characterized by a smooth and broad spectrum and an autocorrelation trace of a narrow peak on a wide pedestal [257, 258]. Since the pulse energy of

noise-like pulses is higher than the pulse energy output by traditional soliton and stretch pulse fiber lasers, they have potential applications in many fields, such as the generation of supercontinuum and sensing [258, 259]. By

employing 2D material-decorated microfiber SAs, noise-like pulses are generated in mode-locked fiber lasers in both the 1.55 and 2.0 μm wave bands [175, 181, 192, 204, 221]. For example, a special noise-like pulse with Kelly sidebands and second-order HML was demonstrated in a fiber laser with a microfiber-based WS_2 SA [221]. These results could further enhance the understanding of nonlinear dynamics of noise-like pulses.

4.4 Rogue wave generation

Rogue waves, which were initially proposed in oceanography to describe unexpected water waves from the sea with destructive power, would destroy the vessels and then disappear without a slightest trace [260]. Due to the high risk and unpredictable occurrence of rogue waves, it is extremely difficult to investigate them in the real environment, and the physical mechanism of the rogue wave generation has not been completely revealed. In 2007, Solli et al. observed an extreme event in the supercontinuum generation, which is called optical rogue wave. Since then, the investigation of rogue waves was turned into the field of nonlinear optics [261]. An ultrafast fiber laser, as a complex nonlinear dissipative system, easily works in a quasi-mode-locked state or disordered multi-soliton state when the nonlinearity in the cavity is high, showing chaotic or random characteristics. Thus, this feature enables it to become a convenient test bed to observe optical rogue waves [262, 263]. Generally, multi-soliton collisions and the interaction of solitons with dispersive waves play key roles in the formation of rogue waves [264, 265]. The combination of chaotic dynamics, strong nonlinear interactions, and soliton collisions is also conducive to the generation of rogue waves. Therefore, the chaotic multi-soliton patterns, such as chaotic

soliton bunches and noise-like pulses, have become one of the best solutions for studying the phenomenon of optical rogue waves [175, 185, 262]. As we mentioned above, due to the high nonlinearity, 2D material-decorated microfibers have been employed as SAs to relax the requirement of the pump power level in fiber lasers for investigating the dynamics of various chaotic multi-soliton patterns. Therefore, the fiber lasers based on 2D material-decorated microfiber SAs can be considered a powerful tool to investigate the optical rogue wave generation.

Indeed, the generation of optical rogue waves via the long-range interaction of chaotic soliton bunches in a fiber laser with a TI-deposited microfiber photonic device was demonstrated [185]. For demonstrating the generation of rogue waves, the evolution of chaotic multi-soliton bunches over several cavity roundtrips and the intensity histogram of chaotic multi-soliton bunches are shown in Figure 12. Clearly, some freak pulses with high amplitude appeared unpredictably inside the multi-soliton bunch in Figure 12A. In addition, the intensity histogram measured by the 8 GHz real-time oscilloscope exhibits a long-tailed statistical distribution, and the highest recorded amplitude is about four times that of the significant wave height (SWH). It should be pointed out that the general criterion of optical rogue waves is the highest amplitude of waves larger than twice the SWH. Thus, the rogue waves were indeed generated here. Note that the envelope of the chaotic multi-pulse bunch could reach to tens of nanoseconds, and the long-range interactions among chaotic multi-soliton bunches play a key role in the rogue wave generation. Subsequently, rogue waves induced by the short-range chaotic pulse interactions within the noise-like pulses were also demonstrated in a fiber laser by utilizing 2D material-deposited microfiber SAs [175].

Figure 12: Rogue waves generated in a fiber laser with a TI-deposited microfiber SA.

(A) Evolution of a chaotic multi-pulse bunch over several cavity round trips. (B) Intensity histogram on the log scale of the chaotic multi-pulse bunch. Reproduced with permission [185]. Copyright 2015, The Optical Society.

