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https://doi.org/10.1038/s42005-019-0134-8

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# Soliton collision induced explosions in a mode-locked fibre laser

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Soliton explosion refers to a striking nonlinear dynamics in dissipative systems. In this state, a dissipative soliton collapses but returns back to its original state afterwards. Yet, the origin of such exotic soliton dynamics remains elusive. Here it is revealed that soliton collision can induce soliton explosions in a mode-locked fibre laser, benefiting from synchronous measurements of the spatio-temporal intensity evolution and the real-time spectra evolution using dispersive Fourier transform. Up to seven nonlinear regimes are observed successively in the laser by increasing the pump power only, including single-pulse mode locking, standard soliton explosions, noise-like mode locking, stable double pulsing, soliton collision induced explosions, soliton molecules, and double-pulse noise-like mode locking. These experimental findings are conducive to understand complex soliton dynamics in many nonlinear dissipative systems.

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Soliton explosions are one of the most fascinating nonlinear dissipative phenomena in soliton dynamics. In this regime, a dissipative soliton undergoes a sudden structural collapse upon propagation. Remarkably, the exploded dissipative soliton could return back to the original state even though it experiences strong energy dissipation. Soliton explosions were firstly predicted in the framework of the complex cubic-quintic Ginzburg-Landau equation (CQGLE)<sup>1</sup>, emphasizing that high-order nonlinear terms are crucial to make a soliton explode. Later on, several numerical investigations have been carried out<sup>2-5</sup>, trying to better understand the intrinsic mechanisms involved in soliton explosions and subsequent revivals of the soliton.

Experimental observations of soliton explosions rely on technical breakthroughs to directly reveal the explosive transient evolutions that are too fast to be captured by standard measurement tools. Cundiff et al. firstly experimentally observed soliton explosions in a mode-locked Ti:sapphire laser, by virtue of a fast spectra measurement technique realized by spectrally dispersing the output of the laser across an array of six detectors and measuring the corresponding temporally resolved spectrum<sup>6</sup>. Later on, with the help of a novel powerful real-time spectra measurement technique called dispersive Fourier transformation (DFT)<sup>7,8</sup>, soliton explosions were also found experimentally in a mode-locked fibre laser 9. The convenient access to the regime of soliton explosions via DFT has boosted the experimental investigations of such exotic dynamics in mode-locked fibre lasers recently<sup>10-12</sup>. Moreover, incoherent dissipative solitons, chaotic yet temporal localized pulses also exhibit similar explosive dynamics, as reported in a mode-locked fibre laser<sup>13</sup>.

Despite significant investigations on soliton explosions, a fundamental question remains elusive: why does a dissipative soliton explode and revive subsequently? For long-cavity fibre lasers (~100 m), Raman scattering was found to be related to soliton explosions<sup>9,10</sup>. However, for those short-cavity lasers in which Raman effect plays a negligible  $role^{6,11-13}$ , the origins of soliton explosions are still unclear. Although soliton explosions were numerically studied in the framework of CQGLE, considering dispersion, self-phase modulation, and high-order non-linearity terms<sup>1,6</sup>, a general qualitative understanding is difficult to achieve. Indeed, it is very challenging to provide the direct physical insights behind the numerical analyses in complex nonlinear systems.

Different from soliton explosions, soliton interactions in general behave like particles. So far, soliton interactions have been discovered as ubiquitous effects accounting for various exotic nonlinear dynamics, including rogue waves<sup>14–16</sup>, Fermi-Pasta-Ulam paradox<sup>17</sup>, and many others<sup>18,19</sup>, as well as for many nonlinear phenomena, including soliton fusion<sup>20</sup>, soliton fission<sup>21</sup>, soliton annihilation<sup>22</sup>, and partial annihilation<sup>23,24</sup>. It seems a reasonable assumption that soliton explosion itself has little to do with soliton interactions. For instance, although soliton collisions were widely investigated in laser optics<sup>25–28</sup>, soliton explosions have not been found in these investigations. In this work, we experimentally study explosions of dissipative solitons in a mode-locked fibre laser, and demonstrate a conceptually different type of soliton explosions induced by soliton collision. By solely increasing the pump power, at least seven distinct nonlinear regimes are discovered successively including stable dissipative solitons, standard soliton explosions, noise-like mode locking, stable double dissipative solitons, soliton collision induced explosions, soliton molecules, and double-pulse noiselike mode locking. We observe soliton collision in a laser cavity, and show that it leads to soliton explosions. DFT technique is implemented to capture these transient laser dynamics. Our experimental exploration proves that soliton explosion closely relates to soliton interactions.

