Excitation of breather solitons in a mode-locked fibre laser

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ABSTRACT

We report on the generation and study of breathing dissipative solitons in a mode-locked fibre laser. Breathers exist in the laser cavity under the pump threshold of stationary mode locking. For the first time to our knowledge, breathing soliton molecules are also observed. Numerical simulations of the laser model support our experimental findings.

Keywords: dissipative nonlinear systems; mode-locked fibre lasers; breather solitons.

1. INTRODUCTION

Dissipative solitons (DSs) in a nonlinear medium are localised coherent structures that result from the composite balance between conservative effects (nonlinearity and dispersion/diffraction) and dissipative ones (gain and loss) [1]. In addition to parameter-invariant stationary DSs, numerous nonlinear systems support breathing (pulsating) DSs, the energy of which is localised in space but oscillates in time, or vice versa [2-5]. Such nonlinear waves are attracting considerable research interest in optics owing to their strong connection with the Fermi-Pasta-Ulam paradox [3], formation of rogue waves, turbulence and modulation instability phenomena. Apart from their fundamental importance in nonlinear science, breathing solitons are also attractive because of their potential for practical applications, such as in spectroscopy [6]. Yet, the observation of these breathers has been mainly restricted to optical microresonator platforms [4,5].

In this paper, we report on the direct experimental observation of breathing DSs in a passively mode-locked fibre laser [7]. Remarkably, in the normal-dispersion regime of the laser cavity, breathers are excited in the laser under the pump threshold for stationary DS mode locking. Breathing solitons feature periodic spectral and temporal evolutions over cavity round trips. Although breathing soliton generation has been predicted theoretically in mode-locked fibre lasers [8], to date the experimental observation and characterisation of such lasing regimes is challenging due to the fast evolutionary behavior of breathers, beyond the speed of traditional measurement tools. We capture the fast breather dynamics spectrally and temporally in real time using time-stretch dispersive Fourier transform (TS-DFT) based single-shot spectral measurements [9] and spatio-temporal intensity measurements [10]. For the first time to our knowledge, breathing soliton pair molecules are also generated in the cavity, which represent double-breather bound states with a close intra-pulse separation. Numerical simulations of the laser model described by the complex Ginzburg-Landau equation support our experimental findings.

2. EXPERIMENTAL OBSERVATION OF BREATHING SOLITONS

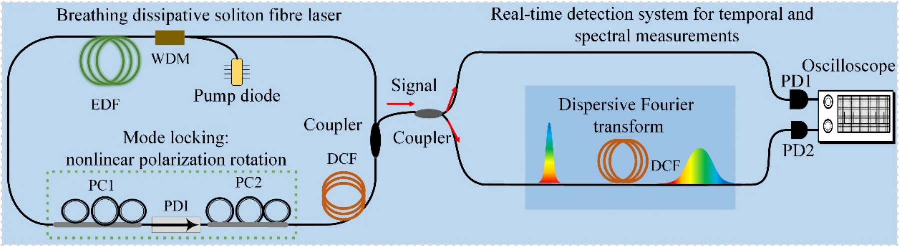

Figure 1. Schematic of the breathing dissipative soliton fibre laser and the real-time detection system. WDM, wavelength-division multiplexer; EDF, erbium-doped fibre; PC, polarization controller; PDI, polarization-dependent isolator; DCF, dispersion-compensating fibre; PD, photodetector.

The laser used in our experiment (Fig. 1) operates in the telecommunication optical band where the employment of a dispersion-compensating fibre (DCF) allows the laser to work in the normal-dispersion regime. The cavity incorporates three types of fibres: a short length (1.4 m) of erbium-doped fibre (EDF) providing gain, DCF used for dispersion compensation, and standard single-mode fibre (SMF) from the pigtails of the optical components used. The group-velocity dispersion (GVD) values of these fibres are 65, 62.5, and −22.8 ps^2/km, respectively. During the experiment, the length of the EDF was fixed, and dispersion management in the cavity was accomplished through variation of the relative length of DCF and SMF. The EDF is pumped through a 980/1550 wavelength-division multiplexer by a 976-nm laser diode. The mode-locking mechanism is nonlinear polarisation rotation (NPR), facilitated through the inclusion of a combination of two polarisation controllers (PCs) and an in-fbre polarisation-dependent isolator. The output of the laser is split into two paths by an optical coupler. One path (undispersed) is used to record the evolution of the instantaneous intensity pattern $I(t)$. The signal from the other port is fed into a long (~11 km in our experiment) normally dispersive fibre to temporally stretch the pulses and thus acquire TS-DFT based spectral measurements [9]. The signals from the two paths are detected by two identical high-speed photodetectors (PD1 and PD2) with 50-GHz bandwidth and captured by a real-time oscilloscope with 80-GSa/s sampling rate and 33-GHz bandwidth (Agilent), which ensures a resolution of ~0.025 nm for the TS-DFT measurements.