5 2D material-decorated microfiber photonic devices on all-optical signal processing

5.1 Optical modulator

Optical modulator is a device that is used to modulate (alter) the characteristics of a light beam, categorized as an amplitude, phase, or polarization modulator. It has attracted great interest due to its photonic and optoelectronic applications, such as optical interconnects, environmental monitoring, bio-sensing, medicine, or security applications. 2D materials have exceptional nonlinear optical response, such as extremely broadband optical response, less scattering loss, and high-speed carrier response [78, 266, 267], and hence could be excellent candidates for an optical modulator.

5.1.1 Intensity modulator

In 2014, an all-optical, all-fiber graphene modulator was demonstrated [130]. It was fabricated by wrapping a thin

layer of graphene around a microfiber (a waist diameter of about $1\ \mu\text{m}$), which is a section with the ends tapered down from a standard telecom optical fiber. The modulation comes from the enhanced light-graphene interaction due to the optical field confined to the wave guiding microfiber. The response time of the modulator is $\sim 2.2\ \text{ps}$, corresponding to a maximum modulation rate of $\sim 200\ \text{GHz}$ for Gaussian pulses (Figure 13). It is limited only by the intrinsic graphene response time. In addition, the modulation depth of the modulator could reach 38%. This modulator is compatible with current high-speed fiber-optic communication networks and may open the door to meet future demand of ultrafast optical signal processing. However, the low modulation depth and overall transmission resulting from graphene properties and modulation schemes limit the applications of this kind of optical modulators. Then in 2016, Yu et al. reported an all-optical, all-fiber optical modulator with a Mach-Zehnder interferometer (MZI) structure, where the graphene-clad-microfiber (GCM) acts as a phase modulator in one arm of the MZI (Figure 14) [268]. The phase modulation from the GCM could be converted to intensity modulation with high modulation depth through interference at the output of the MZI. Compared with graphene modulators relying

Figure 13: All-optical, all-fiber graphene modulator based on GCM.

(A) Schematic illustration of all-optical modulation setups. (B) Pulses switched out from a 1550 nm CW beam in a GCM by a 5 ns 1064 nm pump pulse train. The induced differential transmittance is $\sim 30\%$. (C) Time profile of a switched-out pulse. (D) Differential transmittance of the probe light through a $1.4\ \mu\text{m}$ GCM with $20\ \mu\text{m}$ long graphene cladding as a function of the pump-probe time delay with a pump power of 200 nW, showing a response time of $\sim 2.2\ \text{ps}$. The inset shows the dependence of the modulation depth on pump intensity. Reproduced with permission [130]. Copyright 2014 American Chemical Society.

Figure 14: GCM-based all-optical modulators.

(A) Schematics of GCM-based all-optical modulators based on optically induced loss modulation in a GCM. (B) Schematics of GCM-based all-optical modulators based on optically induced phase modulation in a GCM in one arm of an all-fiber MZI. (C) Top panel, pairs of switching pulses; middle panel, pulse-modulated signal from a GCM-contained fiber; bottom panel, pulse-modulated signal from an MZI as a result of phase modulation in the GCM-contained arm. (D) Modulation depth of the output signal as a function of the peak switching power for the GCM-contained fiber modulator (red solid line), for the MZI modulator (blue solid line), and for the MZI modulator with only loss modulation in the GCM-contained arm of the MZI (blue dashed line). (E) Modulation depth versus overall transmittance (OT) for the GCM-contained fiber modulator (red line) and the MZI modulator (blue line) with different graphene cladding lengths as indicated. Reproduced with permission [268]. Copyright 2016, The Optical Society.

on loss modulation [130], higher modulation depth and overall transmission could be achieved with the MZI modulator.

