Review Article

ADVANCED PHOTONICS

Recent progress on optical rogue waves in fiber lasers: status, challenges, and perspectives

Yufeng Song,[a,†] Zhenhong Wang,[a,†] Cong Wang,[a] Krassimir Panajotov,[b,c] and Han Zhang[a,*]
[a]Shenzhen University, Institute of Microscale Optoelectronics, Collaborative Innovation Center for Optoelectronic Science and Technology, Shenzhen Engineering Laboratory of Phosphorene and Optoelectronics, Shenzhen, China
[b]Vrije Universiteit Brussel, Department of Applied Physics and Photonics, Brussels Photonics, Brussels, Belgium
[c]Bulgarian Academy of Sciences, Institute of Solid State Physics, Sofia, Bulgaria

Abstract. Rogue waves (RWs) are rare, extreme amplitude, localized wave packets, which have received much interest recently in different areas of physics. Fiber lasers with their abundant nonlinear dynamics provide an ideal platform to observe optical RW formation. We review recent research progress on rogue waves in fiber lasers. Basic concepts of RWs and the mechanisms of RW generation in fiber lasers are discussed, along with representative experimental and theoretical results. The measurement methods for RW identification in fiber lasers are presented and analyzed. Finally, prospects for future RW research in fiber lasers are summarized.

Keywords: fiber lasers; nonlinear fiber optics; rogue wave.

Received Dec. 4, 2019; accepted for publication Feb. 14, 2020; published online Apr. 9, 2020.

[DOI: 10.1117/1.AP.2.2.024001]

1 Introduction

Rogue waves (RWs), also known as "extreme waves," "freak waves," and "abnormal waves," are the waves that are much greater in amplitude than the close-by waves, unpredictable, and usually appearing unexpectedly from directions other than dominant wind and waves.[1,2]

The concept of RWs is believed to be first established in the ocean, in reference to the giant waves on the surface of the sea. In oceanography, RWs can be defined as extreme waves with a height more than twice the significant wave height (SWH), which is the mean amplitude of the largest third of waves. According to this definition, RWs are not necessarily the biggest waves found in the ocean, but they are extremely dangerous even to large ships such as ocean liners because of their unexpected and sudden appearance.

The RW concept is also extended to other fields of science, such as matter physics, superfluidity, optics, and even economics.[3] There have been various RWs studied, including oceanic RWs,[1,2,4] optical RWs,[5] acoustic RWs,[6,7] capillary RWs,[8] electromagnetic RWs,[9,10] and even financial RWs.[11,12] Several defining properties of RWs can be summarized in three points. First, a large amplitude is required, typically more than twice that of the average amplitude of the highest third of the waves (called SWH). Second, unpredictability of the pulse should be fulfilled. Third, RWs should be rare, i.e., probability distribution function of the wave amplitude should have an L-shape (or other specific long-tail shape).[13]

Currently, it is well known that RWs are generated in the nonlinear systems.[14,15] However, the mechanism driving the emergence of RW is different, depending on the properties of the system.[14] In the field of optics, the description of RW generation is typically described by the nonlinear Schrödinger equation (NLSE),[15,16] which also governs the pulse propagation and soliton formation in the media.[17–26] Indeed, RW dynamics are closely related to the nonlinear breather and soliton formation induced by modulation instability.[27] Within the framework of the one-dimensional NLSE, Peregrine solitons described by a class of nonlinear Akhmediev breather[28] are considered as a prototype of RW.[27–31]

Experimentally, in nonlinear optical systems, RWs, also called optical RWs, were first investigated through the supercontinuum (SC) generation process based on the optical fibers.[5] From then on, there have been many studies directed to generating RWs in a variety of optical systems. Optical fiber oscillating systems are well known for providing convenient platforms to investigate versatile fundamental nonlinear phenomena, such as modulation instability,[32–34] soliton formation and dynamics,[21,35] and self-similarity.[36] Study of optical RW in fiber lasers

*Address all correspondence to Han Zhang, E-mail: hzhang@szu.edu.cn
†Contributed equally to this work.

has attracted plenty of attention since its first demonstration in 2011.[13,37] The investigation of the mechanisms of optical RWs in fiber lasers has enabled researchers to deeply understand the generation principle of optical RWs, which can offer a chance to control the operation of optical RWs. There have been several review articles covering the previous study of RWs.[38,39] However, to the best of our knowledge, there is no specific review on the dynamics of RWs in fiber lasers.

In this review, the latest research progress on optical RWs in fiber lasers is highlighted. The scope of the paper is mostly focused on experimental investigation of RWs in fiber lasers. In Sec. 2, a brief introduction to the basic concept of optical RWs is given, along with a comparison between optical RWs and ocean RWs. In Sec. 3, we discuss the experimental methods of generating optical RWs in nonfiber lasers. In Sec. 4, we introduce experimental observation of RWs in fiber lasers. In Sec. 5, various measurement methods of optical RWs are discussed. The challenges and outlook on optical RWs in fiber lasers will be discussed in Sec. 6.

2 Basic Concept of Optical Rogue Waves

An optical RW corresponds to extreme optical pulses that appear suddenly and rarely. A remarkable characteristic of optical RWs is their exceptionally large amplitudes; the largest ones have an intensity at least 30 to 40 times the average intensity.[5] RWs are closely related to modulation instability and soliton formation, which are all developed in a nonlinear optical system. The role of modulation instability on the RWs is demonstrated in Ref. 14, where it is shown that modulation instability is crucial for RW generation in many optical systems.

A number of theoretical studies have been advanced for optical RW generation. In 2013, Akhmediev et al.[38] previewed the development of optical RWs. In 2016, a roadmap on the optical RWs was summarized by Akhmediev et al.;[40] thanks to their review, research of RWs is developing fast.

2.1 Comparison Between Ocean RWs and Optical RWs in Fiber Lasers

Apart from the optical RWs, the ocean RWs are also greatly important. There are various physical processes in ocean systems, such as wave breaking, dissipation, currents, and wind force.[41] The wave breaking is a natural nonlinear process while the dissipation, currents, and wind force are either nonlinear or linear. In a word, the observations of ocean RWs are very complicated. Actually, there are similarities and differences between ocean RWs and optical RWs. In both cases, there is a similar mathematical equation in the form of an NLSE, which can be used for describing the evolutionary process of the envelope in time and space.[41,42] In fiber laser, there is the sinusoidal underlying carrier wave at frequency ω while there is the Stokes wave modulated by the NLSE envelope, which (to the second order) includes contributions at both ω and the second harmonic 2ω.[43] In both cases, the measurement methods in the domain are also different. In the fiber laser experiments, only the time-domain envelope intensity is generally measured, and there is no information about carrier oscillations recorded. However, there are many individual carrier wave amplitudes directly recorded in oceanic systems, which are more complicated. In addition, the statistics in both systems are usually taken into account. However, there are important differences. In fiber laser experiments, the statistics are determined by the peaks of intensity envelopes. However, in water waves, the statistics are generally dominated by the amplitudes (or trough-to-crest heights or crest heights) of individual waves. In addition, in the fiber laser, the criterion of the RW generation is that its amplitude (the envelope peak intensity) is more than twice that of SWH. In the ocean system, there is the same criterion, but it is expressed in terms of the trough-to-crest height. Although there is an analogy between the generation of ocean RWs and the propagation of pulses in fiber lasers, due to the complexity of ocean RWs, more precisely targeted research in their natural environment is urgently required.

3 Experimental Observation of Optical Rogue Waves in Nonfiber Lasers

Optical RWs have been experimentally verified in plenty of physical systems. Solli et al.[5] demonstrated the first observation of optical RWs, which was based on a platform of SC generation in a photonic crystal fiber. Since then, a variety of nonlinear optical systems have been used for generating RWs. Apart from the SC process,[44–51] there are other nonlinear optical schemes, such as mode-locked pulse fiber laser[52–55] and Raman amplifier systems,[56,57] which also provided the excellent platforms for investigating the generation of RWs. However, most of these research works in versatile nonlinear optical systems are concerned with the observation of optical RWs, and there is also a strong motive to deeply investigate physical mechanisms of optical RW formation. In this section, RW generation in different platforms apart from fiber lasers is summarized.

In the case of SC generation, an ultrashort pulse generated from a laser was typically inserted into a segment of highly nonlinear optical fiber. The RWs were captured by a real-time measurement system based on time stretching, which will be further discussed in Sec. 5. A typical diagram of experimental setup is shown in Fig. 1. RWs can appear as rare solitons. It has been shown that the optical rogue structures could be efficiently isolated by an adequate spectral filtering based on an off-centered optical band pass filter.[5,45,58] In addition, rogue-wave-like extreme value fluctuation in Raman fiber amplifier systems was first reported by Hammani et al.[57] A typical diagram of experimental setup of Raman RW generation is shown in Fig. 2. In 2012, they experimentally reported the observations of extreme optical fluctuations in lumped Raman fiber amplifiers.[59] In addition, RW statistics during high power femtosecond pulse filamentation in air were reported in 2008.[60] In these reports, the RWs are typically in a conservative system without gain and loss in the system, which is distinct from a fiber laser system. In nonconservative systems, deterministic RWs were found

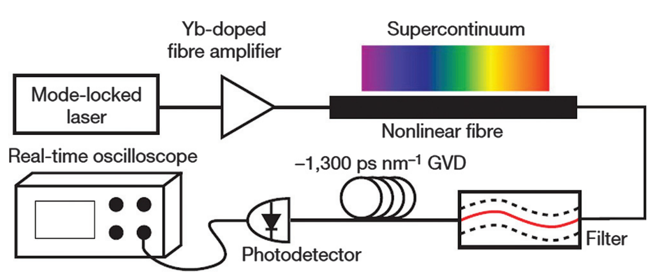

Fig. 1 The optical set-up for RW generation in a supercontinuum system. Reproduced with permission from Ref. 5.

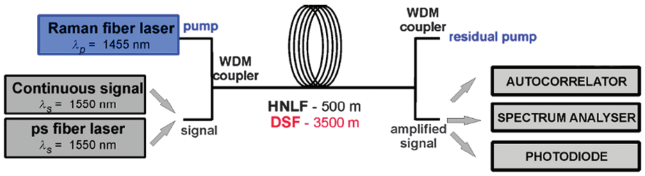

Fig. 2 The optical set-up for RW generation in a fiber Raman amplification system. Reproduced with permission from Ref. 57.

in an optically injected semiconductor laser[61] and semiconductor laser with saturable absorber for the two-dimensional (2-D) case.[62]

4 Optical Rogue Waves in Fiber Lasers

Fiber laser, as a dissipative nonlinear optical system, has been intensively employed for the study of optical solitons.[21,63–65] Soliton dynamics including soliton interactions,[66–68] soliton molecules,[69–71] soliton rains,[72–75] noise-like pulses (NLPs),[76,77] and soliton explosions,[78] which could be highly related to the RW generation, has been intensively studied in ultrafast fiber lasers. Therefore, fiber lasers also provide an appropriate platform for the generation of dissipative RWs.[79] In a fiber laser, dynamic of RWs can be measured within each round trip.[40] RWs in fiber lasers were experimentally studied as early as 2011[13] and numerically studied in 2012.[80] Since then, the study of dissipative RWs in fiber lasers has been rapidly developing.[53–55,79,81–97] RWs in fiber lasers can be categorized by pulse duration as three types,[94] namely slow RWs, fast RWs, and ultrafast RWs. These RWs are generated by different mechanisms. Ultrafast RWs are difficult to measure using the traditional method, which will be discussed in Sec. 4. According to the formation mechanism, there are mainly three kinds of dissipative RWs generated in the fiber lasers.[98] The first type of RWs can be achieved via the chaotic structures among the NLPs. The second one is dark three-sister RWs,[99] and the third one is the pulse waves generated from the multiple-pulse interaction,[100,101] which have been identified as the aperiodically generated temporal structures.

