Optical Wave Turbulence in Fibre Lasers

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Weak irregular nonlinear interactions of a large number of cavity modes are responsible for practically important characteristics of fibre lasers, such as spectra of generated radiation. The total generated fibre laser power is distributed between millions of resonator modes, each with very small amplitude. However, the overall effect of the interactions between such small amplitude modes is easily observable. The nonlinear Kerr effect in fibre affects the propagation of light in the cavity and leads to a nonlinear mixing of longitudinal modes. As a result, the resonator is not linear and the operation and performance of such lasers is changed with changing power. For instance, the spectra of generated radiation experience spectral broadening as the laser power increases. Despite fast progress in fibre lasers and their growing applications, there remains a surprising lack of a comprehensive understanding of the underlaying physics behind their operation, as well as such practical features as fibre laser spectral characteristics. This is because fibre laser is not only a remarkable engineering device, but also a complex nonlinear physical system with a rich repertoire of dynamic behaviour and phenomena.

Any particular four-wave-mixing induced elementary interaction between four resonator modes can be considered to be a weak – the properties of each wave are not changed substantially during a single interaction event. However, accumulating such weak nonlinear interactions and mixing them with optical noise leads to a randomised energy transfer between waves and to effective mode de-phasing [1]. This physical process calls for kinetic description and has a lot in common with the classical theory of wave turbulence. Turbulence is a state of physical system with many degrees of freedom far from equilibrium. Even when an external excitation only effectively acts on one or a few waves, nonlinear interactions between waves lead to the excitation of many waves and turbulence. Wave turbulence theory deals with the statistical behaviour of a large number of interacting waves. The mathematical description of nonlinear systems with a large number of degrees of freedom, far from thermodynamic equilibrium remains one of the major challenges of the modern theoretical physics, and is also of great importance for various optical applications [1-10].

There has been a recent surge in studies of the similarities between optics and hydrodynamics (see [11, 12] and references therein). Wave turbulence in fibre lasers has an interesting and rather nontrivial link to fluid flows. We recently observed [6] the analogy between hydrodynamic laminar–turbulent transition and transition between two operational regimes in a fibre laser system and identified the critical role of coherent structures – dark and grey solitons – in this transition. Studying the transition from a linearly stable coherent laminar state to a highly disordered state of turbulence is conceptually and technically challenging, and of great interest because all pipe and channel flows are of that type. In optics, understanding how a system loses coherence, as spatial scale increases, is a fundamental problem of practical importance. In this talk, I will overview recent progress in the field.

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