But the relatively weak absorption in graphene (only 2.3% of incident light per single layer) might significantly weaken its light modulation ability, while its semimetallic band gap can result in a low on/off ratio in electronics [79, 269]. Then other 2D materials with band gap offer advantages over graphene for optical intensity modulators. In 2017, by coating the MoSe₂ nanosheets on the microfiber, the active light control by light was achieved when pumped by a 405 nm laser (out-fiber-pumped) and a 980 nm laser (in-fiber- and out-fiber-pumped) (Figure 15) [270]. The light in the microfiber could be changed by the pumped laser, since it would interact with the MoSe₂

nanosheet through the evanescent wave. The response sensitivities of the microfiber coated with MoSe₂ to the out-fiber-pumped 405 nm laser is ~0.165 dB/mW. The sensitivities of the 980 nm in-fiber and out-fiber experiments are 0.092 and 0.851 dB/mW, respectively. The response times to the 980 nm pumped light are 0.4 and 0.6 s in the rise and fall processes, respectively.

In addition, Figure 16 presents that using few-layer phosphorene-decorated microfibers, all-optical thresholding and optical modulation are also demonstrated for optical communications [271]. The few-layer phosphorene-decorated microfiber was fabricated using the convenient evanescent-field-induced deposition method. Taking the advantage of the properties of few-layer phosphorene and the device structure, the signal-to-noise ratio

Figure 15: All light-control-light based on the microfiber coated with MoSe₂.

(A) Schematic of the 980 nm in-fiber pumped experimental setup. (B) The optical transmitted power of the microfiber with MoSe₂ for different 980 nm laser powers. Reproduced with permission [270]. Copyright 2017, The Optical Society.

Figure 16: All-optical modulation based on a phosphorene-decorated microfiber.

(A) Schematic diagram of the experiment setup. (B) Optical spectrum of the output light after the OBPF with CW on. (C) Optical spectrum of the output light after the OBPF without CW. (D) Waveforms of the output light after the OBPF with CW on or without CW. (E) Comparison of the single pulse waveform between the original switch light and the new modulation light. Reproduced with permission [271]. Copyright 2017 John Wiley and Sons.

can be enhanced and the deteriorated signal pulse can be reshaped. Therefore, it could be employed as an efficient noise suppressor. In addition, it could also switch the signal on/off by pumping light as an optical modulator. With this scheme, a large number of intensity modulators based on 2D material-decorated microfiber photonic devices have been developed [272–276].

5.1.2 Phase shifter and optical switch

All-optical phase shifters and switches play an important role for various all-optical applications including

all-optical signal processing, sensing, and communication. It has been demonstrated that with 2D material-decorated microfiber photonic devices, the phase shifters and optical switches could be realized [277–282]. In 2015, Gan et al. demonstrated an all-fiber phase shifter by employing graphene's optical absorption and excellent thermal properties [277]. The graphene-coated microfiber (GMF) was integrated into an MZI (Figure 17). In the GMF, graphene's ohmic heating would lead to the temperature rise in the microfiber, and then induce an efficient fiber index change and phase shift via the thermo-optic effect. When pumping with 980 nm (1540 nm) continuous-wave light, a phase shift of 21π was measured with a nearly linear

Figure 17: All-fiber phase shifter and optical switching based on GMF.

(A) Schematic of the experimental setup for measuring the phase shift in GMF. (B) Measured interference fringes without (blue) and with (red) pump. (C) All-optical switching by the GMF. (D) Temporal response of the optical switching. Reproduced with permission [277]. Copyright 2015, The Optical Society.

Figure 18: All-fiber phase shifter and optical switch based on a WS₂-deposited microfiber.

(A) Experimental setup. (B–D) Transmission spectra of the MZI with 0 (blue) and 5π phase shift (red) using (B) a continuous wave laser source and (C) a mode-locked laser source. (D) Phase shift with respect to the injected pump power with two input power levels. (E) Pulsed pump light (yellow) and switch output at “output 1” port (blue). (F) A zoomed view of a single off-on-off transition of the switch (blue) and exponential fit (red), (G) complementary output at “output 2” port. (H) Output breaking when the MZI is over-driven. Reproduced with permission [279]. Copyright 2017, The Optical Society.

slope of $0.091 \pi \text{ mW}^{-1}$ ($0.192 \pi/\text{mW}$). Based on the developed graphene-assisted phase shifter, all-optical switching on the MZI with an extinction ratio of 20 dB and a rise (fall) time of 9.1 ms (3.2 ms) following the 10%–90% rule could be implemented.