4.1 Slow Rogue Waves

Slow RWs are typically with pulse duration from seconds to microseconds and are typically generated in fiber lasers by pump modulation[13] or altering the laser gain.[80] An experimental study in 2016 showed that, by altering the birefringence of the laser cavity, vector RWs can be observed at the pump power slightly above laser threshold.[87] The as-observed optical RWs are generated based on the interaction between the polarization modes with duration from 98 to 255 μs, which can be classified as a type of slow RW. Sergeyev et al. claimed that the increased in-cavity birefringence strength could cause the spatial modulation of the polarization state of the in-cavity lasing field. Based on their numerical predication, a precise polarization control of the pump and the intracavity laser field emitted RWs in an erbium-doped fiber laser (EDFL) has been demonstrated.[102] The typical experimental setup of EDFL is shown in Fig. 3.

4.2 Rogue Waves Generated by Soliton Interaction

Fast RWs typically have durations of hundreds of nanoseconds to tens of picoseconds. Fast RWs are typically generated by soliton

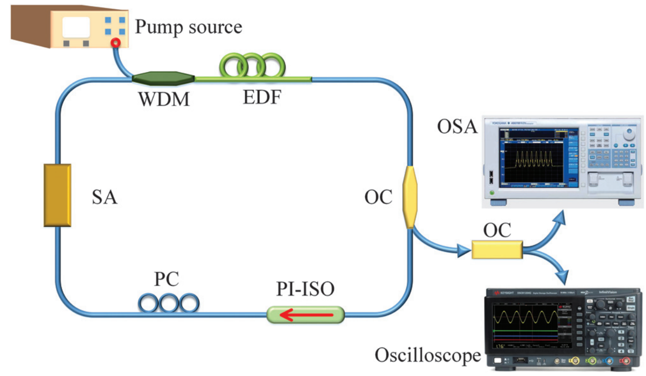

Fig. 3 A typical schematic diagram of a soliton fiber ring laser operating at 1550 nm based on passive mode locking technique. EDF, erbium-doped fiber; WDM, wavelength division multiplexer; SA, saturable absorber; PC, polarization controller; PI-ISO, polarization-independent isolator; OC, optical coupler; OSA, optical spectrometer.

interaction in mode-locked fiber lasers (MLFLs). Dissipative RWs generated by chaotic pulse bunching are reported in the literature,[81] and Peng et al.[89] reported RW generation based on the soliton collision. Peng and Zeng[103] demonstrated the generation of RWs among the soliton molecules by the soliton interactions, which could be related to the cavity dissipative effects and high pulse energy. RWs can appear via soliton collisions, producing events with high redshifted energy.[104,105] The energy exchange between the solitons is promoted by Raman effects and third-order dispersion.[106,107]

When the dissipative nonlinear optical systems deviate from equilibrium state, the fiber lasers can produce short and low coherence pulse packets. Such peculiar pulse regime has been first reported in details from the MLFL experiment in 1997,[108] which is then called NLPs. NLPs have been found in the fiber lasers based on the multiple mode-locking mechanisms[96,109–114] and, therefore, are characterized with universality. In other words, NLP generation is quite generic dynamics for partially mode-locked lasers that emit pulse packets of optical noise burst with the fundamental frequency or the harmonics. There are, however, some factors, including the long cavity and the high pumping power, that are quite conducive to generating the NLPs. In the early days, due to the lack of real-time detecting techniques adapted to the time scales of the NLP structures with picosecond or subpicosecond time scales, it is difficult to resolve the internal structure of the NLPs, which increases the sense of mystery about their detailed characteristics and physical forming process to some extent. The measurements based on the commercial optical spectrum analyzer in the NLP regime, generally show the characteristics of stable, smooth, and wideband spectra,[76,110,115–118] which may be broader than the bandwidth of the gain medium. In addition, the NLPs possess a special autocorrelation trace, with a double-scaled structure with an ultrashort coherent spike located in a wide pedestal, which cannot represent the pulse width of the NLPs. In fact, the narrow peak reflects the typical temporal timescales of the internal noisy pulse packets; the broad baseline suggests that the pulse regime consists of packets with picosecond or subpicosecond range, possessing the fine inner temporal structure with randomly diverse noisy pulse.[119] At this stage, due to the low-level information collection through the traditional measuring scheme, including the averaged spectral measurement and the autocorrelation recording, it has been difficult to figure out the formation of the NLPs. In fact, the majority of chaotic pulses, including NLPs, found in the fiber lasers have not yet been resolved in real time. The temporal duration of these pulses is usually in the range of picosecond or subpicosecond, which is smaller than or equal to the temporal resolution of the photoelectric detection system. In addition to the improvement of the electronic detection bandwidth, there is another way to realize the fast detection in real time, i.e., to record shot-to-shot spectra based on the high-speed real-time oscilloscope. In order to achieve such shot-to-shot spectral measurements, a new detection technique can be applied, which is known as the dispersive Fourier-transform (DFT) technique.[120] In the fiber lasers, the DFT technique is generally implemented by sending the ultrafast output pulses through a long fiber with either positive or negative dispersion, producing the sufficient accumulated dispersion so that the spectral fluctuations of these pulses are mapped into a temporal intensity waveform, which can be captured by the real-time oscilloscope with high electronic bandwidth. In this way, shot-to-shot spectra of the internal pulse dynamics can be analyzed. DFT has been used for observing the generation of RWs in the NLP regime.[82,121–124] However, it is important to note that not all the NLPs could be considered as RWs. When the pulse-energy distribution of the NLPs is always Gaussian profile, this pulse state may be not the RW regime.[124] In the literature,[123] even though the pulse-energy distribution of the NLPs in the normal dispersion is nearly Gaussian, the distribution of the peak optical spectral intensity for these pulses displays the obvious non-Gaussian statistics, which implies that this NLP regime could be related to RWs. In the former, the observation of the little deviation from Gaussian statistics is mainly caused by the insufficient temporal resolution of the detection scheme; the DFT technique is implemented in the latter, which can significantly improve the temporal resolution.

4.3 Recent Works

Apart from the above-mentioned methods, there are also several observations of RWs in fiber lasers reported in the last 3 years. Stimulated Brillouin scattering (SBS) has been recently considered as a trigger effect for the generation of RWs. Experimentally, Brillouin scattering-induced RWs in self-pulsing fiber lasers,[91] Q-switched random laser,[125] and high power amplifier[126] were reported. Boukhaoui et al. numerically studied the influence of SBS on the occurrence of RWs in self-pulsing fiber lasers.[127] They showed that the RW generation in the SBS process is highly related to high-order Stokes generation while acoustic noise effect is negligible for the occurrence of extreme events. Recently, dissipative RWs generated in a linear cavity normal dispersion ytterbium-doped fiber laser have been reported.[55] The as-mentioned laser is mode locked by SESAM, and a chirped fiber Bragg grating was introduced into the cavity

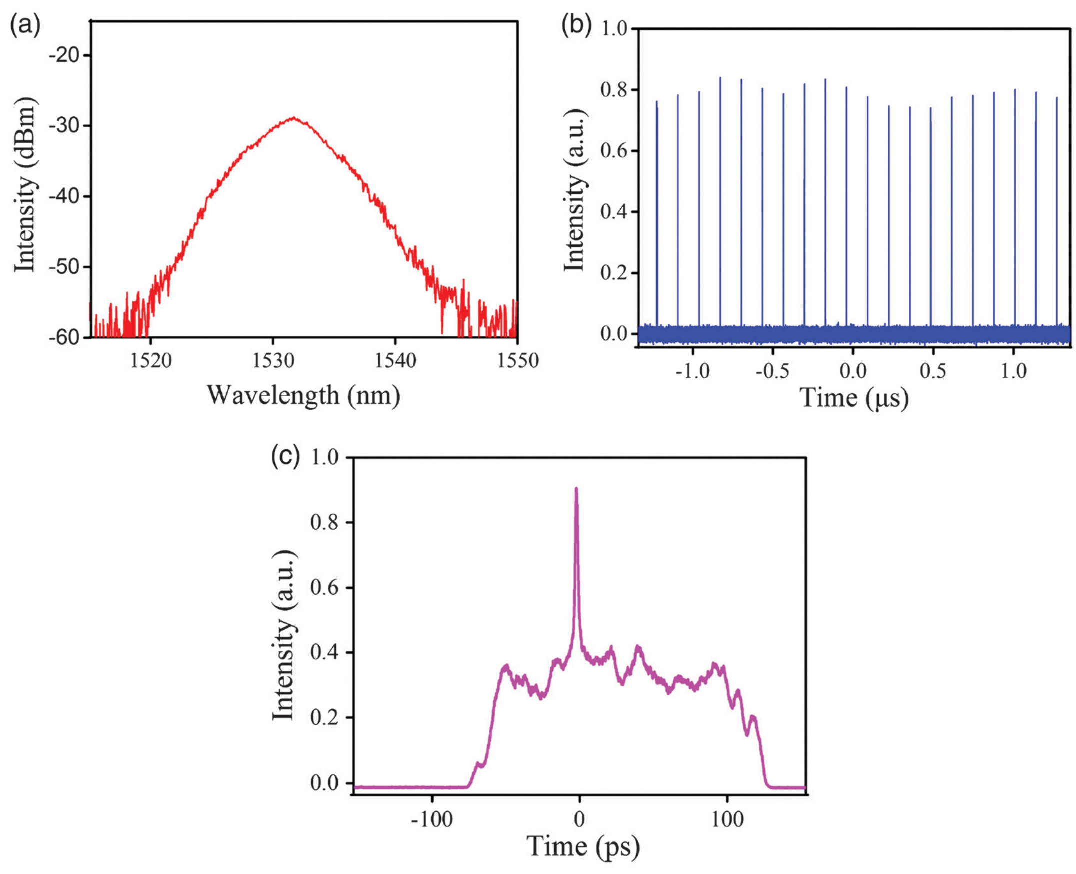

Fig. 4 The output characteristics of the NLPs: (a) the optical spectrum, (b) the pulse trains, and (c) the autocorrelation trace. Reproduced with permission from Ref. 90.

for dispersion compensating. It is claimed that the generation of RWs may be attributed to the filtering effect of the chirped fiber Bragg grating, which induces multipulsing instability to the cavity. In 2018, researchers demonstrated observation of optical RWs in the fiber laser with the generation of random dissipative soliton.[95] It was shown that, with proper adjustment of the cavity parameters, i.e., intracavity polarization state and pump power level, the random dissipative soliton buildup can be obtained in multiple-pulse regime. Along with the process of dissipative soliton buildup, high-amplitude waves were analyzed by studying the real-time spectral dynamics and the temporal pulse trains, which was considered as further confirmation of optical RWs using the method of statistics. The achieved results offer a promising choice for the investigation of the optical RW phenomenon in the pulsed fiber lasers and are valuable for further revealing the physical mechanism for optical RW generation.

Cai et al.[121] reported on the generation of RWs among the NLPs in the mode-locked EDFL with microfiber-based graphene saturable absorber (see Fig. 4). The pulse regime shows the smooth and broad optical spectrum and the temporal trains with a fundamental frequency of 7.35 MHz. This pulsating state has an autocorrelation trace with a narrow coherent peak rooted from the wide shoulder. The statistical distribution for the pulse-amplitude fluctuations of the NLP packet is shown in Fig. 5(a). As shown, this distribution curve exhibits an obvious structure of elevated tails, which is non-Gaussian. In addition, the intensity of the maximal amplitude is more than twice the intensity of SWH that is one of the key criteria for generating RWs.