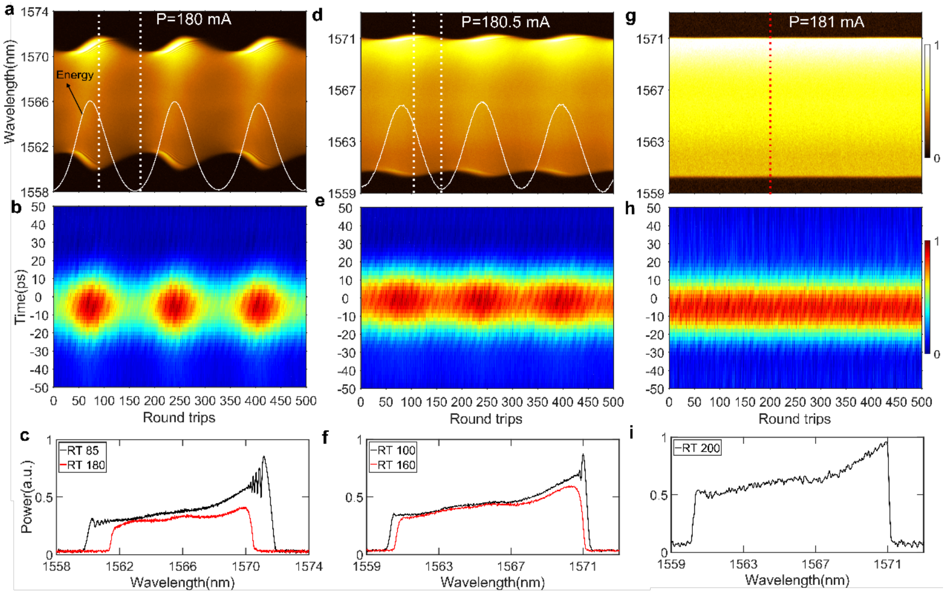

Figure 2. Experimental observation of breathing dissipative solitons. (a-c) Dynamics of a breather at a pump current of 180 mA. (d-f) Dynamics of a breather at a pump current of 180.5 mA. (g-i) Stationary dissipative soliton at a pump current of 181 mA. (a), (d), (g): TS-DFT recording of single-shot spectra over consecutive round trips; (b), (e), (h): Temporal evolution of the intensity relative to the average round-trip time over consecutive round trips; (c), (f), (i): Single-shot spectra at the round-trip numbers of maximal and minimal spectrum extents within a period.

We have found that there exist two mechanisms through which breathing DSs can be excited in the laser. A first, fully controllable way of accessing breathers relies on decreasing the pump strength starting from stationary DS mode locking. Alternatively, breathers can also be induced through rotation of the PCs within the NPR settings starting from a continuous-wave regime in which the pump power is below the threshold for stationary mode locking. These two procedures for accessing the breathing laser state were verified across a large range of net cavity dispersion values from 0.0020 to 0.14 ps^2, thereby establishing that a new operation regime of the laser – the breather mode-locking regime – exists under the threshold of standard mode locking. Figure 2 presents the experimental results obtained for a net cavity dispersion of 0.14 ps^2. Above this dispersion value, no stationary mode locking existed and only noise-like pulses were emitted from the laser. Panels a, b of Fig. 2 show the respective spectral and temporal evolutions of a breathing DS over cavity round trips, as recorded by TS-DFT and spatio-temporal intensity measurements. The pulse spectrum compresses and stretches periodically with a period of approximately 170 cavity round trips. The evolution of the pulse temporal profile over cavity round trips is periodic and the peak intensity varies within each period, with the highest (lowest) peak intensity naturally occurring in the vicinity of the position where the spectrum reaches the largest (narrowest) width. The evolution of the pulse energy over cavity round trips (Fig. 2a, white curve) shows that the highest energy within each period exceeds the minimal one by nearly two times. Starting from this breather generation regime, increasing the pump power resulted in an increasingly smaller breathing ratio (defined as the ratio of the largest to the narrowest spectrum width within a period) until the breathing ratio reached the value of one meaning that a stationary DS had formed. This process is illustrated in panels a, d, and g of Fig. 2, in which the pump current is increased gradually. While the breathing ratio is 1.35 in Fig. 2a, it is 1.05 in Fig. 2b. Such relationship between pump power and breathing ratio was also verified in laser cavities with varied dispersion. We ascribe this relationship to the saturation of the energy of the pulse with the broadest spectrum. As a consequence, an increase in pump power only transfers energy to the weak pulses, hence entailing a reduced breathing ratio. The process is reversible: by decreasing the pump power, the stationary DS returned back to the breathing state.