## Results

Standard soliton explosions. The laser setup is shown in Fig. 1 (see 'Methods' for details). The fibre laser was mode-locked via nonlinear polarization rotation, which could be realized by tuning the polarization controllers in the cavity. In order to study the laser dynamics in the same polarization states, we fixed the polarization controllers once mode-locking was initiated. Only the pump power was adjusted to determine its influence on the laser dynamics. Stable dissipative solitons were established as the pump power reached the mode-locking threshold (~129 mW under our experimental configuration). Figure 2a depicts the pulse spectra measured by DFT, indicating no soliton explosions. As shown in Fig. 2b, the pulse spectra measured by DFT agree well with those attained with a commercial optical spectrum analyzer (OSA), confirming the accuracy of DFT employed in the experiment. The pulse duration is 6.4 ps as measured by an autocorrelator (FR-103 XL) and the spectral width is 25 nm, indicating that the pulse is highly chirped, a distinguished feature of mode-locked normal dispersion fibre lasers<sup>29</sup>. Standard soliton explosions were observed when the pump power was increased to 155 mW. Figure 2c shows the real-time spectra dynamics in the regime of soliton explosions. As one can see, the stable spectra undergo drastic changes suddenly, but recover to its original state after more than  $\sim 10^4$  round trips (RTs). Such transitions are shown in Fig. 2d, which displays the cross-sections of the stable and chaotic spectra. The spectra of the exploded solitons broaden significantly and present several peaks, indicating that self-phase modulation could be involved in soliton explosions in this case. Soliton explosion events occurred more frequently when the pump power was further increased. One example is shown in Fig. 2e at a pump power of 157 mW. Compared to the lower pump power case (Fig. 2c), Figure 2e shows that the exploded solitons generally last for a longer time. The longest time is 179 ms  $(340 \times 10^4 \text{ RTs})$  in Fig. 2e while it is only 0.96 ms  $(1.8 \times$ 10<sup>4</sup> RTs) in Fig. 2c. The pump power is changed by only 2 mW from Fig. 2c to Fig. 2e, demonstrating that the dynamics of soliton explosions are very sensitive to the pump power. Further pump power increasing resulted in noise-like mode locking<sup>9,30</sup>.



Fig. 1 Schematic of the mode-locked fibre laser and the detection system. WDM wavelength-division multiplexer, EDF erbium-doped fibre, PC polarization controller, PDI polarization-dependent isolator, DCF dispersion-compensating fibre, PD photodetector



**Fig. 2** Stable mode-locking and standard soliton explosions measured by dispersive Fourier transformation (DFT). **a** The spectra measured under stable mode locking. **b** The good agreement between the spectra measured by OSA (optical spectrum analyzer) (red) and DFT (blue) under stable mode-locking, confirms the accuracy of DFT. **c** The spectra measured by DFT capture soliton explosions when the pump power is increased. **d** The two cross-sections in **c** highlighting the different spectra of stable solitons and exploded solitons. **e** The dynamics of soliton explosions when the pump power is further increased. **f** The two cross-sections in **e** showing the spectra of stable and exploded solitons

Remarkably, stable double pulses were observed when the pump power was increased to 188 mW. The corresponding spectra measured by DFT are also stable. There are no soliton explosions in this case. The transition from noise-like mode locking to stable double pulsing by solely pump power increasing is found for the first time here. The origin is beyond the scope of this work. The two pulses are temporally separated by 19 ns as shown in Fig. 3.

**Soliton collision induced explosions**. The double pulses kept stable until the pump power was boosted to 228 mW. Remarkably, a novel type of soliton explosions was observed under this pump power. The results are plotted in Fig. 4. Figure 4a shows the temporal intensity evolution of the laser outputs over consecutive RTs. As shown, two pulses (parent pulses) initially separated by 260 ps, attract each other before merging to be a 'single pulse'. Three representative cross-sections are shown in Fig. 4b, at a RT number of 5000, 10,000 and 15,000, respectively. It is beyond the resolution of the photodetector to resolve the fine structures of the exploded pulse (the 'single pulse') in the temporal domain.



**Fig. 3** Stable double pulses separated by 19 ns obtained by pump power increasing from the standard soliton explosion state

However, DFT-measured spectra help to confirm and characterize soliton explosions in the spectral domain<sup>9,11,13</sup>. The synchronous spectra measured by DFT is presented in Fig. 4c. It shows that the spectrum of the exploded pulse is broad and chaotic. A representative cross-section at a RT number of 10,000 is shown in Fig. 4d (red).