However, for the phase shifter, uniform absorption in a wide spectrum of graphene is not desired since additional loss is induced at the signal wavelength. It would be better if the material absorbs more at the pump wavelength and less at the signal wavelength. In addition, to incorporate into telecommunication applications easily, the signal wavelength should be compatible to the current fiber system near 1550 nm. As we know that the band gap of WS₂ near 1.3 eV (954 nm) [278] allows good absorption of the pump (control light) at 980 nm and weak absorption of the signal light near 1550 nm, therefore, WS₂ could be a good candidate for the phase shifter. In 2017, Wu et al. demonstrated a fiber all-optical phase shifter using few-layer 2D material tungsten disulfide (WS₂) deposited on a tapered fiber [279], and the results are shown in Figure 18. Similar to the above one, this

phase shifter is also based on the thermo-optic effect. The maximum phase tuning range is 6.1π with a slope efficiency of $0.0174 \pi/\text{mW}$. By incorporating this WS₂-based phase shifter to a fiber MZI, an all-optical switch with an extinction ratio of 15 dB and a rising time of 7.3 ms was also demonstrated.

In addition, an all-optical modulator using MXene Ti₃C₂T_x deposited on a microfiber was proposed by Wu et al. in 2019 [280]. By inserting it into one arm of an MZI, the maximum phase shift of 16π could be obtained, and an efficient all-optical switch with an extinction ratio of more than 18.53 dB and a rise time constant of 4.10 ms is demonstrated, which can be seen from Figure 19.

Besides the thermo-optic effect, an optical switch (phase shifter) based on a 2D material-decorated microfiber could also be realized using the nonlinear Kerr effect. Owing to the large Kerr coefficient of TI, a TI-coated microfiber (TICM) could operate as an effective optical Kerr switcher at the telecommunication band [281]. The mutual nonlinear interaction between the pump and probe signals would result in an additional nonlinear

Figure 19: All-optical modulator using the $\text{Ti}_3\text{C}_2\text{T}_x$ ($T = \text{F}, \text{O}, \text{or OH}$) deposited microfiber.

(A) System configuration. (B) Interferometric spectra of Output 1 and Output 2. (C) Measured interference fringes with a pump power of 122 mW at Output 1 (phase shift of 9π). (D) Phase shift of the modulator as the 980 nm pump takes different powers. (E) Waveform of the 980 nm pump light. (F) On-off transition of Output 1 and Output 2 (exponential fitting curve is indicated by the red dashed line). (G) Output breaking. (H) Signal waveforms at 40 Hz. Reproduced with permission [280]. Copyright 2019 John Wiley and Sons.

phase shift. Since TI possesses a large nonlinear refractive index and the mutual interaction length is long enough, the probe signal might encounter a cross-phase modulation, leading to the polarization rotation of the probe signal after propagating along the TICM.

5.2 Wavelength converter

All-optical signal processing is a promising and extensively employed technique of crucial importance in the current modern optical communications because signal processors play a key role in optical communication systems [91, 92]. Wavelength converter is one of the important nonlinear functional devices which has also been studied. 2D materials, such as graphene, TI, TMDs, BP, and so on, own a highly nonlinear refractive index, together with the high nonlinearity of a microfiber, which are suitable for the realization of wavelength converters [128, 281, 283–287]. In 2014, Wu et al. demonstrated effective FWM wavelength

