Breathing Solitons in a Passively Harmonic Mode-Locked Fibre Laser

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Abstract: We report on the first experimental observation of breathing solitons in a passively harmonic mode-locked fibre laser. Various features of a 4th-harmonic operation state showing breather oscillations with a period of 5 roundtrips are discussed.

1. Introduction

In addition to their growing use as sources of ultrashort pulses for many applications [1], passively mode-locked fibre lasers constitute an ideal platform for the fundamental exploration of complex nonlinear wave dynamics. Indeed, the high levels of linear and nonlinear effects accumulated during a single roundtrip in such lasers entail a wealth of complex short-pulse dynamics [2] that can be accessed through control of the cavity parameters. These include, for example, harmonic mode locking (HML) [3], where multiple pulses circulate in the laser cavity with a constant temporal spacing, thus entailing a multiplied repetition rate of the laser. Breathing solitons (BSs) can also be excited in ultrafast fibre lasers [4]. BSs exhibit periodic temporal and spectral evolutions over cavity roundtrips hence, a characteristic feature of the breather regime is the appearance of frequencies in the radiofrequency (RF) spectrum of the laser emission that are submultiples of the roundtrip frequency of the laser.

The coexistence of harmonic and breather mode locking in a laser is quite counterintuitive. Whilst BSs propagating around a laser cavity can interact and form robust multi-breather bound states [5,6], the experimental observation of breathers uniformly distributed along the cavity has never been reported before. In this paper, we provide the first evidence of BS dynamics in a passively HML fibre laser and highlight the distinctive spectral features of this laser operating regime.

2. Experimental Setup and Results

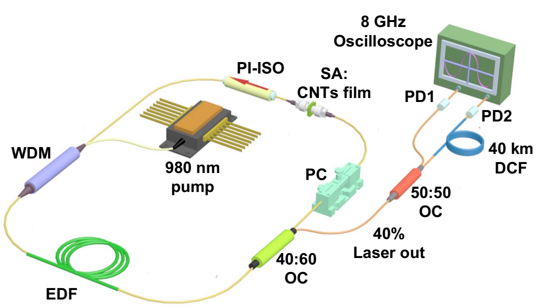

Fig. 1. Schematic diagram of the erbium-doped fibre laser and real-time detection system. WDM: wavelength-division multiplexer; EDF: erbium-doped fibre; OC: output coupler; PC: polarisation controller; SA: saturable absorber; CNT: carbon nanotube; PI-ISO: polarisation-dependent isolator; DCF: dispersion-compensating fibre; PD: photodiode.

The experimental setup is sketched in Fig. 1. The laser is a fibre ring cavity, which includes a 1-m-long erbium-doped fibre, and pieces of standard single mode fibre from the pigtails of the optical components used. The cavity dispersion is ~ −0.47 ps^2, triggering conventional soliton pulse shaping in the laser, and the fundamental repetition rate is 9.97 MHz. Mode locking is obtained thanks to a carbon nanotube-doped polymer film. A fraction of the laser output is directly detected by a fast photodiode (PD1) plugged to a high-speed real-time oscilloscope. The remaining laser output is sent through a time-stretch dispersive Fourier transform (DFT) setup consisting of a long segment of dispersion-compensating fibre that provides a total accumulated dispersion of −660 ps/nm. From the photodetection of the DFT output signal on a fast photodiode (PD2), the optical spectrum for each pulse is obtained directly on the oscilloscope, with a resolution of 0.18 nm. The spectral properties of the laser output are further characterised by an optical spectrum analyser (OSA) and a RF spectrum analyser.

Under a pump power of 120 mW and suitable setting of the polarisation controller (PC), the laser mode locks at the

4th harmonic (39.88 MHz) of the roundtrip frequency in the soliton generation regime. The output pulse train displays an equal pulse spacing of 25 ns, and the RF spectrum features a super-mode noise suppression level of 50 dB (Fig. 2(a)), ensuring good stability of the mode-locking operation. The roundtrip evolutions of the DFT spectra and pulse energy (Fig. 2(b)) confirm the stationary nature of the observed soliton state. A further signature of this stationary-soliton (SS) state is the existence of Kelly sidebands (KSs) in the optical spectrum (Fig. 2(c)).