**Fig. 4** Soliton collision induced explosions. **a** The spatio-temporal intensity evolution. The solid white line shows the energy evolution (The red dots are drawn for vision guiding). The inset (top right) is a magnified version of the small dashed box showing the generation of a second pulse. **b** Three representative cross-sections in **a**. **c** The synchronous real-time spectra evolution measured by dispersive Fourier transformation. **d** Three representative cross-sections in **c**. **e** The magnified portion of the figure in **d** (black) shows interference patterns

Interference patterns presenting on the spectra before the occuring of soliton explosion indicate that the two pulses are coherent. A cross-section is shown in Fig. 4d (black) at a RT number of 5000. The modulation on the spectrum is magnified in Fig. 4e. The period is 0.063 nm, corresponding to a temporal separation of 130 ps between the two pulses. Such a separation is in good agreement with the one (124 ps) shown in Fig. 4b (black), given the limited resolution of the photodetector. Moire fringes are also shown on the spectra as seen in Fig. 4c since the period of the modulation on the spectra is extremely small.

To investigate the details of the soliton collision process, Fig. 4c is magnified from the RT number of 8500 to 9000, as depicted in Fig. 5a. Three representative cross-sections are shown in Fig. 5b, at a RT number of 8600, 8850, and 8900, respectively. Note that the related temporal intensity measurements shown in Fig. 4a fail to resolve the temporal dynamics due to limited resolution (33 ps). Fortunately, field autocorrelation traces shed light on the temporal dynamics. A field autocorrelation trace can be obtained through the Fourier transform of each single-shot spectrum using the Wiener-Khinchin theorem. This method has been used to probe the evolving soliton separation within soliton molecules<sup>24,31,32</sup> and reveals the ordering of incoherent dissipative solitons<sup>13</sup>. If the number of pulses is *n* then the corresponding field autocorrelation trace gives 2n-1 peaks. The Fourier transforms of the spectra (Fig. 5a) yielded the field autocorrelation traces shown in Fig. 5c. The field autocorrelation traces reveal that the two pulses attract each other before explosion. Well-defined interference patterns are

present on the spectra from the RT number of 8500 to ~8800. An example is shown in Fig. 5b at a RT number of 8600. The patterns become unstable between the RTs of ~8800 and 8900, but modulations are still present on the spectra. An example is shown in Fig. 5b at a RT number of 8850. The corresponding field autocorrelation traces show noisy structures. This indicates that fine structures appear on the two pulses. Finally, the spectra become chaotic starting from the RT number of 8900 (Fig. 5a). A cross-section is shown in Fig. 5b at that round trip. This means explosions of the two pulses. The corresponding autocorrelation traces also indicate that the two pulses with fine structures attract each other to form a single complex. The energy evolution gives additional insights on the dynamics, as shown in Fig. 5a (the white solid line). The energy evolution of the whole process is shown in Fig. 4a. The energy suddenly increases once soliton explosion takes place around the RT number of 8900 (Fig. 5a). The energy decreases afterwards due to two dissipative processes. On the one hand, the spectra of the exploded solitons are very broad, hence the limited gain bandwidth of erbium-doped fibre (EDF) (gain filtering) dissipates the pulse energy and gives rise to narrower spectra as shown in Fig. 5a after the RT number of 8900. On the other hand, soliton explosion means a soliton explodes to pieces in the temporal domain, and therefore the weak components suffer from losses from the saturable absorber (nonlinear polarization rotation) which imposes large loss on the weak pulses. Such intensity-dependent loss is crucial for the build-up of a dissipative soliton in a mode-locked fibre laser, which dissipatives the weak



**Fig. 5** The details of the soliton collision phase. **a** The real-time spectra evolution showing interference patterns of double solitons (from a round-trip number of 8500 to 8800) and subsequent chaotic spectra from soliton explosions; The white line shows the energy evolution. **b** Three representative cross-sections at a round-trip number of 8600, 8850, 8900, respectively. **c** The field autocorrelation traces calculated from the spectra evolution. **d** Three representative cross-sections in **c** 



**Fig. 6** The details in the revival phase of the double solitons. **a** The real-time spectra evolution showing chaotic spectra from a round-trip number of 12,000 to -14,000 and subsequently stablized spectra; The white line shows the energy evolution. **b** The corresponding temporal intensity evolution measured by a photodetector. **c** Three representative cross-sections in **a** at a round-trip number of 12,900, 13,500, 14,500, respectively. **d** The corresponding cross-sections in the temporal domain



**Fig. 7** The dynamics of soliton molecules. **a** The evolving spectra patterns measured by dispersive Fourier transformation. Note that only a small portion of the spectra is shown as plotting the whole spectra causes the patterns invisible. **b** An example of the whole spectrum shows very dense peaks. **c** The period is visible by magnifying the spectrum from 1576 to 1578 nm in **b**. **d** The field autocorrelation traces calculated from the whole spectra evolution show that the separation between the solitons is stable (120 ps). **e** A cross-section in **d** 

pulses and leaves only the stronger one, as revealed both in the mode locking build-up phase and the soliton interaction phase<sup>24</sup>.