Notably, in addition to the single breathing DSs described above, we also observed breathing soliton pair molecules in our experiment for the first time. They were found when the net dispersion of the laser cavity was decreased to 0.0020 ps^2 by increasing the pump power from the single breather state. The dynamics are illustrated in Fig. 3. The spectrum of the breather pair features the typical interference pattern that is present in the spectrum of a soliton molecule [11]. Although the spectral width experiences large periodic variations, the separation between the peaks of spectral intensity remains fixed at 0.18 nm over consecutive round trips. Constant spectral peak spacing implies a constant pulse separation in the time domain. The corresponding spatio-temporal intensity dynamics (Fig. 3c) indeed reveal that the intra-molecular temporal separation has a constant value of 45 ps, which is in excellent agreement with the spectral peak separation value. Moreover, the spatio-temporal intensity evolution indicates that the two breathers are in phase. We have also investigated the temporal dynamics of the breather molecule using field autocorrelation analysis, which showed good agreement with Fig. 3c. Besides breather pair molecules with a close pulse separation, we also observed bound double breathing solitons widely separated by 34 ns when the net cavity dispersion was increased relative to the molecule state. The mechanism responsible for binding of such largely spaced pulses can be deemed to be a pulse interaction mediated by acoustic waves [12].

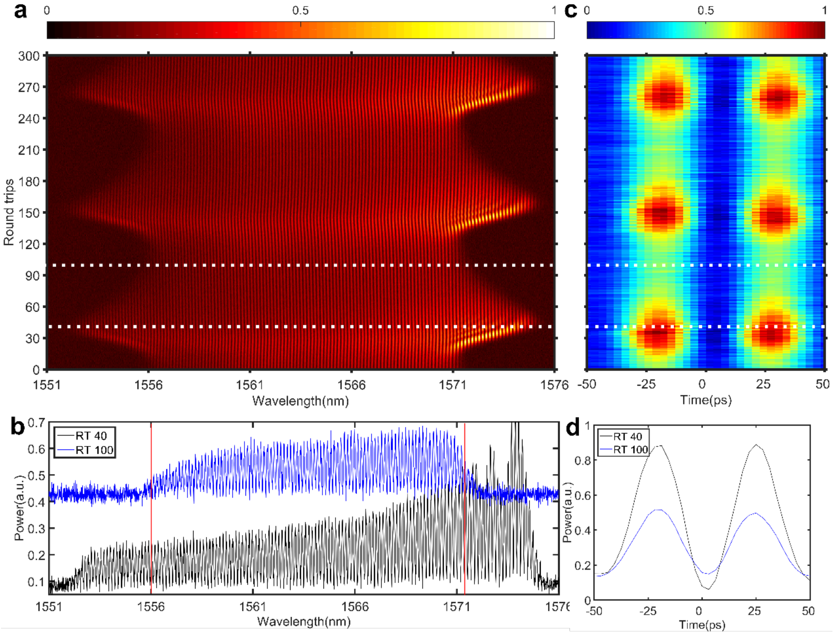

Figure 3. Dynamics of a breathing soliton pair molecule. (a) TS-DFT recording of the shot-to-shot spectral evolution; (b) Single-shot spectra at the round-trip numbers of maximal and minimal spectrum extents within a period; (c) Temporal intensity evolution relative to the average round-trip time; (d) Temporal intensity profiles at the round-trip numbers of maximal and minimal spectrum extents within a period.