Adjusting the PC at the same pump power gives rise to very different laser dynamics as shown in Fig. 2(d-f). While the laser still works in the 4th harmonic mode-locked regime, the RF spectrum now displays new frequency components symmetrically located around the 4th harmonic frequency at the distance 2.08 MHz, i.e., nearly one fifth of the fundamental repetition frequency (Fig. 2(d)). The output pulse train seems to be unchanged as compared to the previous case. Yet, the oscillatory behaviour of the pulses is revealed by the false-colour plot of successive DFT measurements over cavity roundtrips shown in Fig. 2(e): the pulse spectra experience synchronous periodic variations in intensity and shape with a period of 5 roundtrips. While the corresponding oscillations of the pulse energy are relatively small, new sidebands (parametric sidebands, PSs) develop in the optical spectrum (Fig. 2(f)), where the energy exchanges among these sidebands are directly related to the breathing dynamics. Whilst the KSs do not evolve significantly over cavity roundtrips (the DFT measurements show a nearly constant intensity level), the PSs clearly experience periodic fluctuations.

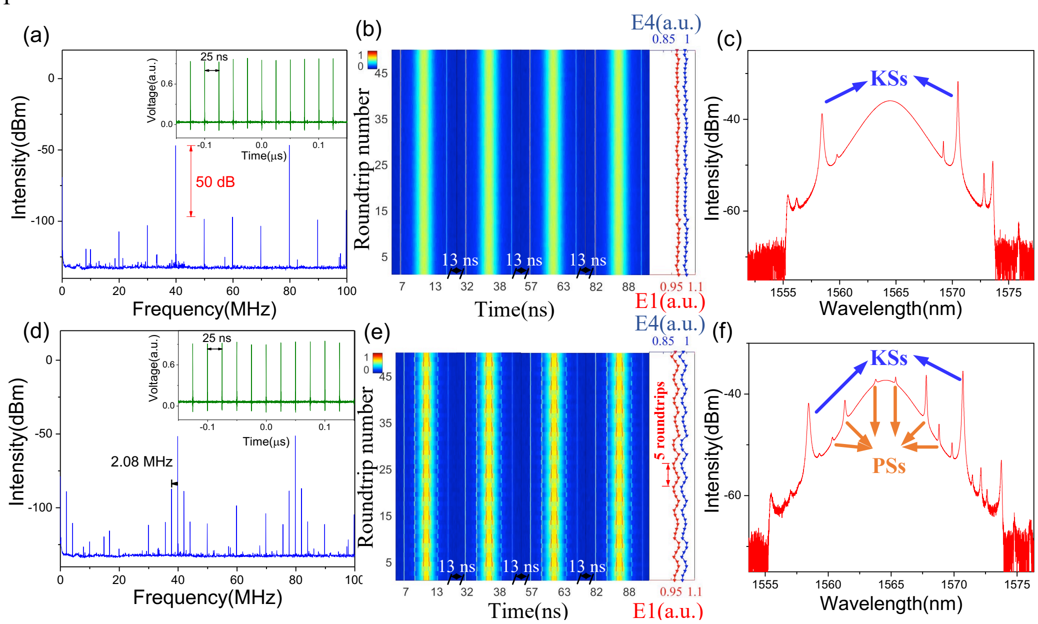

Fig. 2. Two different operations of the 4th HML laser: (a-c) SS state and (d-f) BS state. (a), (d): RF spectra. The insets show the photo-detected pulse trains. (b), (e): DFT recording of single-shot spectra over consecutive cavity roundtrips. The DFT time base is plotted over the 100.3-ns range of a roundtrip. Also shown are the energy evolutions for the leading and trailing pulses. (c), (f): OSA-recorded optical spectra.

3. Conclusion

We have provided the first experimental evidence of the existence of BSs in a passively HML fibre laser. When the laser operates at the 4th harmonic, the four pulses circulating in the cavity show synchronous periodic evolutions over cavity roundtrips with a period of 5 roundtrips. Direct signatures of the BS HML regime appear in the RF and optical spectra, and in the DFT measurements. Given the polarisation dependence of these states, further insight into the observed dynamics will be provided by an analysis of the two orthogonal polarisation components.

Acknowledgments

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