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Dispersive temporal holography for single-shot recovering comprehensive ultrafast dynamics

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Abstract: It is critical to characterize the carrier and instantaneous frequency distribution variation in ultrafast processes, all of which are determined by the optical phase. Nevertheless, there is no method that can single-shot record the intro-pulse phase evolution of pico/femtosecond signals, to date. By analogizing holographic principle in space to the time domain and using the time-stretch method, we propose the dispersive temporal holography to single-shot recover the phase and amplitude of ultrafast signals. It is a comprehensive technology and can be applied to analyze ultrafast signals with highly complex dynamics. Encouraged by the accurate restoration of self-similar amplification of parabolic pulses, we track rogue wave and breathers' formation and evolution. The details of rogue waves emerging from the Fermi-Pasta-Ulam-Tsingou recurrence and chaotic modulation instability were experimentally demonstrated for the first time. The method provides a powerful tool for exploring ultrafast science, which may benefit many fields, including laser dynamics, ultrafast diagnostics, nonlinear optics, and so on.

Main Text:

Introduction

One of the most fundamental and challenging problems throughout ultrafast science is to fully characterize the complex electric fields of the ultrashort optical pulses. Nowadays, in laboratories and industry, the techniques called FROG (Frequency-Resolved Optical Gating) (1, 2), SPIDER (Spectral Phase Interferometry for Direct Electric-field Reconstruction) (3), and IAC (Interferometric Autocorrelation) (4) have been used for pulse reconstruction. However, in some crucial explorations (such as how the ultrafast processes occur and evolve), the recordings must be genuine real-time and accurate. The above mainstream correlation-based methods require multi-point scanning to determine the phase and cannot track the ultrafast signals consecutively. Furthermore, the nonlinear-effect-dependent single-shot detections (5) must satisfy some certain conditions, such as phase matching or pretty high peak power. That means such reconstructions, or to say a kind of estimation, are affected by the pulse signals themselves. It may have considerable errors to reveal the irregular pulse waveforms has a single occurrence.

Recently, a technique independent of nonlinear effects called dispersive Fourier transform (DFT) (6, 7) made it possible to real-time detect spectral evolution in ultrafast systems (8, 9). Utilizing the spectral interference, the relative carrier phase and the time interval limited at soliton molecules can also be retrieved (10, 11). The dynamics such as the mode-locking buildup (8), breathers (9), supercontinuum (12), pulsating solitons (13) were studied using DFT measurement. However, the method cannot describe the panorama enough. It missed the complex waveform shapes and the phase distribution, and failed to directly reveal the intrinsic physical mechanism.

The basic behavior of many vital nonlinear dynamics is still unknown because of lacking real-time time-domain measurements. An example is the optical rogue wave (14), which always appears and disappears suddenly like ocean rogue wave (15). Closely related to the breathers (16, 17), they have a strong connection with the Fermi-pasta-Ulam-Tsingou (FPUT) paradox (18), and the modulation instability (19). Previous researches only report the time-stretch spectroscopy or the oscilloscope traces, but the transient phase evolution is more significant for determining the origin of rogue waves. Therefore, it is urgent and essential to develop a single-shot phase and amplitude reconstruction technology for detect complex ultrafast dynamics.

Fig. 1. The basic idea of dispersive temporal holography. (a) The signal and reference pulses are stretched by a large amount of dispersion, and the formed interference fringes are recorded by an oscilloscope. (b) The information in the fringes can be retrieved by the reference beam. Corresponding to (d) “intervene recording” and (e) “diffraction reappearance” in classical holography. (c) Holograms of signal pulses with different chirps. (f) The corresponding reconstructions.

Principle of DTH

The holography (20) is a technology that can reconstruct the 3-D image from 2-D holograms via recovering both the intensity and the phase in physics. Another feature is that, it transfers the measurement of the signal to the holograms, making the needed sampling rate no longer depends on the signal itself (21). Applying such a principle on ultrafast signals can restore the intensity or phase in the hologram and vastly reduce the sampling requirements. The proposed method (Figs. 1a and b) one-to-one maps with the classical spatial holography (Figs. 1d and e). In spatial holography, the signal and the reference can be regarded as point sources, and the interference patterns are distributed along the divergent propagation. The interference period increases with the propagation distance L and inversely proportional to the initial spacing Δz . Similarly, the signal and the reference pulses in DTH (assuming their spectra are overlapped) can be considered "point sources" in the time domain. Applying the time-stretch (TS) technology to the ultrafast signals can create temporal interference fringes. The period is determined by two factors: the dispersion D and the time interval Δt . Different from restoring the holograms by holographic plates, the temporal "holograms" are recorded by the oscilloscopes.

