Breathing soliton dynamics in mode-locked fibre lasers

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NONLINEAR EVOLUTION EQUATIONS: ANALYTICAL AND GEOMETRICAL METHODS AND NEW PERSPECTIVES

Abstract

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 [3]. Such nonlinear waves are attracting considerable research interest in optics owing to their strong connection with the Fermi-Pasta-Ulam paradox, 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. Yet, the observation of these breathers has been mainly restricted to optical microresonator platforms [2].

In this talk, I will report on the generation and study of breathing DSs in passively mode-locked fibre lasers [4]. Breathing solitons feature periodic spectral and temporal evolutions over cavity round trips. Experimentally, we capture such fast dynamics spectrally and temporally in real time using time-stretch dispersive Fourier transform based single-shot spectral measurements [5] and spatio-temporal intensity measurements. 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. For the first time in experiments with mode-locked fibre lasers, breathing soliton pair molecules are also generated in the cavity, which represent double-breather bound states with a close intra-pulse separation. 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 cubic-quintic Ginzburg-Landau equation (CQGLE) [1]. When the laser has an average anomalous cavity dispersion, we observe a regime of operation where the laser oscillator generates multiple pulsating solitons with extreme ratios of maximal to minimal intensities in each period of pulsations. The soliton spectra also experience large periodic broadening and compression. These observations are, to the best of our knowledge, the first of their kind in a laser system.

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, such as nonlinear waves, superconductivity, superfluidity, Bose-Einstein condensates, liquid crystals, plasmas, and numerous other phenomena. 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.

References

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