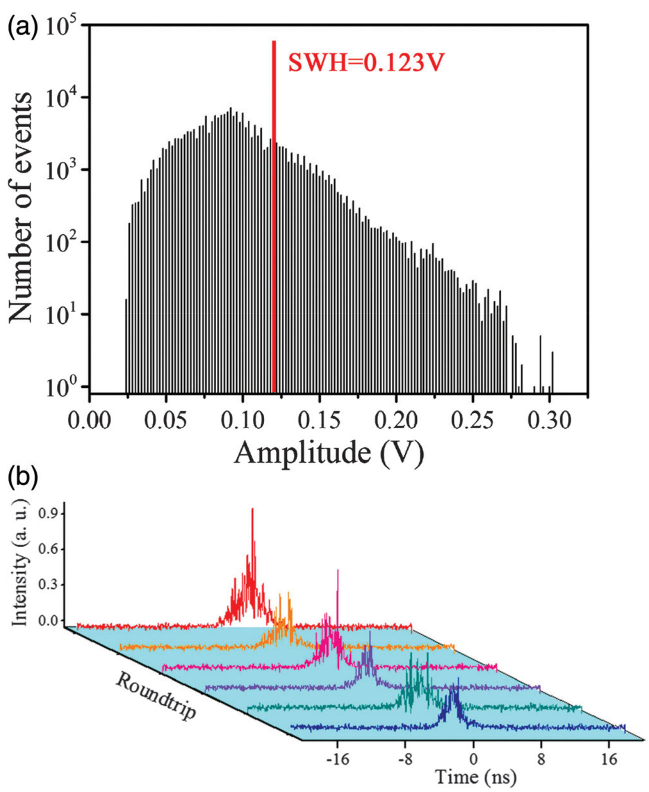

Fig. 5 (a) The pulse–amplitude statistical distribution histogram for the NLP regimes and (b) the temporal evolution of the localized NLPs. Reproduced with permission from Ref. 90.

Finally, by utilizing the DFT technique, they provided the evolution of the sectional NLP packet in several roundtrips, as shown in Fig. 5(b). From this figure, one can see that there is a clear chaotic wave with large amplitude appearing in the NLP packet, which is similar to the stroboscopic recording of the RW event in the literature[128] and to reported numerical simulations of dissipative RWs.[37] These experimental results suggest that there are typical RWs appearing in the NLP regime. In addition, Wang et al. demonstrated in 2018 by numerical simulations dissipative RWs among the NLPs, providing in such a way a possibility to investigate their evolution,[96] as shown in Fig. 6. From this figure, it can be seen that, for a saturation energy of $E_{sat} = 0.06$ and 0.12 nJ, the evolution of the pulse did not clearly lead to an NLP regime but to stable single-pulse and two-pulse operations, respectively. When the value of E_{sat} is set to 0.4 nJ, more pulses are obtained. By further increasing the saturation energy to 8 nJ, RWs appear among the NLP regime. In other words, with the increment of E_{sat}, the pulse number in the laser cavity also increases, which can lead to the formation of the many pulse bunches. And the pulse-to-pulse interaction in these bunches enables the formation of the RWs.[37,79,128] Figure 7 shows the theoretical statistical properties of the pulses for different E_{sat} values. Obviously, the highest amplitude for each E_{sat} value is more than twice the SWH, which confirms the generation of optical RWs.

5 Optical Rogue Wave Measurement

For the measurement of slow optical RWs, it is convenient to use a high-speed oscilloscope combined with a wide bandwidth photodetector.[53,79,128] Ultrafast RWs cannot be directly measured by real-time oscilloscope. Indeed, there are two challenges for the real-time measurement of ultrafast RWs: the limitation of the data converter and the trade-off between the sensitivity and the speed of the optoelectronic front-end. Currently, there have been mainly two measurement methods developed for ultrafast RWs: time stretching and time lensing.

5.1 Time Stretching

Time stretching is a real-time measurement technique based on DFT,[120] which enables fast real-time measurements in optical imaging and spectroscopy. The DFT technique can map the optical spectrum to temporal pulse waveform by a dispersive medium: the intensity envelope in the time domain is equivalent to the optical spectrum as, e.g., measured by optical spectrum analyzer. For this to happen, one should satisfy a certain condition: the pulses are properly stretched by the dispersive element so that the corresponding temporal waveform is equivalent to the analogy of the far-field diffraction condition in the spatial domain. A typical schematic diagram of time-stretching technique is shown in Fig. 8. The waveform of the input pulses can be stretched in time by the dispersive element with large group-velocity dispersion. Then, the output pulse trains are captured by the high-speed photodetector and oscilloscope, realizing the real-time measurement. Herein, the chirped fiber Bragg grating, a normal dispersion fiber or an anomalous dispersion fiber can be used as dispersive element. In general, the normal dispersion fiber is used in the vast majority of the reports with the DFT technique, because the anomalous dispersion fiber may have a lower threshold for nonlinearity and necessitate lower power levels (reducing the signal-to-noise ratio at the

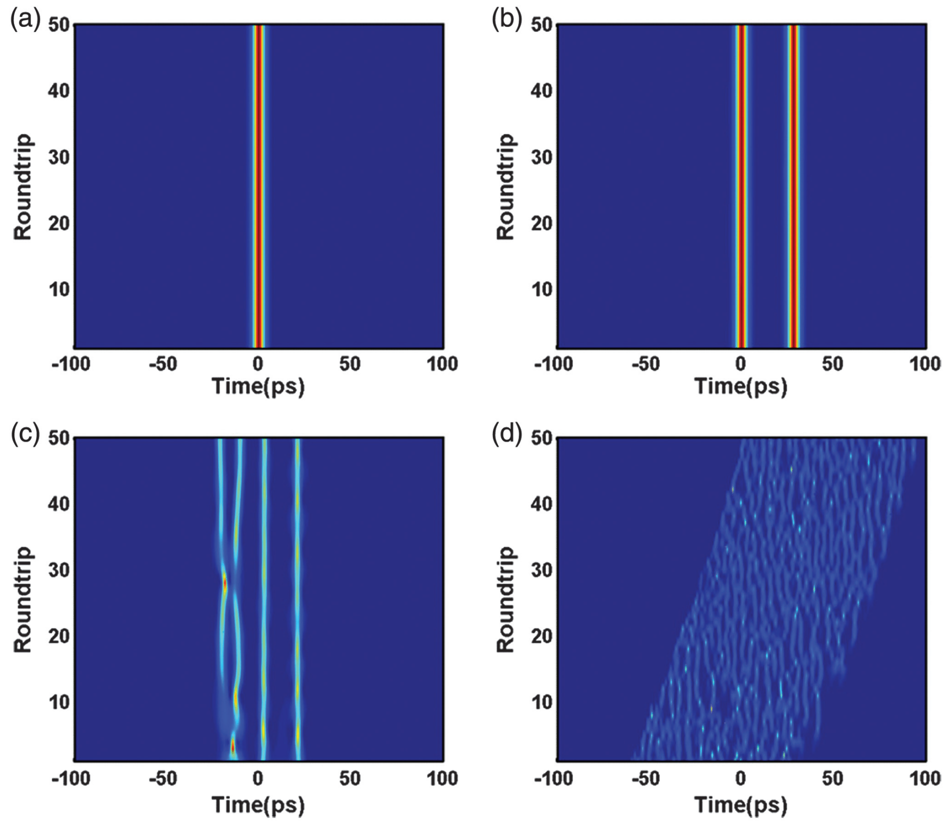

Fig. 6 The numerical evolutions of the pulses for different E_{sat} values of (a) 0.06 nJ, (b) 0.12 nJ, (c) 0.4 nJ, and (d) 8 nJ. Reproduced with permission from Ref. 96.

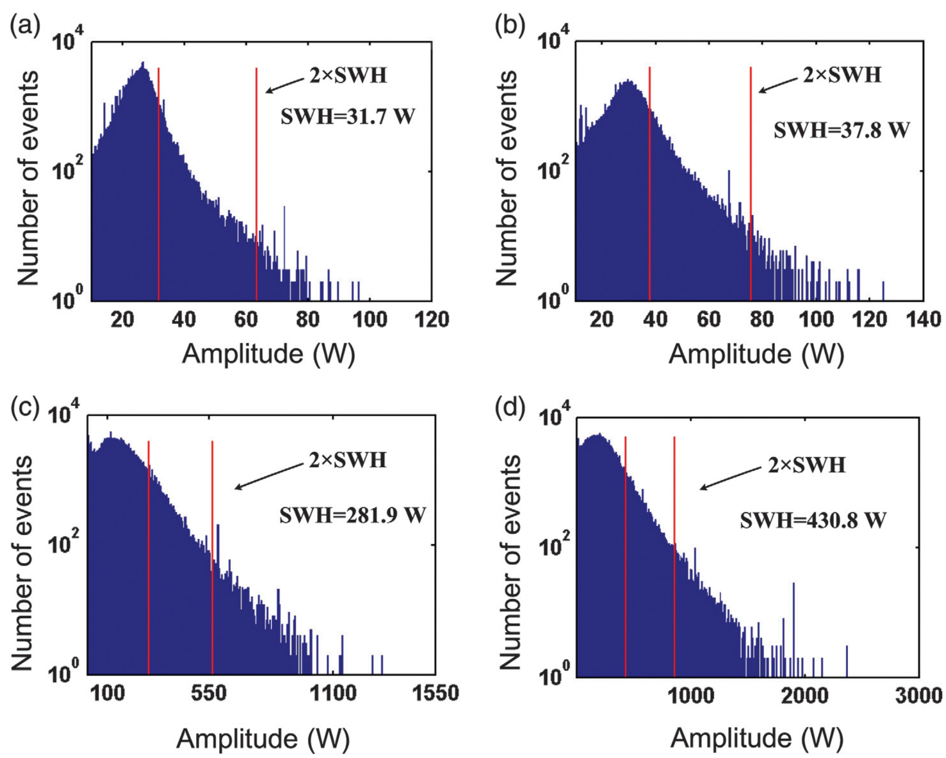

Fig. 7 The numerical statistical distribution of RWs for different E_{sat} values of (a) 0.6 nJ, (b) 0.8 nJ, (c) 8 nJ, and (d) 14 nJ. Reproduced with permission from Ref. 96.

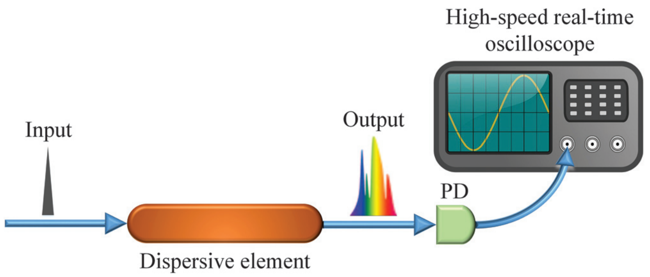

Fig. 8 The optical set-up for the time-stretching measurement method. PD, photodetector.

measurement oscilloscope). By using the time-stretching method, Fourier transform of optical pulses can be monitored in real time. In other words, one can measure the optical spectrum of optical pulses in real time. Time-stretching methods have been widely employed in the experimental investigation of optical pulses in the fiber lasers by researchers, including the dissipative solitons,[52,129,130] soliton molecules,[131–133] chaotic pulses,[134,135] intermittent pulses,[78,136] transition dynamics, and other nonlinear dynamics.[137–139] In 2014, the Raman RW generation in the pulse fiber lasers was provided by the research group of Runge et al.[82] By employing the pulse stretching method, the statistical histograms of wave events in more detail were investigated and the spectral evolution of RWs in real time was analyzed. Also in 2014, Lecaplain et al.[123] demonstrated RW emission in a fiber laser operating in the NLP regime. In the experiment, they used time-stretching measurement method to make the statistical distribution histogram of pulse spectral intensity, which could display the strong deviation from the Gaussian shape and the typical long-tail structure. In addition, the maximal amplitude was more than twice the SWH. Clearly, these characteristics indicated the generation of RWs. In 2015, researchers reported RWs in the Yb-doped fiber laser with normal dispersion.[124] The consecutive single-shot spectra of RWs were presented by the time-stretching measurement. Chowdhury et al.[55] presented experimental investigation of RWs in the linear cavity Yb-doped fiber laser. They employed the dispersive Fourier transform method to observe the existence of RWs and to analyze the corresponding spectral evolution. In short, using the time-stretching method, RW generation can be effectively verified. However, the phase information of the RWs is usually missing.[140,141] Therefore, more measuring methods should be considered to further investigate the comprehensive characteristics of RWs.