In holography, the Nyquist sampling frequency F_{Ns} (21, 22) is determined by the interference period, which can be controlled by spatial expanding. As shown in Fig. 1d, the holographic plate for measurement at a more distant location L_2 should be larger in size, but it can be lower-resolution, comparing with L_1 . The same principle applies to the DTH, and TS plays the same role as spatial expanding. If we define time-stretching ratio as $g = D_2 / D_1$, F_{Ns} can be reduced by g times. When TS is enough, the oscilloscope with a several-GHz sampling rate can record the holograms of ultrafast signals without distortion.

In holographic principle, the outgoing light $A_{out}(z, T)$ is expressed as:

$$A_{out}(z, T) = I_H A'_r = (|A_r|^2 + |A_s|^2) A'_r + A_s A_r^* A'_r + A_s^* A_r A'_r, \quad (1)$$

where I_H represents the intensity distribution of the hologram. $A_s(z, T)$, $A_r(z, T)$ and $A'_r(z, T)$ are the complex amplitude of the signal, recording and reappearance references. z and T are the space and time coordinates. Three terms on the right-hand side of the equation correspond to the 0th, +1st, and -1st order diffraction light. If $A'_r(z, T)$ is exactly the same as $A_r(z, T)$, the second term is expressed as $|A_r|^2 |A_s| e^{i\phi_s}$, and thus the signal can be exactly recovered.

Since the above equations should not certainly depend on time or space coordinates, the holographic principle is actually applicable to the time dimension. The "diffraction reappearance" step of DTH shown in Fig. 1b is computer generated. The reference signal $A'_r(z, T)$ after TS can be expressed as $A'_r(z, \omega) e^{iD\omega^2/2}$, where the $A'_r(z, \omega)$ is the frequency-domain description, D is the total dispersion used for stretching. On the other hand, the sampling rate of I_H should ascend to the same level with $A'_r(z, T)$, it is achieved by zero-padding in the frequency domain (22). Then, the outgoing light after diffraction is $I_H A'_r$. Just like the reappeared virtual object image after diffraction is spatially reversed, we can obtain the recovery signal by removing the introduced dispersion to realize the temporal inversion. The +1st order signal is $|A_r|^2 |A_s| e^{i\phi_s}$, that means we get the all-round information, including the pulse shape, phase, and duration. If $A'_r(z, T)$ is a constant C , the +1st order term is expressed as $CA_r^* A_s = C |A_r A_s| e^{i(\phi_s - \phi_r)}$, and the relative phase can be retrieved.

In spectral interferometry, or FROG and SPIDER, the expansion terms consist of convolution or correlation functions in time-domain, requiring multi-point scanning to reconstruct the phase.

However, in DTH, the expansions are the products of the temporal terms, which can directly describe the signal. Hence, the single-shot measurement can be achieved. Besides, in spectral interferometry, the relative carrier phase and time interval are retrieved by the interference fringes location and spacing (10, 11). In principle, any phase change does exert influence on the fringes. For instance, if the signal is chirped, the fringes are sparse on the one side and dense on the other side. As shown in Figs. 1c and f, holograms in more chirped cases tend to be more unevenly distributed. Like holography can decode the spatial hologram patterns, DTH provides a method to extract the hidden information.

Fig. 2. Replication experiments. (a) Top left: The reconstructed amplified pulse with linear chirp. Top right: The corresponding phase. Bottom left: The measured spectrum of the seed parabolic pulse. Bottom right: Explanation of the chirp map. (b) Top: The holograms of the SSA, measured by an oscilloscope. The rests: The retrieved pulse waveforms, phase, and chirp of successively 170000 roundtrips, according to the holograms. (c) The results of moving the optical delay line in the signal arm. (d) To test the proposed method in case of arbitrary spectrum. Top left: The spectrum measure by an optical spectrum analyzer. Bottom left: The holograms. Top right: The Fourier transformation of the retrieved pulse. Bottom right: The reconstructed pulse.