conversion in a $2\text{ }\mu\text{m}$ microfiber attached onto a graphene film [283]. The interaction length between the evanescent field of the microfiber and the graphene film is much longer, which induces large nonlinearity for the FWM. The increase of the contact length between the microfiber and the graphene film would enhance the nonlinearity, which could further increase the conversion efficiency. Figure 20 illustrates that the highest conversion efficiency reaches -28 dB with a contact length of 10 mm, wavelength difference of 0.5 nm, and input powers of 600 and 100 mW for the two pumps. The maximum wavelength tuning range is $\sim 4.5\text{ nm}$. Then they modified the fabrication method of wavelength converter from deposition method to coating method, and further optimizing the parameters, such as microfiber diameter, interaction length, insertion loss. Using the improved graphene/microfiber hybrid waveguide, the effective multi-order cascaded FWM is demonstrated in Figure 21. In the FWM, the detuning was tuned from 0 to 5 nm, with a conversion efficiency of up to -20 dB [284].

Figure 20: FWM wavelength conversion using microfiber-attached graphene.

(A) Experimental setup for the observation of FWM, where two pump beams derived from a fixed-wavelength laser (λ_{p1}) and a wavelength-tunable laser (λ_{p2}), respectively, are launched into a microfiber attached graphene. (B) Output spectra from the microfiber-attached graphene with a contact length of 8 mm, measured at three wavelength detuning values (from top to bottom): 1, 2, and 4 nm with the two pump powers fixed at 1.25 W and 200 mW, respectively. (C) Dependence of the conversion efficiency at λ_1 on the pump power at λ_{p1} for different contact lengths L with the wavelength detuning fixed at 2 nm and the power of λ_{p2} fixed at 200 mW, respectively. (D) Dependence of the conversion efficiency at λ_1 on the wavelength detuning for different contact lengths L with the two pump powers fixed at 1.25 W (λ_{p1}) and 200 mW (λ_{p2}), respectively. Reproduced with permission [283]. Copyright 2014, IEEE Photonics Society.

However, the low damage threshold of graphene might delimit the applications in the wavelength converter where a strong light-matter interaction exists [102, 285]. As we know, Bi_2Te_3 , a few-layer TI, has been measured to have a high nonlinear refractive index, which suggests that TI shows a larger nonlinear Kerr coefficient than graphene at the communication band. Then, TI should be a better material for the wavelength converter. The TICM device was demonstrated using optical deposition methods [281]. The FWM-based wavelength converter-based TICM has a maximum conversion efficiency of -34 dB, a maximum tuning range of 6.4 nm, and a damage threshold of >20 dB (Figure 22). In addition, MXene-, bismuthene-, and black phosphorus quantum dot-assisted all-optical wavelength conversion at the telecommunication band was realized [288–290].

6 Conclusions, challenges, and perspectives

Thanks to the excellent photoelectric properties of 2D materials, they have received intensive attention in recent years. Great effort has been made on the discovery of new type 2D materials, optical property investigations, and their applications in diverse fields. In particular, the preparation methods of photonic devices based on 2D materials are crucial for the applications. Compared to the other preparation methods, a 2D material-decorated microfiber offers many advantages, such as all-fiber structure, greater nonlinearity, and enhanced damage threshold. With this kind of device, a great deal of important results have been achieved. In this review, we focused

Figure 21: Cascaded FWM based on a graphene/microfiber hybrid waveguide.

(A) Schematic diagram of the GCM, in which graphene is wrapped around the microfiber with diameter D . (B) For the microfiber without graphene, no FWM was observed (1545–1560 nm). Inset: zoom-in figure with the window of 1549–1551 nm. (C) Spectra of the GCM under the pump powers of 0.2 mW (red), 1.0 mW (blue), and 3.0 mW (green). Inset: zoom-in figure with the window of 1549–1551 nm. (D) Spectra of cascaded FWMs for the detuning of 1 nm (red), 2 nm (blue), and 5 nm (green), respectively. (E) Time profile of the transmitting light of the GCM, before CW launched (red boxes) and after CW launched (blue circles). Reproduced with permission [284]. Copyright 2015, The Optical Society.

Figure 22: FWM wavelength conversion based on a TI-coated microfiber.

