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.

© The Authors. Published by SPIE and CLP under a Creative Commons Attribution 4.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [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 capillary RWs,5 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 breather28 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,22–24 soliton formation and dynamics,21,35 and self-similarity.36 Study of optical RW in fiber lasers...
has attracted plenty of attention since its first demonstration in 2011.\textsuperscript{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.\textsuperscript{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.

\section{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.\textsuperscript{3} 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.\textsuperscript{38} previewed the development of optical RWs. In 2016, a roadmap on the optical RWs was summarized by Akhmediev et al.,\textsuperscript{40} thanks to their review, research of RWs is developing fast.

\subsection{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.\textsuperscript{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.\textsuperscript{42} In fiber laser, there is the sinusoidal underlying carrier wave at frequency $\omega$ while there is the Stokes wave modulated by the NLSE envelope, which (to the second order) includes contributions at both $\omega$ and the second harmonic $2\omega$.\textsuperscript{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.

\section{3 Experimental Observation of Optical Rogue Waves in Nonfiber Lasers}

Optical RWs have been experimentally verified in plenty of physical systems. Solli et al.\textsuperscript{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,\textsuperscript{48–51} there are other nonlinear optical schemes, such as mode-locked pulse fiber lasers\textsuperscript{52} and Raman amplifier systems,\textsuperscript{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.\textsuperscript{5,45,58} In addition, rogue-wave-like extreme value fluctuation in Raman fiber amplifier systems was first reported by Hammani et al.\textsuperscript{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.\textsuperscript{59} In addition, RW statistics during high power femtosecond pulse filamentation in air were reported in 2008.\textsuperscript{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

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{The optical set-up for RW generation in a super-continuum system. Reproduced with permission from Ref. 5.}
\end{figure}
in an optically injected semiconductor laser and semiconductor laser with saturable absorber for the two-dimensional (2-D) case.

### 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. Soliton dynamics including soliton interactions, soliton molecules, soliton rains, noise-like pulses (NLPs), and soliton explosions, 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. In a fiber laser, dynamic RWs can be measured within each round trip. RWs in fiber lasers were experimentally studied as early as 2011 and numerically studied in 2012. Since then, the study of dissipative RWs in fiber lasers has been rapidly developing. RWs in fiber lasers can be categorized by pulse duration as three types, 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. The first type of RWs can be achieved via the chaotic structures among the NLPs. The second one is dark three-sister RWs, and the third one is the pulse waves generated from the multiple-pulse interaction 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 or altering the laser gain. 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. 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. Sergeev et al. claimed that the increased intracavity 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. 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 interaction in mode-locked fiber lasers (MLFLs). Dissipative RWs generated by chaotic pulse bunching are reported in the literature, and Peng et al. reported RW generation based on the soliton collision. Peng and Zeng 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. The energy exchange between the solitons is promoted by Raman effects and third-order dispersion.

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, which is then called NLPs. NLPs have been found in the fiber lasers based on the multiple mode-locking mechanisms 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, 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 ultra-short 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. At this stage, due to the low-level information collection through the traditional measuring scheme,

---

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

**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.
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 photodetector 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. In the fiber lasers, the DFT technique is generally implemented by sending the ultrashort 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. 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. In the literature, 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, Q-switched random laser, and high power amplifier were reported. Boukhaoui et al. numerically studied the influence of SBS on the occurrence of RWs in self-pulsing fiber lasers. 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. 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. 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. 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.

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 and to reported numerical simulations of dissipative RWs. 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, as shown in Fig. 6. From this figure, it can be seen that, for a saturation energy of $E_{\text{sat}} = 0.06$ 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 $E_{\text{sat}}$ 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 $E_{\text{sat}}$, 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. Figure 7 shows the theoretical statistical properties of the pulses for different $E_{\text{sat}}$ values. Obviously, the highest amplitude for each $E_{\text{sat}}$ 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. 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, 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 $E_{\text{sat}}$ 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 $E_{\text{sat}}$ values of (a) 0.6 nJ, (b) 0.8 nJ, (c) 8 nJ, and (d) 14 nJ. Reproduced with permission from Ref. 96.
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, soliton molecules, chaotic pulses, intermittent pulses, transition dynamics, and other nonlinear dynamics. In 2014, the Raman RW generation in the pulse fiber lasers was provided by the research group of Runge et al. 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. 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. The consecutive single-shot spectra of RWs were presented by the time-stretching measurement. Chowdhury et al. 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. 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. Time-lensing measurements can support real-time measurement of ultrashort pulses with a subpicosecond resolution. The time-lensing method has been applied to the research of incoherent soliton propagation in optical turbulence and stochastic breather emergence in modulation instability. Using the time-lensing method, ultrafast RWs in a vector field have been demonstrated. In the time-lensing measurement of RWs, the imaged signal must be synchronized for a specific timing. 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. Li et al. 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
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.\textsuperscript{146,150,151} Ryczkowski et al.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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 five 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.\textsuperscript{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, \textit{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 fiber lasers, which benefits the formation of RWs. Different
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.\(^{155} \)

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\(^ {55} \) 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,\(^ {55} \) topological insulators,\(^ {55} \) and transition metal dichalcogenides,\(^ {166-172} \) have been widely applied as optical saturable absorbers for MLFLs and have been studied for RW generation.\(^ {55} \) In the last three years, there have been many 2-D materials reported for application in ultrafast fiber lasers,\(^ {166-172} \) 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\(^ {56} \) 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.\(^ {176} \) According to the recent works, it is easy to find that the mechanism and nonlinear dynamics of the RWs at 2 \( \mu \)m are comparable to those observed at 1 and 1.5 \( \mu \)m. 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 \( \mu \)m; RWs at 3 \( \mu \)m 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 \( \mu \)m with a human-like algorithm has been presented in the literature.\(^ {178} \) 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. Recently, the spatiotemporal dynamics of optical pulses have been demonstrated in the MMFs, such as the spatiotemporal mode-locking, the soliton molecules, harmonic mode locking, the spatiotemporal instability, and beam self-cleaning. 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. 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, the optical fibers, and the SC generation. 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., 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, optical micromanipulation, rotation detection, WDM (mode-division multiplexing) systems, and nonlinear fiber optics.

In the fiber systems, the vortex beams are generally realized by the modulating elements, including the mode selective couplers, long period fiber gratings, and microstructured fiber facets. The mode-locked vortex beams through the mode fibers in the all-fiber lasers have been reported. 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. At present, TCSs have been intensely reported in fiber laser cavities due to their potential applications in the all-optical buffer and coherent frequency combs. Researchers have reported the experimental observation of TCS bound states in universal mechanisms. 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.

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


159. Z. Wang et al., “Harmonic mode-locking and wavelength-tunable Q-switching operation in the graphene-Bi2Te3 heterostructure
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.