Replication experiments

To test the proposed method, we use an ultrafast Er-doped fiber laser (26) as the source, and divide it to two output paths by a 50:50 optical coupler. One path experiences certain events, while the other serves as the reference.

The first event (see Supplementary Information Fig. 1) is the self-similar amplification (SSA) of parabolic pulses (23). We reconstructed the amplified pulse, whose duration is ~450 fs as shown

in the top of Fig. 2a. It performs a linear chirp and a parabolic phase distribution, in agreement with the theoretical prediction (24, 25). The optical spectrum of seed pulse is shown in Fig. 2a bottom left, and can also be parabolic fitted. The holograms show the power and phase change in Fig. 2b. As the amplification, the reconstructed pulse shape is near parabolic evolved, as is shown below. Because the complex amplitude of the field is described as $A(T) = |A(T)|e^{i\varphi(T)+ia_0T}$, it has a carrier modulation and causes oscillation in the phase. In order to visualize the phase evolution, what we draw in Fig. 2b is $\varphi(T)$. The phase always keeps a parabolic shape in the SSA process. No matter at normal or abnormal dispersion, the chirp-free pulse is broadened, and the peak power is decreased, as shown at the bottom of Fig. 2a. We can visualize the chirp variation as long as recording the peak power change. In this way, we draw the chirp map at the bottom right of Fig. 2b. The linear chirp is gradually accumulated during SSA, because the Kerr effect in SSA brings the additional intensity-dependent phase shift and positive chirp (26). For comparison, we carried out the numerical simulations (see Supplementary Information Fig. 2). The nonlinear phase shift of nearly 4π is generated in the center of the pulse with the chirp of $\sim 0.0016ps^2$, close to the experimental value.

The second event (see Supplementary Information Fig. 3) is tuning the optical delay line in the signal arm (Fig. 2c). The interference fringes of the hologram indicate the relative phase has a shift, and the restored signals' temporal position has a delay of $\sim 75fs$ in total, in agreement with the carrier phase shift ($\sim 30\pi$) in the phase diagram. It shows that the method can accurately determine the phase and group velocity respectively. The retrieved chirp in the bottom diagram stays no change because the signal properties keep unchanged.

In the last event (see Supplementary Information Fig. 4), we filter out the $16nm$ spectrum of the signal to test the method applying to arbitrary spectrum pulses. According to the holograms (Fig. 2d bottom left), we get the retrieved pulse shape, as shown in the bottom right of Fig. 2d. We find the recovered spectrum (Fig. 2d top right) is the same as its original spectrum in the top left of Fig. 2d. It demonstrates the feasibility of measuring complex ultrafast signals, which is the inherent advantage of holography (20), independent of the specific characteristic of the signals. Also, we should note that the proposed method is a direct measurement instead of an estimation because it does not depend on any intermediate nonlinear processes (5).

Measurement accuracy

Actually, there are many factors can lead to measuring error, such as the noise of signals, or the mechanical vibration. We believe the main factor affecting the accuracy of our method is the sampling for the holograms. We test the phase of the pulse center at different time intervals Δt , as shown in Fig. 3a. At the fixed sampling rate F_{os} (10 Gbit/s), the F_{Ns} of the holograms increases with the increasing Δt . In the range of 0-4ps for Δt , the standard deviation increases linearly to $0.04ps^2$. The chirpiness of the signal pulse, which make the holograms uneven distributed, can also influence the F_{Ns} . The test result in the middle of Fig. 3a shows that the deviation is nearly exponential to the chirpiness. Although the retrieved phase error at the edge is larger than the pulse center, shown in Fig. 3a below. But for all that, the standard deviation of the reconstructed phases is less than $0.05rad$, demonstrating the accuracy of the DTH method.