(A) Experimental setup. (B) Output FWM spectra against wavelength detuning. Reproduced with permission [281]. Copyright 2015 John Wiley and Sons.

on the recent progress on optical pulse shaping and all-optical signal processing based on 2D material-decorated microfiber photonic devices. The two main fabrication methods of 2D material-decorated microfiber photonic devices, namely deposition and coating methods, were introduced first. Then, we illustrated in detail the applications of 2D material-decorated microfiber photonic devices in pulse generation, soliton dynamics, and all-optical signal processing. In Section 3 on pulse generation, the fiber laser results are presented by the operation waveband (1.0, 1.5, and 2.0 μm), which are also summarized in Table 1, and 2D material-decorated microfiber photonic devices are mostly served as SAs with a higher damage threshold. In Section 4 on soliton dynamics, HML operation, soliton molecules, disordered multi-soliton patterns, and rogue wave generation based on 2D material-decorated microfiber photonic devices in fiber lasers have been exhibited. In this field of application, the main advantage of the 2D material-decorated microfiber photonic devices

is the highly nonlinear effect realized by the long interaction length between the 2D material and light. In the last section on all-optical signal processing, applications in fields of the intensity modulator phase shifter, optical switch, and wavelength converter have been introduced. Here, the optical absorption, thermo-optic effect, and Kerr nonlinear effect of 2D materials are the main functions to realize the all-optical signal process.

There are two main challenges for the development of 2D material-decorated microfiber photonic devices. (1) Environmental instability: the 2D material-decorated microfiber photonic devices attract considerable attraction in pulse shaping and all-optical signal processing. However, due to the strong evanescent fields of the microfiber, these kinds of photonic devices are very susceptible to environmental disturbances. Therefore, in order to avoid being affected by the environment, it is necessary to integrate them into a confined space such as a tube, which would also solve the problem of fragility. (2) Mass

production: large production of the 2D material-decorated microfiber photonic devices is beneficial for industrial purposes and commercialization. However, there are too many parameters of the 2D material-decorated microfiber photonic devices to control, such as the diameter, length, loss of microfiber, and thickness of the deposited/covered 2D material. The inevitable uncertainty during the fabrication of the microfiber and the decorating processes leads to the poor repeatability, which is the main constraint for mass production. In addition, although the fabrication methods of an ultra-low loss microfiber have been demonstrated, it can be seen from Table 1 that almost half of the 2D material-decorated microfiber photonic devices have nonsaturable loss larger than 50%. Consequently, mass production of 2D material-decorated microfiber photonic devices with ultralow loss and environmental stability is quite challengeable, though it is extremely important for industrial applications.

As the future perspective of a 2D material-decorated microfiber, there are three points to be investigated in the further research. First, miniaturization and integration will be the important development trend of optical devices in the future, so it is necessary to study how to integrate the 2D material-decorated microfiber as a compact device. It has been demonstrated that the 2D material-decorated microfiber could be placed into a semicircular tube and fixed by adhesive dropped at the end [161], which could be regarded to be compact and stable due to the small size of the 2D material-decorated microfiber and environmental stability in the enclosed space. The idea is competitive but still needs to be explored more in the future. Second, as we know, most of the 2D materials own the similar characteristics, such as broadband saturable absorption and a highly nonlinear effect. However, since there are too many variable parameters of 2D material-decorated microfiber photonic devices in each area of applications, such as the microfiber parameters, deposition parameters, and setup parameters in different cases, it is hard to identify the unique points of each kind of 2D materials. Therefore, it is necessary to systematically investigate the unique features of 2D materials using a control variable method. Third, more in-depth studies of 2D material-decorated microfiber photonic devices on pulse shaping and all-optical signal processing should be conducted. For example, pulse generation in the ultraviolet and 2 to 4 μm wavebands, more fascinating soliton dynamics, and more signal-processing devices should continue to explore. It is believed that 2D material-decorated microfiber photonic devices will continue to develop rapidly and the practical industrial applications could be realized soon, which will open new opportunities in the related fields.

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