3. NUMERICAL SIMULATIONS

For our passively mode-locked laser model, we applied the master-equation approach [13], which is one of the main techniques used in the theory of passively mode-locked lasers. Namely, we used the complex cubic-quintic Ginzburg-Landau equation (CQGLE) [1,7]. This continuous model has an analogue in the corresponding lumped model, and the net linear gain/loss parameter (denoted here by θ) is directly related to the small-signal gain of the active fibre, thus it plays alike role to the pump power in the experiment. Figure 4 shows typical examples of the solutions to the CQGLE that we have found numerically for $\theta = -0.1$ and $\theta = 0.05$. Panels a, b ($\theta = -0.1$) show periodic breathing dynamics of a single pulse. The evolution of the temporal intensity of the soliton shows large variations in each period of oscillation. The spectrum widens at the positions of the spikes of temporal intensity creating subsequently discrete sidebands symmetrically located at each side. The latter decay quickly before the next spike is generated. For a net cavity dispersion of 0.14 ps^2 and taking the unit of the dimensionless time variable to be 2 ps, the period of oscillation in our simulation is approximately 170 cavity round trips, in accordance with the experiment. Increasing the parameter θ to 0.05, we observed that the pulse solution stabilises to a stationary state after an initial transient stage (Fig. 4c, d). While the pulse solution shown in Fig. 4a, b exhibits the qualitative features of the experimentally observed breathing solitons, it resembles the strongly pulsating solitons demonstrated theoretically in [8]. We would like to point out, however, that theoretical modelling is used here to account qualitatively for the observed pulse dynamics rather than to provide an accurate quantitative comparison with the experiment. In this light, comparison of Figs. 2 and 4 makes a strong case that the formation of breathers is ubiquitous in normal-dispersion mode-locked fibre lasers when they are operated below the pump threshold for stationary mode locking. We have also found breathing soliton pair molecules by solving the CQGLE numerically.

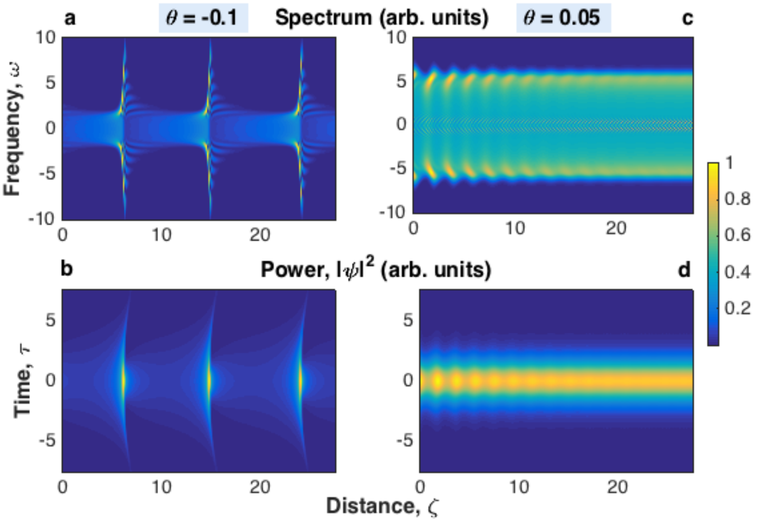

Figure 4. Evolutions of the spectrum and temporal intensity of the solutions of the CQGLE found for θ = −0.1 (subplots a and b) and θ = 0.05 (subplots c and d).

4. CONCLUSIONS

We have demonstrated experimentally the formation of breathing DSs in a normal-dispersion passively mode-locked fibre laser. This pulse generation regime is induced in the laser cavity by operating the laser under the pump threshold for stationary DS mode locking. The universal nature of the breather formation is indicated by our observation in a varying-length cavity, and further confirmed by numerical simulations of the laser model described by the complex CQGLE. Breathing soliton pair molecules have also been observed for the first time in experiments with mode-locked fibre lasers. Breathers introduce a new regime of mode locking into ultrafast lasers. These findings not only carry importance from an application perspective, but also contribute more broadly to the fundamental understanding of dissipative soliton physics. Our observations further demonstrate that mode-locked fibre lasers are an ideal test bed for the study of complex nonlinear wave dynamics relevant to a large variety of physical systems. More generally, the complex CQGLE is the most common mathematical implementation of a dissipative system, describing many different nonlinear effects in physics. Therefore, it is reasonable to assume that the breathing DS dynamics found in this work are not limited to optical systems and will also be discovered in various other physical systems.

ACKNOWLEDGEMENTS

We would like to acknowledge the support of the National Natural Science Fund of China (11434005, 11621404, 11561121003, 61775059 and 11704123).

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