Fig. 3. Measurement accuracy and breather mode-locking. (a) Top: The retrieved phase and the standard variance at different initial time interval. Center: Relationship between phase accuracy and signal chirp, the experimental method is cutting the dispersion compensation fiber in the signal arm and adjust the time interval by a delay line in the reference arm. Bottom: Phase at different position of the retrieved pulse. Each green cycle is calculated by 1000 RTs. (b) Oscilloscope trace of mode-locking buildup. (c) The real-time spectrum recorded by DFT. (d) Top left: DFT spectrum of the high energy state of mode-locking. Top right: The holograms. Center left: The reconstructed signal of 1st diffraction. Center right: X-Z angle of view. Bottom left: The phase map. There are phase hops (2.68~3.32rad) at each pulse dips, for instance, the phase jump marked by the blue circle. Bottom right: The chirp map.

Characterizing breathers and rogue waves

The oscillator for test is an Er-doped fiber laser mode-locked via nonlinear polarization rotation (27). At the pump power of 400mW, we observe the trace of output pulse train as shown in Fig. 3b. This special mode-locking state performs periodical fluctuation on the power. It has ~600 pulses in a period. There are periodic spectrum broadening and compressing in high-intensity parts (Figs. 3c and d, recorded by DFT), which is one of the features of breathers. The stereogram in Fig. 3c shows recurring periods of symmetrical spectral gain on both sides, akin to the modulation instability gain (28) or FPUT recurrence (29, 30). Because the mode-locking always establish at random time, it is impossible to create a synchronous external reference signal. We use the output pulse in the $n+1$ th roundtrip as the reference of the n th one. In this way, the reconstructed pulse amplitude of the -1st diffraction is $|A_n||A_{n+1}|$, and the phase is described as $\varphi_n - \varphi_{n+1}$. We record the DFT spectrum and the holograms of 2/3 period in Fig. 3b (centered at high-intensity parts), and drawn the reconstructions in Fig. 3d. The recovered pulse waveforms show that the periodic dips appeared on both sides when the pulse "breathing". The higher the signal's peak power, the deeper

the dips are. According to the color in corresponding positions of the two side dips in phase map, the phase distributions have sudden changes of near π . Such patterns have been reported in theoretical or numerical studies (17, 31). However, there has been no experimental verification for the lack of measurement technology. It highlights the importance of DTH in revealing ultrafast dynamics directly in the time domain. SPM and dispersion effect common embodies the chirp properties of the pulse. The SPM is proportionate to pulse peak power, and the pulse width can affect the dispersion (because the dispersion length is determined by the pulse width). Therefore, the chirp map in Fig. 3d bottom right also shows the “breath” patterns as the pulse width and peak power “breath”.

Fig. 4. The formation of rogue waves and breathers. (a) The single pulse energy of the whole build-up process. (b) Top: Real-time spectrum. Center: Holograms of another recording. Bottom: The reconstructed waveforms of the build-up according to the holograms. (c) Left: The detailed formation of the rogue wave. Center: A multi-pulse case under noise-like mode-locking state, corresponding to the red cycle in (a). Right: The build-up process of the rogue wave recorded by DFT.

To find out the origin of this state, we record the buildup process, as shown in Fig. 4a. It starts from the Q-switched mode-locking, and the spectral broadening at a particular moment brings noise-like pulses (32). After 1.5 ms, the pulses eventually became breathers. Figure 4b shows the spectrum recorded by DFT, the holograms, and the reconstructed pulse evolutions. We notice that near the critical point of the transition in Fig. 4a, there are some special interference fringes (Fig.

4c right). These fringes may be caused by modulation instability induced pulse splitting. In the noise-like state, each time such patterns (Fig. 4c middle) appeared, the spectrum was broadened, and the single-pulse energy also has a maximum, corresponding to the red circle positions in Fig. 4a. Inspired by recent reports (33, 34), we believe the significant broadening and energy maximum in the transition boundary of our reconstructed image may be rogue waves. The detailed is shown in Fig. 4c left, noise pulse turns into a giant pulse, coming and disappearing suddenly. The reason results from that, the change of system parameters such as the intensity fluctuation, can make the rogue waves degenerate into breathers (35). The reconstructed images demonstrate this transformation. Also, it proves that the rogue wave generation may be another way to buildup mode-locking.