A second pulse suddenly appears around a RT number of 13,000, as shown in Fig. 4a (dashed box). A magnified version is exhibited in the inset of Fig. 4a (top right). More detailed investigations are provided in Fig. 6a, b which are the close-up versions of Fig. 4a, c between the RT number 12,000 and 14,500. The gradual growth of the second pulse is depicted in Fig. 6b before a RT number of 13,000. Since the energy of the exploded pulse decreases (Fig. 4a, the white line) due to dissipative processes as discussed above, the remaining gain of the laser is transferred to a new pulse (the second pulse). This process illustrates the revival of the double solitons. Figure 6a depicts that there are mainly three types of spectra in the figure (denoted as '1', '2', and '3'). The spectra are broader in the beginning (RTs 12,000 to ~13,000, stage 1), but become narrower later (RTs ~13,000 to 14,000, stage 2). This could be understood from the temporal dynamics as shown in Fig. 6b. In stage 1, there are one strong pulse and a growing weak pulse, while there are two pulses with equal energies in stage 2 (the weak pulse grows up). Most of the energy is owned by the strong pulse, therefore self-phase modulation is stronger in stage 1, giving rise to broader spectra. Typical cross-sections are shown in Fig. 6c, d, at RT numbers of 12,900, 13,500 and 14,500, respectively.

Although there are two pulses between the ~15,000 and 25,000 RTs in Fig. 4c, no spectral interference patterns are observed. A cross-section is shown in Fig. 4d (blue), at a RT number of 15,000. This is because the spectral patterns are too dense to be resolved by DFT which has a resolution of 0.025 nm (see 'Methods'). Such a spectral resolution cannot resolve the spectral interference patterns of double pulses with a separation larger than 326 ps.

Further increasing the pump power resulted in the generation of bound solitons which are usually termed as soliton molecules<sup>33,34</sup>. Various internal dynamics of soliton molecules have been experimentally revealed using DFT to measure the evolving spectra patterns of soliton molecules<sup>31,32,35</sup>. A small

portion of the spectra is shown in Fig. 7a. Plotting the whole spectra makes the patterns invisible because the period of the patterns is extremely small (0.07 nm) compared to the whole spectra (25 nm). An example of the whole spectra measured by DFT is displayed in Fig. 7b in which the period of the pattern is not visible. The period becomes visible as depicted in Fig. 7c, by magnifying the spectrum from 1576 to 1578 nm in Fig. 7b. Although the spectra changes in Fig. 7a, the period of the patterns is fixed at 0.07 nm, which is also confirmed by the field autocorrelation traces. The field autocorrelation traces in Fig. 7d, show that the temporal separation is fixed at 120 ps. Therefore, the evolving spectra patterns imply that the phase is changing. Similar dynamics have been reported elsewhere<sup>31,35</sup>. Interestingly, the soliton molecule transferred to stable double solitons separated by 19 ns, exactly the same state shown in Fig. 3, by increasing the pump power. Increasing the pump power from this state, the two coherent pulses became double noise-like pulses, but their separation remained fixed at 19 ns. Further investigation is limited by the available pump power from the laser diode.

Our results show the rich nonlinear dynamics embedded in mode-locked fibre lasers. Seven distinct nonlinear regimes are observed by solely increasing the pump power. Dissipative solitons are established above the mode-locking threshold. Dissipative solitons explode as the pump power is controlled a little bit above the mode-locking threshold, and the exploded solitons evolve to the original states after  $\sim 10^4$  RTs in the cavity. The life time of an exploded soliton depends upon the pump power. A higher pump power gives rise to a longer time in which the exploded solitons circulate in the cavity. Noise-like modelocking is observed when the pump power is increased. As the pump power is further increased, stable double solitons are formed. As the laser gain is increased even further, double solitons become unstable. Soliton collision occurs in the fibre laser cavity, and it induces soliton explosions. Soliton molecules are formed by slightly increasing the pump power, without soliton collision or explosion. Finally, increasing the pump power makes the soliton molecule transfer to double noise-like pulses.