5.2 Time Lensing

Time lensing comes from a temporal imaging system, which is analogous to spatial imaging system. A time lens is capable of compressing or expanding the pulse width of optical waveforms without distortion.[142,143] Time-lensing measurements can support real-time measurement of ultrashort pulses with a subpicosecond resolution.[143,144] The time-lensing method has been applied to the research of incoherent soliton propagation in optical turbulence[145] and stochastic breather emergence in modulation instability.[146] Using the time-lensing method, ultrafast RWs in a vector field have been demonstrated.[147] In the time-lensing measurement of RWs, the imaged signal must be synchronized for a specific timing.[145] The typical experimental observation system of time-lensing measurement is shown in Fig. 9. The statistical distribution with heavy-tailed structure confirmed the generation of RWs. In 2016, the researchers reported the generation of RWs events in the fiber lasers using the real-time measurement based on the time-lensing methods.[146] Li et al.[148] demonstrated the observation of optical RWs in MLFL operating in the NLP state by utilizing the time-lensing technique. In addition, they investigated the round-trip tracking evolution and the detailed temporal patterns of RWs in the time domain at sub-ps resolution. However, compared with the time-stretching

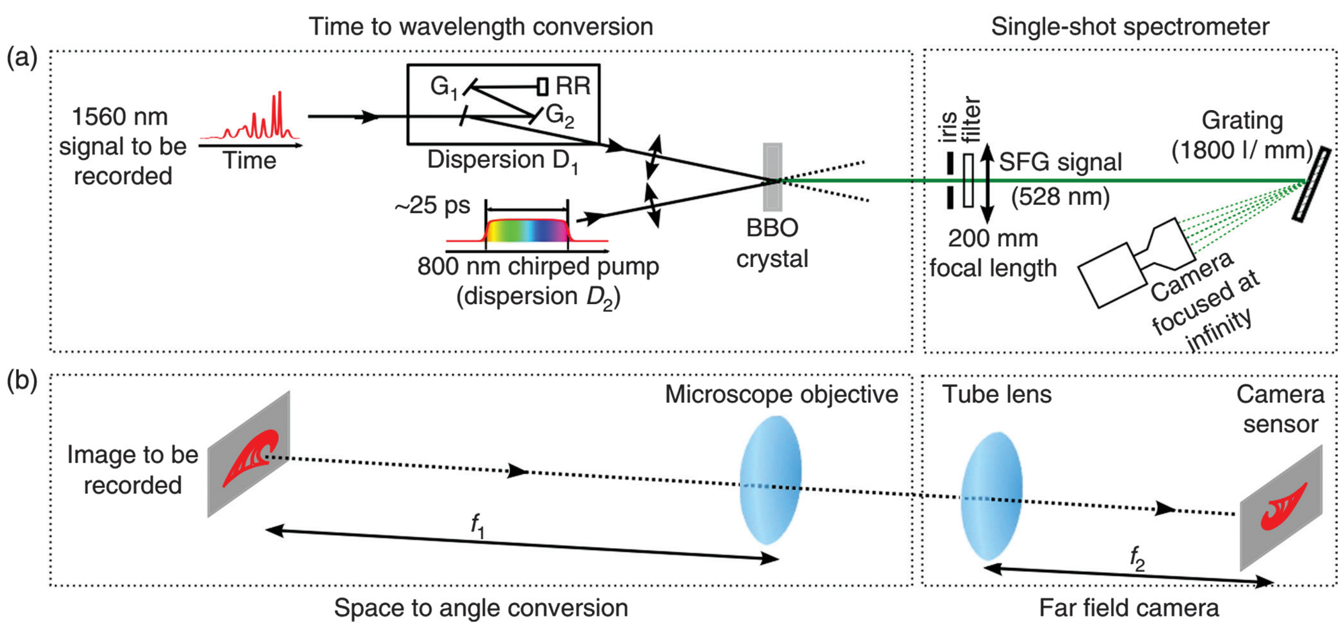

Fig. 9 Time lens for observing RWs: (a) the experimental setup and (b) the spatial analogy. Reproduced with permission from Ref. 145.

measurement, the measuring system of the time-lensing method is more complex, which can increase the experimental cost to some extents.

5.3 Hybrid Method

Time stretching and time lensing are powerful tools to observe fast RWs in fiber lasers. In Ref. 149, systematic and dedicated experimental research on wave-packet formation and shot-to-shot coherence in quasi-mode-locked operation is carried out. Combining the time-stretching and time-lensing methods, simultaneous measurement of spectral and temporal profiles of the soliton dynamics and RWs can be performed. The combination enabled real-time measurement of both the phase and intensity of RWs and unveiled different temporal patterns.[146,150,151] Ryczkowski et al.[152] demonstrated the real-time full-field characterization of unstable pulses in a fiber laser through a saturable absorber mirror (SAM) by simultaneously employing the time-stretching and time-lensing techniques. The simultaneous use of two methods is capable of completely characterizing the real-time evolution of RWs in the spectral and temporal domains, which will be a better way for investigating the generation and dynamics of RWs in fiber lasers in the future (Fig. 10).

5.4 Other Measurements

Apart from the above methods, the direct measurement of RWs in fiber lasers can be conducted by the oscilloscope in some conditions. For the pulse fiber lasers, the pulse amplitudes can be recorded to draw the statistical distribution histogram by utilizing the oscilloscope with the high electronic bandwidths.[79,128] When the pulse repetition frequency is low enough and the time interval between the pulses is sufficiently large, the histogram of pulse amplitude can be created using an oscilloscope with a relatively low electronic bandwidth to continuously record the amplitudes of plenty of pulses and analyze the total pulse intensity. Events with pulse amplitude larger than twice the SWH can prove the generation of RWs. This measuring method based on the oscilloscope can be simpler and more convenient than the time stretching and time lensing in pulse fiber lasers. Liu et al.[53] reported the generation of optical RWs in a pulse fiber laser. In their experiment, the repetition frequency was 5.03 MHz and the corresponding pulse interval was 198.8 ns. They utilized 8-GHz oscilloscope to record 10^5 pulse peak intensity, creating the amplitude histogram with log scale. This histogram exhibited the typical statistical distribution with a long-tail structure. In addition, the largest amplitude of pulses was more than twice the SWH. These features showed that the pulses could be regarded as typical RWs. Wang et al.[96] also investigated RW formation in pulse fiber laser. The repetition rate of their fiber laser was 3.47 MHz and the time interval among adjacent pulses was 288.2 ns. The research group spent several hours in recording about 500 thousand temporal samples on the 2-GHz oscilloscope. The corresponding distribution histogram could display an obvious long-tail structure, and the highest amplitude was twice the SWH, which confirmed the generation of RWs. However, it is difficult to investigate the real-time wave events of RWs by the direct measurement of the oscilloscope. Therefore, it is necessary to combine the various measuring methods to conduct the research of RWs.

6 Outlook

As mentioned above, RWs in fiber lasers are well developed and are still being intensively investigated. In Sec. 4, we discussed the observations of RWs in various fiber lasers, such as the MLFL with different types of saturable absorbers, *Q*-switched random laser, and the self-pulsing fiber lasers. Compared with other kinds of fiber lasers, the MLFL can offer a more convenient playground for observing the generation of optical RWs because of their many advantages, such as low price, ultrashort pulses, simple structure, and good stability. When the fiber lasers are mode locked by the 2-D materials, these materials can not only provide excellent saturable absorption properties but also enhance the nonlinear effects for the pulse interactions in the fiber lasers, which benefits the formation of RWs. Different

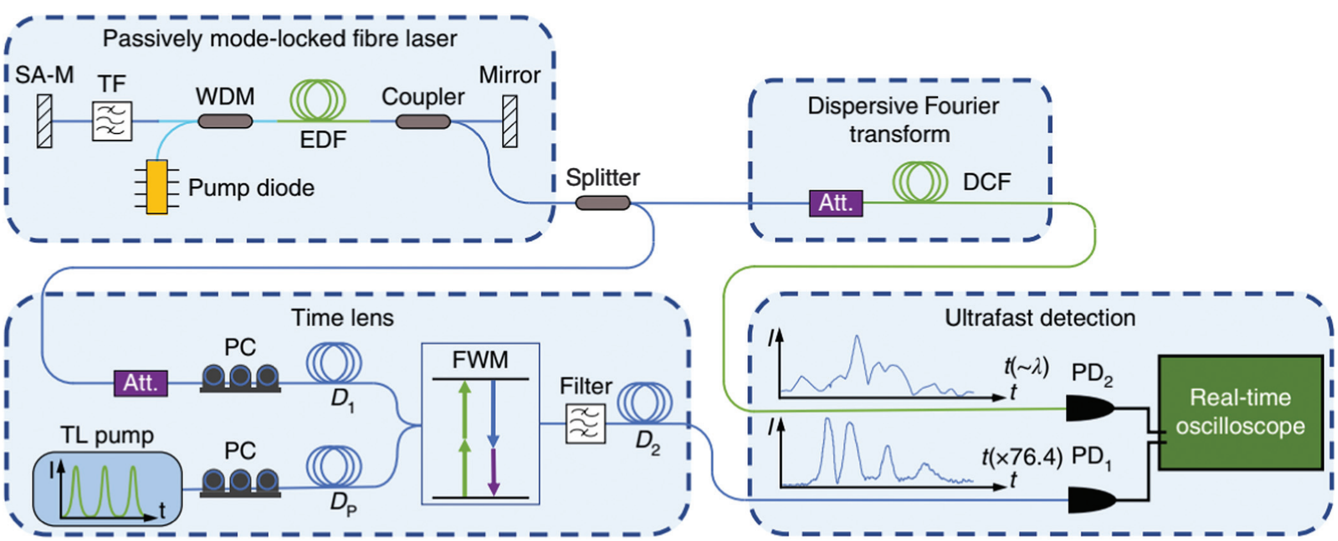

Fig. 10 Experimental setup of the hybrid measurement method based on time stretching and time lensing. Reproduced with permission from Ref. 152.

from the MLFL, the SBS effects can be formed in the *Q*-switched random lasers[125] and the self-pulsing fiber lasers.[127] The influence of SBS can introduce a trigger effect for the RW generation. It can be believed that the observations of RWs in various fiber lasers will attract more attention in the future. As the study of fiber lasers advances, RWs in fiber lasers will be further investigated from the following several aspects.

6.1 Deterministic Rogue Wave in Fiber Lasers

Based on the various experimental observations of RWs in fiber lasers, it is intriguing to investigate the deterministic prediction of RW generation in fiber lasers. Deterministic optical RW generation typically depends on a theoretical prediction combined with proper experimental conditions. Sergeyev et al. presented slow deterministic vector RWs in an EDFL passively mode locked by carbon nanotube. By controlling the polarization state of intracavity and pump wave, deterministic RWs can be generated.[153]

It is also interesting to consider that algorithm-controlled fiber lasers could be a next-generation platform for deterministic RW generation. Algorithm-controlled fiber lasers will be further discussed in Sec. 6.4.