In noise-like area, the chirp and phase map shown in Fig. 5a are quite messy. However, at the breather's zone, both of them turn to be regularly distributed. It indicates that there has a boundary, and then the phase and chirp can vary continuously, or rather the mode-locking established. To find that, we show the detailed phase evolution of the transition zone in Fig. 5b. Here the phase drawn is $\varphi(T) + \omega_0 T$. At first sight, the phase starts to be locked at 127th RT. But it's needed to consider the chirp effect especially where the pulse peak power dramatically varying. To this end, the reconstructed signals are subsequent chirped. The phase should be $\varphi(T) + c_i T^2$ (c_i is the introduced chirp parameter). It can also be expressed as $\varphi_0(T) + (c_i + c_0)T^2$, where c_0 is the chirp parameter of the signal, and $\varphi_0(T)$ is the rest phase. At each certain phase φ_s , we get the solution of $T = \frac{\varphi_s - \varphi_0(T)}{c_i + c_0}$, that means c_0 and $\varphi_0(T)$ can contribute equally to the total phase if introducing an appropriate c_i . In this way, we draw the diagram in below of Fig. 5a and middle of Fig. 5b. The noise patterns in the diagrams indicates that the phase locking has been realized at the ~98th roundtrip (RT), even before the generation of the rogue wave.

The detailed pulse waveforms at the critical region (98th to 127th RT) are present in Fig. 5c top. The disordered multiple pulses gradually disappeared at the 118th to 121th RT, leaving a main pulse with the highest peak power. Then, the rogue wave occurs. We list the adjacent 5 roundtrips near the three maximums, the periodic changed pulse shape indicating the emergence of FPUT recurrence, as shown in Fig. 5c below. As another validation, the periodic spectral evolutions are throughout all the noise-like regime (see Supplementary Information Fig. 5). These findings are consistent with the previous reports (36, 37), the rogue waves start from the chaotic modulation instability and FPUT recurrence, especially in multiple pulse regions. Significantly, the same as in the case of breathers, there also existing dips and sudden phase change on both sides of each maximum. The pulse waveform and phase are shown in bottom of Fig. 5c, the phase hops of in the range of 2.75~3.08 rad coincide with the theoretical prediction (16) and the value for peregrine soliton (π phase hop) (38), which is considered to be the prototype of the rogue wave.

The optical rogue waves are fleeting, and usual detection methods can hardly capture it. How rogue waves and breathers generate and evolve in time/phase domain have never been experimentally observed before. The successful reconstructions proved that the proposed method could be scalable to arbitrary waveforms under highly complex ultrafast dynamics. In addition to measuring optical spectrum and pulse intensity, DTH provide a general and comprehensive analytical method for ultrafast dynamics, and offer a new dimension analysis of the phase domain inside pulse.

Fig. 5. The phase and amplitude evolution in the formation of rogue wave. (a) Top: Phase map. Center: Chirp map. Bottom: The description of phase and chirp. (b) Top: Detailed phase evolution at the transition region. Center: The description of phase and chirp. Bottom: The corresponding pulse peak power. (c) Top: the retrieved waveforms of 98th to 127th RT. Bottom left: Detailed 5 roundtrips around the three maximums. Bottom right: The main pulses and the phase of the maximums.

Conclusion

We propose the DTH technique to reconstruct the ultrafast dynamics, which is a comprehensive single-shot ultrafast measurement method, and suitable for analyzing both phase and amplitude of ultrashort optical signals. We track the formation of the rogue wave and breathers in a mode-locked laser, and proved that even complex dynamic process can be successfully reconstructed by the proposed method. For the first time, the formation mechanism of rogue waves and breathers have been experimentally demonstrated in ultrafast lasers. DTH can provide full detailed information and give an all-round understanding of ultrafast evolution, highlighting the importance of exploring the temporal properties of nonlinear dynamics in real-time. Much rather than a supplementary for FROG, or SPIDER, it can also extract the phase and amplitude inside the pulse, and can be used in ultrafast dynamics, chemical reactions (39), attosecond science (40), etc.