## Discussion

Soliton interactions can be divided to short- and long-range interactions depending on the separation between solitons. Direct soliton-soliton interaction accounts for short-range interaction when solitons are separated by several times their width<sup>36-38</sup>. Long-range interactions are mediated by different mechanisms, including dispersive waves $^{38-40}$ , acoustic effects $^{41-43}$ , and gain depletion and recovery<sup>44,45</sup>. The attractive interactions shown in Fig. 4a refer to long-range interactions as the two solitons are initially separated by 260 ps which is forty times the pulse width; the separation is almost one hundred times the width at the RT number 15,000 (~600 ps). Dispersive waves can be neglected here as they generally do not present in mode-locked normal-dispersion fibre lasers. Acoustic effects make two solitons separated by 260 ps repel each other to a stable separation  $(510 \text{ ps})^{42}$ . However attractive interactions are observed in Fig. 4a, implying that the acoustic effects can also be excluded here. The attractive soliton interactions could arise from gain depletion and recovery. A leading soliton depletes the gain of a laser, resulting in less gain for a tailing soliton until it is recovered to the value before the leading soliton. Such gain dynamics makes two solitons attract (repel) each other if their separation is shorter (longer) than the recovery time<sup>45</sup>. Here, the initial 260-ps separation between the two solitons is much shorter than the recovery time (~ns)<sup>44,45</sup>, resulting in attractive interactions. Note that the recovery time here is different from the standard gain recovery time of EDF which has a typical value of ms<sup>46</sup>.

Finally, we believe that soliton collision induced explosions could also prevail in various laser systems and beyond. In addition, the pieces shed by exploded solitons could relate to turbulence, constituting an excellent platform of wave turbulence investigation. We therefore expect our results to pave the way for extensive investigations on these significant nonlinear phenomena.

## Methods

**The laser setup**. The total cavity length is 10.5 m, consisting of dispersioncompensating fibre (DCF), single-mode fibre, and erbium-doped fibre (EDF), with the corresponding group-velocity dispersion (GVD) of 65.0, 62.5, and -22.8 ps<sup>2</sup>/ km, respectively. The net dispersion of the laser is normal. As shown in Fig. 1, the output of the laser was split into two ports by an optical coupler. One port (undispersed) was used to measure the evolution of the instantaneous intensity I(*t*). The other port was stretched in time domain by using a long dispersive fibre (~11 km in our experiments), in order to imitate its pulse spectrum in real-time according to the stretched temporal waveform via DFT<sup>7,47</sup>. The two identical photodetectors (PD1, PD2) have a bandwidth of 50 GHz, and the signals were measured by a real-time oscilloscope (33 GHz, Agilent). Note that by measuring the delay between the two photodetectors (53.651 µs), synchronous measurements of the spectral and temporal intensities of the output pulses can be realized. In particular, DFT facilitates direct measurements of round-trip resolved spectra and accordingly enables us to reveal various fast laser dynamics<sup>8,13,31,32,35,47-49</sup>.

**The spectral resolution of DFT**. The spectral resolution  $(\Delta\lambda)$  of DFT technique is determined by  $\Delta\lambda = \Delta t/DL$ .  $\Delta t$  is the response time of the system (30 ps), while D and L are the dispersion parameter and the length of the fibre used  $(DL = 1200 \text{ ps m}^{-1})$ . The resulting resolution of DFT is 0.025 nm in our experiment. Time to wavelength conversion can be calculated approximately by multiplication of pulse spectral width and fibre dispersion (DL). The stretched pulses have a duration around 30 ns in our experiments.

**Reporting summary**. Further information on experimental design is available in the Nature Research Reporting Summary linked to this article.

#### Data availability

The data that support the findings of this study are available from the corresponding author on request.

Received: 16 October 2018 Accepted: 22 February 2019 Published online: 22 March 2019

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# ARTICLE

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#### Acknowledgements

We acknowledge the support from the National Key Research and Development Program (2018YFB0407100), National Natural Science Fund of China (11434005, 11727812, 11621404, 11561121003, 61775059 and 11704123), and Key Project of Shanghai Education Commission (2017-01-07-00-05-E00021).

#### Author contributions

H.Z. conceived the idea. J.P. performed the experiments. H.Z. supervised and guided the project. All authors contributed to the writing of the paper.

# Additional information

Supplementary information accompanies this paper at https://doi.org/10.1038/s42005-019-0134-8.

Competing interests: The authors declare no competing interests.

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