6.2 Rogue Waves in Two-Dimensional Material-Based Mode Locked Fiber Laser

In the last decade, the MLFLs based on 2-D materials have been fast developing.[69,154–162] It is worth mentioning that an MLFL with a saturable absorber would be a promising direction for the study of RWs. Earlier works on RWs in fiber lasers were mostly mode locked by nonlinear polarization rotation (NPR). Indeed, recently there have been many results on the RWs in fiber lasers with real saturable absorbers, and it has been demonstrated that saturable absorbers play an essential role in the RW generation.[147] Liu et al.[53] demonstrated dissipative RW generation in pulsed fiber laser with topological insulator saturable absorber on microfiber. The authors ascertained that the topological insulator microfiber device introduces strong nonlinear interactions, which contributed greatly to the generation of RWs. In 2016, their group also reported a dissipative RW induced by soliton explosion in fiber lasers, which are mode-locked by a carbon nanotube.[54] In 2017, RWs in mode ultrafast pulse fiber laser mode locked by graphene-decorated microfiber[90] were reported. In 2018, RWs were reported in MoS_2 MLFL operating at 2000 nm.[96] Klein et al.[94] found ultrafast RWs in a fiber laser with the graphene saturable absorber, which is attributed to the noninstantaneous relaxation of the saturable absorber together with the polarization mode dispersion of the cavity.

Recently, RW generation has been reported in a linear-cavity Yb-doped fiber laser mode-locked by semiconductor SAM.[55] It is noted that the authors mentioned that the SESAM plays an important role on the formation of RWs. However, there have been no systematic studies on the dynamic of RWs in a specific SA-MLFL, which would be a direction for the study in the future. In the last decade, 2-D nanomaterials, including graphene,[73,163–165] topological insulators,[53] and transition metal dichalcogenides,[166–168] have been widely applied as optical saturable absorbers for MLFLs and have been studied for RW generation.[53] In the last three years, there have been many 2-D materials reported for application in ultrafast fiber lasers,[169–172] which has significantly enhanced the development of the ultrafast lasers. Continually searching and employing new materials with good saturable absorptions and highly nonlinear characteristics may sufficiently quicken the above-mentioned process. It can be expected that more 2-D materials-based fiber lasers will provide appropriate platforms for the study of RW generation and dynamics in the future.

6.3 Rogue Waves in Mid-Infrared Fiber Lasers

In recent decades, the study of nonlinear fiber optics has been extended to the mid-infrared band, and mid-infrared fiber lasers have attracted intensive interest. It is natural that study of optical RWs has also been extended to the mid-infrared region. In 2011, the formation of mid-infrared RWs was numerically investigated in the soft glass fibers.[173] In 2017, mid-infrared optical RWs generated by SC in chalcogenide fibers were reported by Liu et al.[174] RWs were subsequently found in mid-infrared ultrafast fiber laser. Researchers reported optical RWs in a Tm-doped fiber laser[96] mode locked by MoS_2. They experimentally observed dissipative RWs in the fiber lasers generated from an NLP state. Another finding of optical RWs in mid-infrared was from Akosman and Sander.[175] They demonstrated the route from a stable mode locking state toward RW formation in a linear cavity Tm/Ho-doped fiber lasers operating at ∼1980 nm.[175] According to the recent works, it is easy to find that the mechanism and nonlinear dynamics of the RWs at 2 μm are comparable to those observed at 1 and 1.5 μm. It indicates that RW generation is a general feature of fiber lasers. So far several works on MIR RWs have been reported with operating wavelength limited to 2 μm; RWs at 3 μm and above have not been discovered. It can be anticipated that study of RWs at mid-infrared band will be another hot topic in the field of nonlinear fiber optics.

6.4 Rogue Waves in Algorithm-Controlled Fiber Lasers

A variety of SAs have been extensively applied to the observation of RW generation in the pulse fiber lasers. However, there are some disadvantages in different SAs. For example, the NPR technique, which is one of the artificial SAs, shows a strong polarization-dependent feature, which can hinder corresponding applications in the research of RWs. Recently, a programmable NPR MLFL at 1.5 μm with a human-like algorithm has been presented in the literature.[176] Stable fundamental mode-locked regime has been automatically obtained in the pulsed fiber laser. In addition, this fiber laser showed the initial mode-locking time of 0.22 s and recovery time of 14.8 ms. In addition, this fiber laser can lock onto *Q*-switched regimes and *Q*-switch mode locking. The intelligent programmable method greatly improves the reliability of MLFL, which may also be used for the observation of RWs in the fiber lasers with SAs. In fact, the NLPs are realized in the machine-learning-based MLFL. Researchers have also demonstrated complex transition pulse regimes from the MLFL based on an intelligent polarization algorithm control. Furthermore, research groups have employed machine learning to analyze the generation of extreme events in optical fiber modulation instability.[177] So far, the investigation of RWs in algorithm-controlled fiber lasers has not been yet demonstrated. We believe that the generating mechanism of rouge waves will be effectively studied in pulse fiber lasers with different SAs through human-like intelligent methods.

6.5 Rogue Waves Based on the Multimode Fiber or Multimode Fiber Lasers

Remarkable research on RWs in single-mode fiber lasers has been widely conducted due to their potential value in the ocean optics. However, the pulse energy of single-mode fiber lasers is approaching limits that may hinder their development and application in scientific research, industrial processing, and other fields. Compared with the single-mode fibers, the multimode fibers (MMFs) can enhance the capacity of communication systems, promoting the potential impact of optical pulses in fiber lasers. The nonlinear propagation in the MMF lasers is closely related to a complex spatiotemporal mixing process caused by the nonlinearity and waveguide imperfections.[178] Recently, the spatiotemporal dynamics of optical pulses have been demonstrated in the MMFs, such as the spatiotemporal mode-locking,[179] the soliton molecules,[180] harmonic mode locking,[181] the spatiotemporal instability,[182] and beam self-cleaning.[183] This research provides new approaches for exploring RW generation in the MMF lasers. In addition, researchers have reported efficient SC generation by employing a 1064-nm laser source to pump a graded index MMF.[184] Indeed, RWs are apt to be observed in the SC generation. Therefore, the MMF is suitable for investigating the generation of RWs. It can be expected that further exploration of RWs in the MMFs or MMF lasers will be a new hot topic in nonlinear fiber optics.

6.6 Rogue Waves Induced by the Optical Vortex Beams in the Fiber Lasers

RWs have been obtained in several optical configurations, such as the photonic crystals,[185] the optical fibers,[186] and the SC generation.[45] Recently, the generation of 2-D optical RWs in the presence of turbulence with the interaction of optical vortices was demonstrated by Gibson et al.,[187] which indicates the optical vortices can induce the generation of RWs. At present, vortex beams in the fiber lasers have been demonstrated because of the promising applications in the quantum optics,[188] optical micromanipulation,[189] rotation detection,[190] WDM (mode-division multiplexing) systems,[191] and nonlinear fiber optics.[192] In the fiber systems, the vortex beams are generally realized by the modulating elements, including the mode selective couplers,[193,194] long period fiber gratings,[195,196] and microstructured fiber facets.[197] The mode-locked vortex beams through the mode fibers in the all-fiber lasers have been reported.[198] Therefore, the optical RWs based on the vortex beams in the fiber lasers will be one of the research hot topics, promoting the further development of nonlinear optics.

6.7 Rogue Waves in Temporal Cavity Soliton Fiber Lasers

Apart from the MLFL, the fiber laser without the mode locker inserted in the cavity can also generate ultrashort pulses, for example, the temporal cavity solitons (TCSs). When the dispersion and nonlinearity are balanced in the fiber lasers, TCSs are formed, which can transmit indefinitely and keep their shape in the fiber cavity.[199] At present, TCSs have been intensely reported in fiber laser cavities[20,199–201] due to their potential applications in the all-optical buffer and coherent frequency combs.[202] Researchers have reported the experimental observation of TCS bound states in universal mechanisms.[201] TCSs in these bound states can interact with each other, which may induce the optical RW generation. At the moment, there is no experimental observation of optical RWs through TCS fiber lasers. We believe that the generation of optical RWs in TCS fiber lasers will be realized in future, a potential hot topic that would further reveal more physical phenomena in nonlinear fiber optics fields.

7 Conclusion

RWs are extreme events first observed in the ocean, showing great threat to the safety of sea-going personnel and ships. The study of RWs in different systems has remained a hot research topic. Fiber lasers provide an ideal platform to observe the generation of optical RWs as well to as investigate their behaviour. We hope that this review will be helpful for future studies of RWs in different optical systems.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China (No. 61705140), the China Postdoctoral Science Foundation (No. 2018M643165), and the Fonds Wetenschappelijk Onderzoek-Vlaanderen FWO (G0E5819N).

References

1. F. Fedele, "Rogue waves in oceanic turbulence," *Phys. D-Nonlinear Phenom.* **237** (14–17), 2127–2131 (2008).
2. K. Dysthe, H. E. Krogstad, and P. Muller, "Oceanic rogue waves," *Annu. Rev. Fluid Mech.* **40**, 287–310 (2008).
3. V. Ruban et al., "Rogue waves: towards a unifying concept? Discussions and debates," *Eur. Phys. J.-Spec. Top.* **185**(1), 5–15 (2010).
4. A. L. Islas and C. M. Schober, "Predicting rogue waves in random oceanic sea states," *Phys. Fluids* **17**(3), 031701 (2005).
5. D. R. Solli et al., "Optical rogue waves," *Nature* **450**(7172), 1054–1057 (2007).
6. W. M. Moslem et al., "Dust-acoustic rogue waves in a nonextensive plasma," *Phys. Rev. E Stat. Nonlinear Soft Matter Phys.* **84**(6), 066402 (2011).
7. Y. Y. Tsai, J. Y. Tsai, and I. Lin, "Generation of acoustic rogue waves in dusty plasmas through three-dimensional particle focusing by distorted waveforms," *Nat. Phys.* **12**(6), 573–577 (2016).
8. M. Shats, H. Punzmann, and H. Xia, "Capillary rogue waves," *Phys. Rev. Lett.* **104**(10), 104503 (2010).
9. J. Borhanian, "Extraordinary electromagnetic localized structures in plasmas: modulational instability, envelope solitons, and rogue waves," *Phys. Lett. A* **379**(6), 595–602 (2015).
10. G. P. Veldes et al., "Electromagnetic rogue waves in beam–plasma interactions," *J. Opt.* **15**(6), 064003 (2013).
11. Z. Y. Yan, "Vector financial rogue waves," *Phys. Lett. A* **375**(48), 4274–4279 (2011).
12. Z. Y. Yan, "Financial rogue waves," *Commun. Theor. Phys.* **54**(5), 947–949 (2010).
13. A. N. Pisarchik et al., "Rogue waves in a multistable system," *Phys. Rev. Lett.* **107**(27), 274101 (2011).
14. J. M. Dudley et al., "Instabilities, breathers and rogue waves in optics," *Nat. Photonics* **8**(10), 755–764 (2014).
15. N. Akhmediev, J. M. Soto-Crespo, and A. Ankiewicz, "Extreme waves that appear from nowhere: on the nature of rogue waves," *Phys. Lett. A* **373**(25), 2137–2145 (2009).