References:

1. R. Trebino, F. R. O. Gating, *Frequency-Resolved Optical Gating: the Measurement of Ultrashort Laser Pulses* (Kluwer Academic, 2002).
2. R. Trebino, K. DeLong, D. Fittinghoff, J. Sweetser, M. Krumbügel, B. Richman. Measuring ultrashort laser pulses in the time-frequency domain using frequency-resolved optical gating. *Review of Scientific Instruments*. **68**, 3277-3295 (1997).
3. C. Iaconis, I. A. Walmsley, Spectral phase interferometry for direct electric-field reconstruction of ultrashort optical pulses. *Optics. Letters*. **23**, 792-794 (1998).
4. K. Naganuma, K. Mogi, H. Yamada, General method for ultrashort light pulse chirp measurement. *IEEE J. of Quan. Elec.* **25**, 1225-1233 (1989).
5. E. A. Anashkina, V. N. Ginzburg, A. Kochetkov, I. V. Yakovlev, A. V. Kim, E. A. Khazanov, Single-shot laser pulse reconstruction based on self-phase modulated spectra measurements. *Scientific Reports*. **6**, 33749 (2016).
6. A. Mahjoubfar, D. V. Churkin, S. Barland, N. Broderick, S. K. Turitsyn, B. Jalali, Time stretch and its applications. *Nature Photonics*. **6**, 341-351 (2017).
7. K. Goda, B. Jalali, Dispersive Fourier transformation for fast continuous single-shot measurements. *Nature Photonics*. **7**, 102-112 (2013).
8. G. Herink, B. Jalali, C. Ropers, D. R. Solli, Resolving the build-up of femtosecond mode-locking with single-shot spectroscopy at 90 MHz frame rate. *Nature Photonics*. **10**, 321-326 (2016).
9. J. Peng, S. Boscolo, Z. Zhao, H. Zeng, Breathing dissipative solitons in mode-locked fiber lasers[J]. Science advances. *Science advances*. **5**, eaax1110 (2019).
10. G. Herink, C. Ropers, F. Kurtz, B. Jalali, D. Solli, Real-time spectral interferometry probes the internal dynamics of femtosecond soliton molecules. *Science*. **356**, 50-54 (2017).
11. T. Xian, L. Zhan, W. Zhang, W. Zhang, L. Gao, Single-shot detection time-stretched interferometer with attosecond precision, paper presented at the Optical Fiber Communications Conference and Exhibition (OFC), IEEE, 2020.
12. S. Grzegorz, R. Soboń, V. Lindberg, T. Pasiskevicius, J. Martynkien, Shot-to-shot performance analysis of an all-fiber supercontinuum source pumped at 2000 nm. *Journal of the Optical Society of America B*. **36**, A15-A21 (2019).
13. M. Liu, Z. Wei, H. Li, T. Li, Z. Luo, Visualizing the "Invisible" Soliton Pulsation in an Ultrafast Laser. *Laser & Photonics Reviews*. **14**, 50-54 (2020).
14. D. R. Solli, C. Ropers, P. Koonath, B. Jalali, Optical rogue waves. *Nature*. **450**, 1054-1057 (2007).
15. M. Hopkin, Sea snapshots will map frequency of freak waves. *Nature*. **430**, 492 (2004).
16. D. H. Peregrine, Water waves, nonlinear Schrödinger equations and their solutions. *The ANZIAM Journal*. **25**, 16-43 (1983).
17. N. Akhmediev, I. Korneev, Modulation instability and periodic solutions of the nonlinear Schrödinger equation. *Theoretical and Mathematical Physics*. **69**, 37-66 (1986).
18. J. Ford, The Fermi-Pasta-Ulam problem: paradox turns discovery. *Physics Reports*. **213**, 271-310 (1992).
19. M. Närhi, B. Wetzell, C. Billet, S. Toenger, T. Sylvestre, J. M. Merolla, R. Morandotti, F. Dias, G. Genty, J. M. Dudley, Real-time measurements of spontaneous breathers and rogue wave events in optical fibre modulation instability. *Nature communications*. **7**, 13675 (2016).
20. D. Gabor, Holography. *Science*. **177**, 299-313 (1972).
21. C. Wagner, W. Osten, W. Jüptner, Digital recording and numerical reconstruction of lensless Fourier holograms in optical metrology. *Applied Optics*. **38**, 4812-4820 (1999).
22. S. K. Mitra, *Digital signal processing* (McGraw-Hill Companies, 2004).

