How Optical Spectrum of Random Fiber Laser is Formed

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Abstract: We experimentally and theoretically describe formation of random fiber laser's optical spectrum. We propose a new concept of active cycled wave kinetics from which we derive first ever nonlinear kinetic theory describing laser spectrum.

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1. Introduction

Kinetic theory describes statistics of systems with many degrees of freedom. Traditional kinetics describes slow evolution of wave spectrum to statistical equilibrium via numerous weakly nonlinear interactions. In many optical systems, key properties are defined by a large ensemble of light waves, randomized through optical noise, random scattering and nonlinear interaction, which makes them a natural object for wave kinetic description [1]. The wave kinetic approach could provide a straightforward description for the slow relaxation of the optical spectrum to statistical equilibrium.

However, many practically important optical systems, like lasers, are dissipative (active) in their nature. Moreover, in many systems dissipation and pumping of energy occurs in periodic way, like in lasers, where the periodicity exist because of the existence of the optical cavity. In such systems internal intra-cavity nonlinear dynamics can lead to substantial change of the optical spectrum during evolution within each cavity round-trip [2]. Traditional wave kinetics cannot be applied for such systems.

Here, we introduce a conceptually new class of cyclic wave systems, characterized by non-uniform, double-scale dynamics, with strong periodic changes of the energy spectrum and slow evolution from cycle to cycle, to a statistically steady state. Taking a practically important example –random fiber laser – we derive a nonlinear kinetic theory of the laser spectrum, generalizing the seminal linear model results of Schawlow and Townes. We perform experiments whose results agree with our theory.

2. Nonlinear kinetic description of random fiber laser spectrum and experimental confirmation

Firstly we introduce the concept of active cycled wave kinetics. In classical wave kinetics, initial wave spectrum (optical spectrum) evolves gradually to a statistically stationary wave spectrum when energy pumping/dumping is homogeneous over the evolution time, Fig. 1a. The evolution is governed by wave kinetic equation. In active cyclic systems, like lasers, the energy pumping and dumping act in a periodic way resulting in cycling dynamics and double-scale evolution of the wave spectrum, Fig. 1b. The resulting the wave spectrum is locally non-stationary exhibiting strong changes within each cycle (cavity round-trip). This evolution is governed by a local pumping-driven wave kinetic equation, which we derive in our work. At the same time, the spectrum evolves in a gradual incremental way from cycle to cycle similar to classical wave kinetics. If overall pumping within the cycle is equal to energy dumping, the system approaches the global stationary solution, which can be found. In this way the laser spectrum can be described.

The described concept directly corresponds to fiber lasers having very large number of longitudinal modes weakly interacting via Kerr nonlinearity. Moreover, we apply it to random fiber laser having no cavity of fixed length and no cavity modes operating via Rayleigh scattering [3,4]. In a random fiber laser, the optical gain is distributed over the fiber, while losses mainly occurs at fiber ends where the radiation goes out. Each pass of the optical fiber is one cycle. The generation spectrum exhibits strong changes during evolution within each cycle because of optical gain. Random distributed feedback couples the optical spectrum on consequent cycles. Note that description of random lasers' spectrum is challenging task just because most of laser theories are dynamical and imply introduction of some generation modes. In the field of random lasers it can be done, for examples, via introduction special kind of modes of constant flux [5] or via introduction of sets of localized and/or extended modes [6].

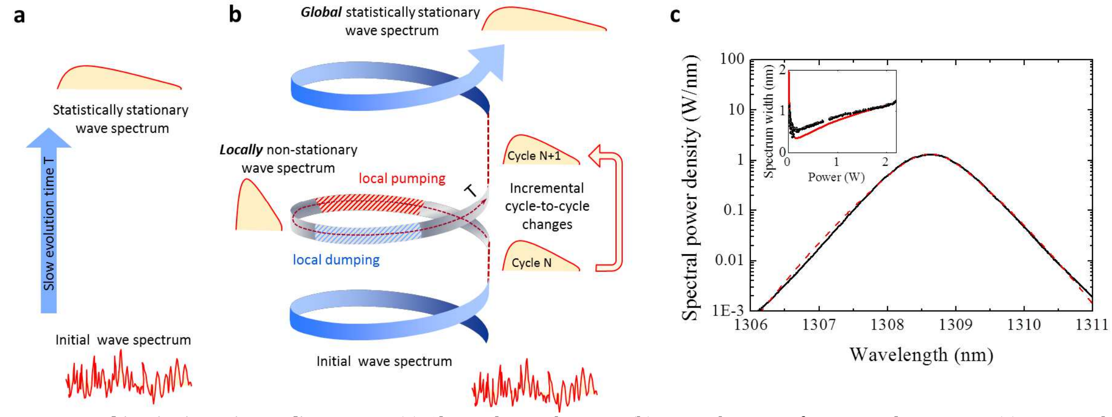

Fig. 1. **Wave kinetics in active cyclic systems.** (a) Classical wave kinetics. (b) Wave kinetics of active cyclic systems. (c) Measured (black line) and calculated within nonlinear kinetic theory (red line) generation spectrum of random fiber laser. At insert: spectrum broadening over generation power in experiment (black) and theory (red).

Here, the derived local wave kinetic equation allows us to formulate a nonlinear kinetic theory of the laser spectrum generalizing the famous linear kinetic theory by Schawlow and Townes [7]. We found in our calculations that depending on the value of the dispersion, the wave spectrum, i.e. the generation spectrum of the random fiber laser, has a different shape. In the case of small dispersion, we found that the laser has a spectrum of the shape of hyperbolic secant.

To experimentally verify the predictions of the developed nonlinear kinetic theory, we designed a random fiber laser. The laser is built using 850 meters of a phosphosilicate fiber. We choose the phosphosilicate fiber because of specific Raman gain profile: it is close to be Gaussian that is important assumption in our theoretical consideration. Under pumping at 1,115 nm, the laser generates at 1,308 nm. We use a random fiber laser configuration with a broadband mirror of a reflectivity close to 100% from one fiber end and only random feedback from other fiber end. Due to the symmetry, this configuration is equivalent to the configuration of the laser having twice a fiber length, no point-based reflectors, and pumped from both fiber ends [4]. In our experiments, we observe the spectrum exactly of hyperbolic secant shape, Fig. 1c. Moreover, the spectral broadening observed experimentally is very similar to those predicted within the nonlinear kinetic theory, Fig. 1c, insert. Thus, we described the generation spectrum of the random fiber laser for the first time. Moreover, we derived first ever nonlinear kinetic theory of the laser spectrum formation.

The general formalism of wave kinetics of active cyclic systems could be applied for various optical systems where stochasticity is important: random lasers of other types, lasers with open or unstable resonators, multi-mode lasers with large number of modes, long-haul fiber transmission links, and other systems. However, it could be applied beyond photonics for description of other non-Hamiltonian systems, which evolve to the statistical equilibrium in cycles: day and year cycles in meteorology, Rayleigh-Taylor instabilities in various media (water, atmosphere, coatings in surfaces).

4. References

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