Intelligent Control of Complex Wave Dynamics Generation in Fibre Lasers

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***Abstract*—We review our recent work on the use of genetic algorithms to assist in the control and study of non-stationary nonlinear wave dynamics in ultrafast fibre lasers. These include repetitive patterns, such as breathing solitons and breather molecular complexes, and non-repetitive rare events.**

***Index Terms*—machine learning, breathing solitons, rogue waves, nonlinear dissipative systems**

The pulse generation mechanism in ultrafast fibre lasers usually involves a complex interplay among the effects of nonlinearity, dispersion and dissipation, and reaching a specific operating regime requires precisely adjusting multiple parameters in a high-dimensional space, which is a laborious task if addressed via trial and error. Machine-learning tools, especially the use of evolutionary and genetic algorithms (GAs), have recently shown promising for the design of smart lasers that can tune themselves into desired operating states [1]. Yet, these algorithms have been mainly designed to target regimes of parameter-invariant, stationary pulse generation. In this paper, we review our recent progress in the control and study of highly dynamic, non-stationary operating regimes of ultrafast lasers assisted by GAs.

Breathing solitons exhibiting periodic oscillatory behaviour have recently emerged as a ubiquitous ultra-short pulse regime of passively mode-locked fibre lasers thanks to various studies that have revealed their fast spectral and temporal evolutions over cavity roundtrips using real-time detection techniques [2], [3]. In [4], we have introduced a GA-based approach for the generation of breather dynamics with controlled characteristics. We have employed merit functions relying on the peculiar features of the radio-frequency (RF) spectrum of the laser emission to drive the optimisation of a four-parameter nonlinear polarisation evolution transfer function for the auto-setting of the laser into various breather states. These included single breathers with controllable breathing period and ratio (defined as the ratio of the largest to the narrowest width of the pulse spectrum within a period), and stable multi-breather bound states (breather molecular complexes) with a controllable number of elementary constituents.

A laser working in the breather generation regime shows competition between the frequency of the breather oscillations f_b and the cavity repetition frequency f_r. In [5], we have reported frequency locking at Farey fractions of a breather laser by demonstrating for the first time that the winding numbers f_b/f_r show the hierarchy of the Farey tree and the structure of a devil's staircase, in accordance with the predictions from the theory of nonlinear systems with two competing frequencies [6]. A further development of our GA-based optimisation approach was the key to manipulating the breathing frequency of the laser system, hence to establishing the link between breathing solitons and the universal frequency-locking phenomenon. The locked breathing frequencies feature a high signal-to-noise ratio and can give rise to dense RF combs with a line spacing which is not constrained by the cavity length and can reach the sub-megahertz range. Our further study [7] has also shown the subharmonic synchronisation and de-synchronisation of breather molecules in a laser cavity, thus opening the possibility to study the dynamics of nonlinear systems with three or more interacting frequencies.

In [8], we have extended the use of GAs to the active control of extreme wave events or rogue waves (RWs) in a fibre laser cavity. By employing GA's merit functions based on the statistical defining characteristics of RWs to optimise the cavity parameters, we have been able to trigger the generation of extreme spectral events that also correlate to extreme fluctuations of the pulse energy in the cavity, and to tailor their intensity. Quite remarkably, we have observed significant frequency up- or down-shifting of the optical spectrum in the rising phase of these waves, which has suggested a new physical scenario for their emergence and disappearance.

As demonstrated by our work in the particular case of a laser system, the use of control algorithms can make complex dynamics and instabilities easily accessible, where this facilitates the exploration of the rich underlying physics.

References

[1] F. Meng and J. M. Dudley, Light Sci. Appl., vol. 9, 26, 2020.

[2] J. Peng, S. Boscolo, Z. Zhao, and H. Zeng, Sci. Adv., vol. 5, eaax1110, 2019.

[3] J. Peng, Z. Zhao, S. Boscolo, C. Finot *et al.*, Laser Photon. Rev., vol. 15, 2000132, 2021.

[4] X. Wu, J. Peng, S. Boscolo, Y. Zhang *et al.*, Laser Photon. Rev., vol. 16, 2100191, 2022.

[5] X. Wu, Y. Zhang, J. Peng, S. Boscolo, *et al.*, Nat. Commun., vol. 13, 5784, 2022.

[6] M. H. Jensen, P. Bak, and T. Bohr, Phys. Rev. Lett., vol. 50, pp. 1637–1639, 1983.

[7] X. Wu, J. Peng, S. Boscolo, C. Finot, *et al.*, Phys. Rev. Lett., vol. 131, 263802, 2023.

[8] X. Wu, Y. Zhang, J. Peng, S. Boscolo, *et al.*, Laser Photon. Rev., 2200470, 2023.