23. J. Buckley, F. W. Wise, F. Ilday, T. Sosnowski, Femtosecond fiber lasers with pulse energies above 10 nJ. *Optics Letters*. **30**, 1888-1890 (2005).
24. G. I. Barenblatt, *Scaling* (Cambridge University Press, 2003).
25. M. E. Fermann, V. I. Kruglov, B. C. Thomsen, J. M. Dudley, J. D. Harvey, Self-Similar Propagation and Amplification of Parabolic Pulses in Optical Fibers. *Physical Review Letters*. **84**, 6010-6013 (2000).
26. G. P. Agrawal, *Nonlinear fiber optics* (Springer Berlin Heidelberg, 2014).
27. H. Luo, L. Zhan, L. Zhang, Z. Wang, C. Gao, X. Fang, Generation of 22.7-fs 2.8-nJ pulses from an erbium-doped all-fiber laser via single stage soliton compression. *Journal of Lightwave Technology*. **35**, 3780–3784 (2017).
28. D. R. Solli, G. Herink, B. Jalali, C. Ropers, Fluctuations and correlations in modulation instability. *Nature Photonics*. **6**, 463-468 (2012).
29. G. V. Simaey, P. Emplit, M. Haelterman, Experimental demonstration of the Fermi-Pasta-Ulam recurrence in a modulationally unstable optical wave. *Physical review letters*. **87**, 033902 (2001).
30. C. V. Bao, J. A. Jaramillo, Y. Xuan, M. Qi, A. M. Weiner, Observation of Fermi-Pasta-Ulam recurrence induced by breather solitons in an optical microresonator. *Physical review letters*. **117**, 163901 (2016).
31. J. M. Dudley, G. Genty, F. Dias, B. Kibler, N. Akhmediev, Modulation instability, Akhmediev Breathers and continuous wave supercontinuum generation. *Optics express*. **17**, 21497-21508 (2009).
32. Z. Wang, A. Coillet, P. Tchofo, P. Grelu, Buildup of incoherent dissipative solitons in ultrafast fiber lasers. *Physical Review Research*. **2**, 013101 (2020).
33. C. Lecaplain, P. Grelu, Rogue waves among noise-like-pulse laser emission: an experimental investigation. *Physical Review A*, **90**, 013805 (2014).
34. Z. Liu, S. Zhang, F. W. Wise, Rogue waves in a normal-dispersion fiber laser. *Optics letters*, **40**, 1366-1369 (2015).
35. X. Wang, S. Tian, T. Zhang, Characteristics of the breather and rogue waves in a (2+1)-dimensional nonlinear Schrödinger equation. *Proceedings of the American Mathematical Society*, **146**, 3353-3365 (2018).
36. Y. Song, Z. Wang, C. Wang, K. Panajotov, H. Zhang. Recent progress on optical rogue waves in fiber lasers: status, challenges, and perspectives. *Advanced Photonics*, **2**, 024001 (2020).
37. J. Peng, N. Tarasov, S. Sugavanam, and D. Churkin. Rogue waves generation via nonlinear soliton collision in multiple-soliton state of a mode-locked fiber laser. *Optics express*, **24**, 21256-21263 (2016).
38. B. Kibler, J. Fatome, C. Finot, G. Millot, F. Dias, G. Genty, N. Akhmediev, J. M. Dudley. The Peregrine soliton in nonlinear fibre optics. *Nature Physics*, **6**, 790-795 (2010).
39. J. D. Simon, *Ultrafast dynamics of chemical systems* (Springer Science & Business Media, 2012).
40. P. B. Corkum, Attosecond science. *Nature physics*, **3**, 381-387. (2007).

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Author contributions:

L. Z. proposed the conception. L. Z., and W.W. designed and interpreted the results of all experiments. W. W. performed all of the experiments and simulation, analyzed the results. T. X. provided advices. W.W. wrote the paper. L. Z. review and editing the paper.

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Materials & Correspondence: Correspondence and requests for materials should be addressed to L. Z.

Data availability

All data in the main text or the supplementary materials are available from the corresponding authors on reasonable request. Source data are provided with this paper.

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