16. M. Onorato et al., "Rogue waves: from nonlinear Schrodinger breather solutions to sea-keeping test," *PLoS One* **8**(2), e54629 (2013).
17. D. Y. Tang et al., "Dark soliton fiber lasers," *Opt. Express* **22**(16), 19831–19837 (2014).
18. B. A. Malomed, "Bound solitons in the nonlinear Schrodinger–Ginzburg-Landau equation," *Phys. Rev. A* **44**(10), 6954–6957 (1991).
19. B. A. Malomed and L. Stenflo, "Modulational instabilities and soliton solutions of a generalized nonlinear Schrodinger equation," *J. Phys. A-Math. Gen.* **24**(19), L1149–L1153 (1991).
20. D. Y. Tang et al., "Temporal cavity soliton formation in an anomalous dispersion cavity fiber laser," *J. Opt. Soc. Am. B-Opt. Phys.* **31**(12), 3050–3056 (2014).
21. Y. F. Song et al., "Recent progress of study on optical solitons in fiber lasers," *Appl. Phys. Rev.* **6**(2), 021313 (2019).
22. J. Ma et al., "Observation of dark-bright vector solitons in fiber lasers," *Opt. Lett.* **44**(9), 2185–2188 (2019).
23. X. Hu et al., "Observation of incoherently coupled dark-bright vector solitons in single-mode fibers," *Opt. Express* **27**(13), 18311–18317 (2019).
24. J. Guo et al., "Observation of vector solitons supported by third-order dispersion," *Phys. Rev. A* **99**(6), 061802(R) (2019).
25. G. D. Shao et al., "Soliton-dark pulse pair formation in birefringent cavity fiber lasers through cross phase coupling," *Opt. Express* **23**(20), 26252–26258 (2015).
26. Y. F. Song et al., "280 GHz dark soliton fiber laser," *Opt. Lett.* **39**(12), 3484–3487 (2014).
27. V. I. Shrira and V. V. Geogjaev, "What makes the Peregrine soliton so special as a prototype of freak waves?" *J. Eng. Math.* **67**(1–2), 11–22 (2010).
28. K. Hammani et al., "Peregrine soliton generation and breakup in standard telecommunications fiber," *Opt. Lett.* **36**(2), 112–114 (2011).
29. B. Kibler et al., "The Peregrine soliton in nonlinear fibre optics," *Nat. Phys.* **6**(10), 790–795 (2010).
30. H. Bailung, S. K. Sharma, and Y. Nakamura, "Observation of peregrine solitons in a multicomponent plasma with negative ions," *Phys. Rev. Lett.* **107**(25), 255005 (2011).
31. B. Kibler et al., "Peregrine soliton in optical fiber-based systems," in *Conf. Lasers and Electro-Opt. (CLEO)* (2011).
32. M. Haelterman, "Modulational instability, periodic-waves and black-and-white vector solitons in birefringent Kerr media," *Opt. Commun.* **111**(1–2), 86–92 (1994).
33. K. Tai, A. Hasegawa, and A. Tomita, "Observation of modulational instability in optical fibers," *Phys. Rev. Lett.* **56**(2), 135–138 (1986).
34. D. Y. Tang et al., "GHz pulse train generation in fiber lasers by cavity induced modulation instability," *Opt. Fiber Technol.* **20**(6), 610–614 (2014).
35. L. F. Mollenauer, R. H. Stolen, and J. P. Gordon, "Experimental-observation of picosecond pulse narrowing and solitons in optical fibers," *Phys. Rev. Lett.* **45**(13), 1095–1098 (1980).
36. J. M. Dudley et al., "Self-similarity in ultrafast nonlinear optics," *Nat. Phys.* **3**(9), 597–603 (2007).
37. J. Soto-Crespo, P. Grelu, and N. Akhmediev, "Dissipative rogue waves: extreme pulses generated by passively mode-locked lasers," *Phys. Rev. E* **84**(1), 016604 (2011).
38. N. Akhmediev et al., "Recent progress in investigating optical rogue waves," *J. Opt.* **15**(6), 060201 (2013).
39. S. H. Chen et al., "Versatile rogue waves in scalar, vector, and multidimensional nonlinear systems," *J. Phys. A-Math. Theor.* **50**(46), 463001 (2017).
40. N. Akhmediev et al., "Roadmap on optical rogue waves and extreme events," *J. Opt.* **18**(6), 063001 (2016).
41. J. M. Dudley et al., "Rogue waves and analogies in optics and oceanography," *Nat. Rev. Phys.* **1**(11), 675–689 (2019).
42. C. C. Mei et al., *Theory and Applications of Ocean Surface Waves*, Advanced Series on Ocean Engineering, vol. **23**, Expanded ed., World Scientific, Hackensack, New Jersey (2005).
43. A. Chabchoub et al., "The nonlinear Schrodinger equation and the propagation of weakly nonlinear waves in optical fibers and on the water surface," *Ann. Phys.* **361**, 490–500 (2015).
44. J. M. Dudley, G. Genty, and B. Eggleton, "Optical rogue wave dynamics in supercontinuum generation," in *Joint Conf. Opto-Electron. and Commun. Conf. and the Aust. Conf. Opt. Fibre Technol.*, 10202595 (2008).
45. J. M. Dudley, G. Genty, and B. J. Eggleton, "Harnessing and control of optical rogue waves in supercontinuum generation," *Opt. Express* **16**(6), 3644–3651 (2008).
46. G. Genty, B. Eggleton, and J. M. Dudley, "Dynamics and control of optical rogue waves in supercontinuum generation," in *34th Eur. Conf. Opt. Commun.*, IEEE (2008).
47. D. R. Solli, C. Ropers, and B. Jalali, "Optical rogue waves and stimulated supercontinuum generation," *Proc. SPIE* **7728**, 772810 (2010).
48. Q. Li et al., "Control of optical rogue waves in supercontinuum generation with a minute continuous wave," in *Conf. Lasers and Electro-Opt. (CLEO)* (2011).
49. S. T. Sorensen et al., "Influence of pump power and modulation instability gain spectrum on seeded supercontinuum and rogue wave generation," *J. Opt. Soc. Am. B-Opt. Phys.* **29**(10), 2875–2885 (2012).
50. M. Erkintalo, G. Genty, and J. M. Dudley, "Rogue-wave-like characteristics in femtosecond supercontinuum generation," *Opt. Lett.* **34**(16), 2468–2470 (2009).
51. D. R. Solli, C. Ropers, and B. Jalali, "Active control of rogue waves for stimulated supercontinuum generation," *Phys. Rev. Lett.* **101**(23), 233902 (2008).
52. K. Krupa, K. Nithyanandan, and P. Grelu, "Vector dynamics of incoherent dissipative optical solitons," *Optica* **4**(10), 1239–1244 (2017).
53. M. Liu et al., "Dissipative rogue waves induced by long-range chaotic multi-pulse interactions in a fiber laser with a topological insulator-deposited microfiber photonic device," *Opt. Lett.* **40**(20), 4767–4770 (2015).
54. M. Liu et al., "Dissipative rogue waves induced by soliton explosions in an ultrafast fiber laser," *Opt. Lett.* **41**(17), 3912–3915 (2016).
55. S. Das Chowdhury et al., "Rogue waves in a linear cavity Yb-fiber laser through spectral filtering induced pulse instability," *Opt. Lett.* **44**(9), 2161–2164 (2019).
56. Y. E. Monfared and S. A. Ponomarenko, "Non-Gaussian statistics and optical rogue waves in stimulated Raman scattering," *Opt. Express* **25**(6), 5941–5950 (2017).
57. K. Hammani et al., "Optical rogue-wave-like extreme value fluctuations in fiber Raman amplifiers," *Opt. Express* **16**(21), 16467–16474 (2008).
58. C. Lafargue et al., "Direct detection of optical rogue wave energy statistics in supercontinuum generation," *Electron. Lett.* **45**(4), 217–218 (2009).
59. K. Hammani and C. Finot, "Experimental signatures of extreme optical fluctuations in lumped Raman fiber amplifiers," *Opt. Fiber Technol.* **18**(2), 93–100 (2012).
60. J. Kasparian et al., "Optical rogue wave statistics in laser filamentation," *Opt. Express* **17**(14), 12070–12075 (2009).
61. C. Bonatto et al., "Deterministic optical rogue waves," *Phys. Rev. Lett.* **107**(5), 053901 (2011).
62. F. Selmi et al., "Spatiotemporal chaos induces extreme events in an extended microcavity laser," *Phys. Rev. Lett.* **116**(1), 013901 (2016).
63. G. D. Shao et al., "Vector dark solitons in a single mode fibre laser," *Laser Phys. Lett.* **16**(8), 085110 (2019).

64. C. Zhao et al., "Observation of chaotic polarization attractors from a graphene mode locked soliton fiber laser," *Chin. Opt. Lett.* **17**(2), 020012 (2019).
65. G. M. Wang et al., "Indium selenide as a saturable absorber for a wavelength-switchable vector-soliton fiber laser," *Opt. Mater. Express* **9**(2), 449–456 (2019).
66. D. Y. Tang et al., "Soliton interaction in a fiber ring laser," *Phys. Rev. E* **72**(1), 016616 (2005).
67. A. Komarov et al., "Interaction of dissipative solitons under spectral and amplitude control of pulse wings in fiber lasers," *Proc. SPIE* **6612**, 661209 (2007).
68. N. Akhmediev et al., "Dissipative soliton interactions inside a fiber laser cavity," *Opt. Fiber Technol.* **11**(3), 209–228 (2005).
69. Y. F. Song et al., "Coexistence and interaction of vector and bound vector solitons in a dispersion-managed fiber laser mode locked by graphene," *Opt. Express* **24**(2), 1814–1822 (2016).
70. Y. Y. Luo et al., "Real-time access to the coexistence of soliton singlets and molecules in an all-fiber laser," *Opt. Lett.* **44**(17), 4263–4266 (2019).
71. B. Ortac et al., "Observation of soliton molecules with independently evolving phase in a mode-locked fiber laser," *Opt. Lett.* **35**(10), 1578–1580 (2010).
72. S. Chouli and P. Grelu, "Rains of solitons in a fiber laser," *Opt. Express* **17**(14), 11776–11781 (2009).
73. Y. F. Song et al., "Vector multi-soliton operation and interaction in a graphene mode-locked fiber laser," *Opt. Express* **21**(8), 10010–10018 (2013).
74. K. Sulimany et al., "Bidirectional soliton rain dynamics induced by Casimir-like interactions in a graphene mode-locked fiber laser," *Phys. Rev. Lett.* **121**(13), 133902 (2018).
75. C. Y. Bao, X. S. Xiao, and C. X. Yang, "Soliton rains in a normal dispersion fiber laser with dual-filter," *Opt. Lett.* **38**(11), 1875–1877 (2013).
76. D. Y. Tang, L. M. Zhao, and B. Zhao, "Soliton collapse and bunched noise-like pulse generation in a passively mode-locked fiber ring laser," *Opt. Express* **13**(7), 2289–2294 (2005).
77. Y. Takushima et al., "87 nm bandwidth noise-like pulse generation from erbium-doped fibre laser," *Electron. Lett.* **41**(7), 399–400 (2005).
78. A. F. J. Runge, N. G. R. Broderick, and M. Erkintalo, "Observation of soliton explosions in a passively mode-locked fiber laser," *Optica* **2**(1), 36–39 (2015).
79. C. Lecaplain et al., "Dissipative rogue wave generation in multiple-pulsing mode-locked fiber laser," *J. Opt.* **15**(6), 064005 (2013).
80. A. Zaviyalov et al., "Rogue waves in mode-locked fiber lasers," *Phys. Rev. A* **85**(1), 013828 (2012).
81. C. Lecaplain et al., "Dissipative rogue waves through multipulse collisions in a fiber laser," in *Conf. Lasers and Electro-Opt. Eur. and Int. Quantum Electron. Conf. (CLEO Europe/IQEC)* (2013).
82. A. F. J. Runge et al., "Raman rogue waves in a partially mode-locked fiber laser," *Opt. Lett.* **39**(2), 319–322 (2014).
83. A. F. J. Runge et al., "Raman rogue waves in a long cavity passively mode-locked fiber laser," in *Conf. Lasers and Electro-Opt. (CLEO)* (2014).
84. M. I. Afzal, K. Alameh, and Y. T. Lee, "Blue-shifted rogue waves generation in normal dispersion fiber laser," *IEEE Photonics Technol. Lett.* **27**(22), 2323–2326 (2015).
85. L. Gao et al., "Optical polarization rogue waves in fiber laser," in *Conf. Lasers and Electro-Opt. (CLEO)* (2016).
86. H. Kbashi, S. A. Kolpakov, and S. V. Sergeyev, "Temporal scaling of optical rogue waves in unidirectional ring fiber laser," in *18th Int. Conf. Transparent Opt. Networks (ICTON)* (2016).
87. S. A. Kolpakov, H. Kbashi, and S. V. Sergeyev, "Dynamics of vector rogue waves in a fiber laser with a ring cavity," *Optica* **3**(8), 870–875 (2016).
88. S. A. Kolpakov, H. J. Kbashi, and S. Sergeyev, "Slow optical rogue waves in a unidirectional fiber laser," in *Conf. Lasers and Electro-Opt.*, OSA (2016).
89. J. S. Peng et al., "Rogue waves generation via nonlinear soliton collision in multiple-soliton state of a mode-locked fiber laser," *Opt. Express* **24**(19), 21256–21263 (2016).
90. Z. R. Cai et al., "Graphene-decorated microfiber photonic device for generation of rogue waves in a fiber laser," *IEEE J. Sel. Top. Quantum Electron.* **23**(1), 20–25 (2017).
91. P. H. Hanzard et al., "Brillouin scattering-induced rogue waves in self-pulsing fiber lasers," *Sci. Rep.* **7**, 45868 (2017).
92. H. Kbashi et al., "Vector rogue waves in a carbon nanotube mode-locked fiber laser," in *Conf. Lasers and Electro-Opt. Eur. & Eur. Quantum Electron. Conf. (CLEO/Europe-EQEC)* (2017).
93. H. Kbashi et al., "Bright-dark rogue wave in mode-locked fibre laser," *Proc. SPIE* **10228**, 102280P (2017).
94. A. Klein et al., "Ultrafast rogue wave patterns in fiber lasers," *Optica* **5**(7), 774–778 (2018).
95. Z. C. Luo et al., "Optical rogue waves by random dissipative soliton buildup in a fiber laser," *IEEE Photonics Technol. Lett.* **30**(20), 1803–1806 (2018).
96. P. Wang et al., "Dissipative rogue waves among noise-like pulses in a Tm fiber laser mode locked by a monolayer MoS_2 saturable absorber," *IEEE J. Sel. Top. Quantum Electron.* **24**(3), 1800207 (2018).
97. S. Lee et al., "Intermittent burst of a super rogue wave in the breathing multi-soliton regime of an anomalous fiber ring cavity," *Opt. Express* **26**(9), 11447–11457 (2018).
98. S. Smirnov et al., "Generation of spatio-temporal extreme events in noise-like pulses NPE mode-locked fibre laser," *Opt. Express* **25**(19), 23122–23127 (2017).
99. S. Chen, J. M. Soto-Crespo, and P. Grelu, "Dark three-sister rogue waves in normally dispersive optical fibers with random birefringence," *Opt. Express* **22**(22), 27632–27642 (2014).
100. S. Chen et al., "Optical rogue waves in parametric three-wave mixing and coherent stimulated scattering," *Phys. Rev. A* **92**(3), 033847 (2015).
101. S. Chen, J. M. Soto-Crespo, and P. Grelu, "Watch-hand-like optical rogue waves in three-wave interactions," *Opt. Express* **23**(1), 349–359 (2015).
102. S. V. Sergeyev et al., "Vector-resonance-multimode instability," *Phys. Rev. Lett.* **118**(3), 033904 (2017).
103. J. Peng and H. Zeng, "Dynamics of soliton molecules in a normal-dispersion fiber laser," *Opt. Lett.* **44**(11), 2899–2902 (2019).
104. G. Genty et al., "Collisions and turbulence in optical rogue wave formation," *Phys. Lett. A* **374**(7), 989–996 (2010).
105. M. Erkintalo, G. Genty, and J. M. Dudley, "Giant dispersive wave generation through soliton collision," *Opt. Lett.* **35**(5), 658–660 (2010).
106. M. Taki et al., "Third-order dispersion for generating optical rogue solitons," *Phys. Lett. A* **374**(4), 691–695 (2010).
107. M. I. Kolobov et al., "Third-order dispersion drastically changes parametric gain in optical fiber systems," *Phys. Rev. A* **83**(3), 035801 (2011).
108. M. Horowitz, Y. Barad, and Y. Silberberg, "Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser," *Opt. Lett.* **22**(11), 799–801 (1997).
109. Y. Chen et al., "The formation of various multi-soliton patterns and noise-like pulse in a fiber laser passively mode-locked by a topological insulator based saturable absorber," *Laser Phys. Lett.* **11**(5), 055101 (2014).
110. A.-P. Luo et al., "Noise-like pulse trapping in a figure-eight fiber laser," *Opt. Express* **23**(8), 10421–10427 (2015).
111. Y. Mashiko, E. Fujita, and M. Tokurakawa, "Tunable noise-like pulse generation in mode-locked Tm fiber laser with a SESAM," *Opt. Express* **24**(23), 26515–26520 (2016).

112. S. Liu et al., "Noise-like pulse generation from a thulium-doped fiber laser using nonlinear polarization rotation with different net anomalous dispersion," *Photonics Res.* **4**(6), 318–321 (2016).
113. Z.-S. Deng et al., "Switchable generation of rectangular noise-like pulse and dissipative soliton resonance in a fiber laser," *Opt. Lett.* **42**(21), 4517–4520 (2017).
114. Y. Jeong et al., "On the formation of noise-like pulses in fiber ring cavity configurations," *Opt. Fiber Technol.* **20**(6), 575–592 (2014).
115. L. Zhao et al., "120 nm bandwidth noise-like pulse generation in an erbium-doped fiber laser," *Opt. Commun.* **281**(1), 157–161 (2008).
116. L. Zhao and D. Tang, "Generation of 15-nJ bunched noise-like pulses with 93-nm bandwidth in an erbium-doped fiber ring laser," *Appl. Phys. B* **83**(4), 553–557 (2006).
117. G. Sobon et al., "Ultra-broadband dissipative soliton and noise-like pulse generation from a normal dispersion mode-locked Tm-doped all-fiber laser," *Opt. Express* **24**(6), 6156–6161 (2016).
118. H. Chen et al., "0.4 μJ, 7 kW ultrabroadband noise-like pulse direct generation from an all-fiber dumbbell-shaped laser," *Opt. Lett.* **40**(23), 5490–5493 (2015).
119. S.-S. Lin, S.-K. Hwang, and J.-M. Liu, "High-power noise-like pulse generation using a 1.56-µm all-fiber laser system," *Opt. Express* **23**(14), 18256–18268 (2015).
120. K. Goda and B. Jalali, "Dispersive Fourier transformation for fast continuous single-shot measurements," *Nat. Photonics* **7**(2), 102–112 (2013).
121. Z.-R. Cai et al., "Graphene-decorated microfiber photonic device for generation of rogue waves in a fiber laser," *IEEE J. Sel. Top. Quantum Electron.* **23**(1), 20–25 (2017).
122. L. Gao et al., "Coherence loss of partially mode-locked fibre laser," *Sci. Rep.* **6**, 24995 (2016).
123. C. Lecaplain and P. Grelu, "Rogue waves among noiselike-pulse laser emission: an experimental investigation," *Phys. Rev. A* **90**(1), 013805 (2014).
124. Z. W. Liu, S. M. Zhang, and F. W. Wise, "Rogue waves in a normal-dispersion fiber laser," *Opt. Lett.* **40**(7), 1366–1369 (2015).
125. A. V. Kir'yanov, Y. O. Barmenkov, and M. V. Andres, "An experimental analysis of self-Q-switching via stimulated Brillouin scattering in an ytterbium doped fiber laser," *Laser Phys. Lett.* **10**(5), 055112 (2013).
126. Y. Panbhiharwala et al., "Investigation of temporal dynamics due to stimulated Brillouin scattering using statistical correlation in a narrow-linewidth cw high power fiber amplifier," *Opt. Express* **26**(25), 33409–33417 (2018).
127. D. Boukhaoui et al., "Influence of higher-order stimulated Brillouin scattering on the occurrence of extreme events in self-pulsing fiber lasers," *Phys. Rev. A* **100**(1), 013809 (2019).
128. C. Lecaplain et al., "Dissipative rogue waves generated by chaotic pulse bunching in a mode-locked laser," *Phys. Rev. Lett.* **108**(23), 233901 (2012).
129. P. Grelu and N. Akhmediev, "Dissipative solitons for mode-locked lasers," *Nat. Photonics Rev.* **6**(2), 84–92 (2012).
130. L. Gao et al., "Polarization evolution dynamics of dissipative soliton fiber lasers," *Photonics Res.* **7**(11), 1331–1339 (2019).
131. J. S. Peng and H. P. Zeng, "Build-up of dissipative optical soliton molecules via diverse soliton interactions," *Laser Photonics Rev.* **12**(8), 1800009 (2018).
132. H. J. Chen et al., "Dynamical diversity of pulsating solitons in a fiber laser," *Opt. Express* **27**(20), 28507–28522 (2019).
133. X. Q. Wang et al., "Real-time observation of dissociation dynamics within a pulsating soliton molecule," *Opt. Express* **27**(20), 28214–28222 (2019).
134. X. Q. Wang et al., "Transient behaviors of pure soliton pulsations and soliton explosion in an L-band normal-dispersion mode-locked fiber laser," *Opt. Express* **27**(13), 17729–17742 (2019).
135. Z. Wang et al., "Buildup of incoherent dissipative solitons in ultrafast fiber lasers," *Phys. Rev. Res.* **2**(1), 013101 (2020).
136. M. Liu et al., "Successive soliton explosions in an ultrafast fiber laser," *Opt. Lett.* **41**(6), 1181–1184 (2016).
137. Z. H. Wang et al., "Q-switched-like soliton bunches and noise-like pulses generation in a partially mode-locked fiber laser," *Opt. Express* **24**(13), 14709–14716 (2016).
138. X. M. Liu, D. Popa, and N. Akhmediev, "Revealing the transition dynamics from Q switching to mode locking in a soliton laser," *Phys. Rev. Lett.* **123**(9), 093901 (2019).
139. J. S. Peng et al., "Breathing dissipative solitons in mode-locked fiber lasers," *Sci. Adv.* **5**(11), eaax1110 (2019).
140. K. Goda, K. K. Tsia, and B. Jalali, "Serial time-encoded amplified imaging for real-time observation of fast dynamic phenomena," *Nature* **458**(7242), 1145–1149 (2009).
141. K. Goda et al., "Theory of amplified dispersive Fourier transformation," *Phys. Rev. A* **80**(4), 043821 (2009).
142. A. Klein et al., "Temporal depth imaging," *Optica* **4**(5), 502–506 (2017).
143. B. H. Kolner and M. Nazarathy, "Temporal imaging with a time lens," *Opt. Lett.* **14**(12), 630–632 (1989).
144. A. Tikan et al., "Single-shot measurement of phase and amplitude by using a heterodyne time-lens system and ultrafast digital time-holography," *Nat. Photonics* **12**(4), 228–234 (2018).
145. P. Suret et al., "Single-shot observation of optical rogue waves in integrable turbulence using time microscopy," *Nat. Commun.* **7**, 13136 (2016).
146. M. Narhi et al., "Real-time measurements of spontaneous breathers and rogue wave events in optical fibre modulation instability," *Nat. Commun.* **7**, 13675 (2016).
147. A. Klein, H. Duadi, and M. Fridman, "Ultrafast rogue waves in a vector field," *Proc. SPIE* **10903**, 109030D (2019).
148. B. Li et al., "Unveiling femtosecond rogue-wave structures in noise-like pulses by a stable and synchronized time magnifier," *Opt. Lett.* **44**(17), 4351–4354 (2019).
149. S. Lee et al., "Experimental spatio-temporal analysis on the shot-to-shot coherence and wave-packet formation in quasi-mode-locked regimes in an anomalous dispersion fiber ring cavity," *Opt. Express* **25**(23), 28385–28397 (2017).
150. N. K. Fontaine et al., "Real-time full-field arbitrary optical waveform measurement," *Nat. Photonics* **4**(4), 248–254 (2010).
151. O. Pottiez et al., "Statistical characterization of the internal structure of noiselike pulses using a nonlinear optical loop mirror," *Opt. Commun.* **377**, 41–51 (2016).
152. P. Ryczkowski et al., "Real-time full-field characterization of transient dissipative soliton dynamics in a mode-locked laser," *Nat. Photonics* **12**(4), 221–227 (2018).
153. S. V. Sergeyev et al., "Slow deterministic vector rogue waves," *Proc. SPIE* **9732**, 97320K (2016).
154. Q. Bao et al., "Atomic-layer graphene as a saturable absorber for ultrafast pulsed lasers," *Adv. Funct. Mater.* **19**(19), 3077–3083 (2009).
155. L. Kong et al., "Black phosphorus as broadband saturable absorber for pulsed lasers from 1 μm to 2.7 μm wavelength," *Laser Phys. Lett.* **13**(4), 045801 (2016).
156. J. Li et al., "Black phosphorus: a two-dimension saturable absorption material for mid-infrared Q-switched and mode-locked fiber lasers," *Sci. Rep.* **6**, 30361 (2016).
157. J. Liu et al., "Polarization domain wall pulses in a microfiber-based topological insulator fiber laser," *Sci. Rep.* **6**, 29128 (2016).
158. Y. Song et al., "Vector soliton fiber laser passively mode locked by few layer black phosphorus-based optical saturable absorber," *Opt. Express* **24**(23), 25933–25942 (2016).
159. Z. Wang et al., "Harmonic mode-locking and wavelength-tunable Q-switching operation in the graphene-Bi_2Te_3 heterostructure

saturable absorberbased fiber laser," *Opt. Eng.* **55**(8), 081314 (2016).
160. P. Li et al., "Two-dimensional $CH_3NH_3PbI_3$ perovskite nanosheets for ultrafast pulsed fiber lasers," *ACS Appl. Mater. Interfaces* **9**(14), 12759–12765 (2017).
161. B. Guo et al., "Sub-200 fs soliton mode-locked fiber laser based on bismuthene saturable absorber," *Opt. Express* **26**(18), 22750–22760 (2018).
162. X. Zhu et al., "TiS_2-based saturable absorber for ultrafast fiber lasers," *Photonics Res.* **6**(10), C44–C48 (2018).
163. Y. M. Chang et al., "Multilayered graphene efficiently formed by mechanical exfoliation for nonlinear saturable absorbers in fiber mode-locked lasers," *Appl. Phys. Lett.* **97**(21), 211102 (2010).
164. Z. Sun et al., "Ultrafast fiber laser mode-locked by graphene based saturable absorber," in *Conf. Lasers and Electro-Opt. (CLEO) and Quantum Electron. and Laser Sci. Conf. (QELS)* (2010).
165. L. M. Zhao et al., "Dissipative soliton operation of an ytterbium-doped fiber laser mode locked with atomic multilayer graphene," *Opt. Lett.* **35**(21), 3622–3624 (2010).
166. K. Wu et al., "High-performance mode-locked and *Q*-switched fiber lasers based on novel 2D materials of topological insulators, transition metal dichalcogenides and black phosphorus: review and perspective (invited)," *Opt. Commun.* **406**, 214–229 (2018).
167. N. A. A. Kadir et al., "Transition metal dichalcogenides (WS_2 and MoS_2) saturable absorbers for mode-locked erbium-doped fiber lasers," *Chin. Phys. Lett.* **34**(1), 014202 (2017).
168. B. H. Chen et al., "*Q*-switched fiber laser based on transition metal dichalcogenides MoS_2, $MoSe_2$, WS_2, and WSe_2," *Opt. Express* **23**(20), 26723–26737 (2015).
169. Y. F. Song et al., "Few-layer antimonene decorated microfiber: ultra-short pulse generation and all-optical thresholding with enhanced long term stability," *2D Mater.* **4**(4), 045010 (2017).
170. J. Guo et al., "Two-dimensional tellurium-polymer membrane for ultrafast photonics," *Nanoscale* **11**(13), 6235–6242 (2019).
171. Y. Song et al., "Lead monoxide: a promising two-dimensional layered material for applications in nonlinear photonics in the infrared band," *Nanoscale* **11**, 12595–12602 (2019).
172. T. Chai et al., "Few-layer bismuthene for ultrashort pulse generation in a dissipative system based on an evanescent field," *Nanoscale* **10**(37), 17617–17622 (2018).
173. D. Buccoliero et al., "Midinfrared optical rogue waves in soft glass photonic crystal fiber," *Opt. Express* **19**(19), 17973–17978 (2011).
174. L. Liu et al., "Mid-infrared rogue wave generation in chalcogenide fibers," *Proc. SPIE* **10100**, 1010020 (2017).
175. A. E. Akosman and M. Y. Sander, "Route towards extreme optical pulsation in linear cavity ultrafast fibre lasers," *Sci. Rep.* **8**, 13385 (2018).
176. G. Pu et al., "Intelligent programmable mode-locked fiber laser with a human-like algorithm," *Optica* **6**(3), 362–369 (2019).
177. M. Narhi et al., "Machine learning analysis of extreme events in optical fibre modulation instability," *Nat. Commun.* **9**, 4923 (2018).
178. W. H. Renninger and F. W. Wise, "Optical solitons in graded-index multimode fibres," *Nat. Commun.* **4**, 1719 (2013).
179. L. G. Wright, D. N. Christodoulides, and F. W. Wise, "Spatiotemporal mode-locking in multimode fiber lasers," *Science* **358**(6359), 94–97 (2017).
180. H. Q. Qin et al., "Observation of soliton molecules in a spatiotemporal mode-locked multimode fiber laser," *Opt. Lett.* **43**(9), 1982–1985 (2018).
181. Y. H. Ding et al., "Multiple-soliton in spatiotemporal mode-locked multimode fiber lasers," *Opt. Express* **27**(8), 11435–11446 (2019).
182. U. Tegin and B. Ortac, "Spatiotemporal instability of femtosecond pulses in graded-index multimode fibers," *IEEE Photonics Technol. Lett.* **29**(24), 2195–2198 (2017).
183. K. Krupa et al., "Spatial beam self-cleaning in multimode fibres," *Nat. Photonics* **11**(4), 237–241 (2017).
184. G. Lopez-Galmiche et al., "Visible supercontinuum generation in a graded index multimode fiber pumped at 1064 nm," *Opt. Lett.* **41**(11), 2553–2556 (2016).
185. C. Liu et al., "Triggering extreme events at the nanoscale in photonic seas," *Nat. Phys.* **11**(4), 358–363 (2015).
186. S. H. Chen et al., "Super chirped rogue waves in optical fibers," *Opt. Express* **27**(8), 11370–11384 (2019).
187. C. J. Gibson, A. M. Yao, and G. L. Oppo, "Optical rogue waves in vortex turbulence," *Phys. Rev. Lett.* **116**(4), 043903 (2016).
188. J. Leach et al., "Quantum correlations in optical angle-orbital angular momentum variables," *Science* **329**(5992), 662–665 (2010).
189. Z. Shen et al., "Trapping and rotating of a metallic particle trimer with optical vortex," *Appl. Phys. Lett.* **109**(24), 241901 (2016).
190. M. P. J. Lavery et al., "Detection of a spinning object using light's orbital angular momentum," *Science* **341**(6145), 537–540 (2013).
191. H. R. Ren et al., "On-chip noninterference angular momentum multiplexing of broadband light," *Science* **352**(6287), 805–809 (2016).
192. X. D. Qiu et al., "Optical vortex copier and regenerator in the Fourier domain," *Photonics Res.* **6**(6), 641–646 (2018).
193. T. Wang et al., "Generation of femtosecond optical vortex beams in all-fiber mode-locked fiber laser using mode selective coupler," *J. Lightwave Technol.* **35**(11), 2161–2166 (2017).
194. Y. Shen et al., "Radially polarized cylindrical vector beam generation in all-fibre narrow linewidth single-longitudinal-mode laser," *Laser Phys. Lett.* **16**(5), 055101 (2019).
195. Y. Han et al., "Controllable all-fiber generation/conversion of circularly polarized orbital angular momentum beams using long period fiber gratings," *Nanophotonics* **7**(1), 287–293 (2018).
196. Y. H. Zhao et al., "Mode converter based on the long-period fiber gratings written in the two-mode fiber," *Opt. Express* **24**(6), 6186–6195 (2016).
197. Z. W. Xie et al., "Integrated (de)multiplexer for orbital angular momentum fiber communication," *Photonics Res.* **6**(7), 743–749 (2018).
198. D. Mao et al., "Optical vortex fiber laser based on modulation of transverse modes in two mode fiber," *APL Photonics* **4**(6), 060801 (2019).
199. F. Leo et al., "Temporal cavity solitons in one-dimensional Kerr media as bits in an all-optical buffer," *Nat. Photonics* **4**(7), 471–476 (2010).
200. Y. Wang et al., "Universal mechanism for the binding of temporal cavity solitons," *Optica* **4**(8), 855–863 (2017).
201. J. K. Jang et al., "Observation of dispersive wave emission by temporal cavity solitons," *Opt. Lett.* **39**(19), 5503–5506 (2014).
202. K. E. Webb et al., "Experimental observation of coherent cavity soliton frequency combs in silica microspheres," *Opt. Lett.* **41**(20), 4613–4616 (2016).

Yufeng Song received his BS degree in optoelectronics from Tianjin University, China, in 2008 and his PhD from the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, in 2014. From 2013 to 2015, he worked as a research fellow at Nanyang Technological University, Singapore. From 2015 to 2017, he was a post-doctoral research fellow at Shenzhen University, Shenzhen, China. He is currently an assistant professor at Shenzhen University, Shenzhen, China. His current research focuses on the nonlinear fiber optics and all optical signal processing.

Zhenhong Wang received his BS degree from Tianjin University of Technology in 2013 and received his PhD from Nankai University in 2018. Currently, he is a research assistant at Shenzhen University. His PhD research focus investigated the nonlinear soliton dynamics of passively mode-locked fiber lasers. Now, his research interest is to fabricate photonic devices based on innovative 2-D materials and apply them to the ultrafast fiber lasers.

Cong Wang received his BS degree from Shandong Normal University in 2019 and is a doctoral student at Shenzhen University. His research interest focuses on 2-D nanomaterials, optical modulators, and nonlinear optics.

Krassimir Panajotov received his BS, PhD, and DSc degrees in physics from Sofia University in 1982, 1988, and 2002, respectively. Since 1982, he has been with the Institute of Solid State Physics, Bulgarian Academy of Sciences, and as a full professor since 2005. Since 2005, he is 10% ZAP at Vrije Universiteit Brussel. His research activities are in nonlinear optics, semiconductor lasers, photonic crystal devices, nonlinear laser dynamics, and optical solitons. In these fields, he has published more than 200 SCI-listed journal papers.

Han Zhang received his BS degree from Wuhan University in 2006 and received his PhD from Nanyang Technological University in 2010. His current research is on the ultrafast and nonlinear photonics of 2-D materials. He is currently the director of the Shenzhen Key Laboratory of 2-D Materials and Devices and Shenzhen Engineering Laboratory of Phosphorene and Optoelectronics, Shenzhen University.