Disorder-induced acceleration of condensation in multimode fibers

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Recent studies on wave turbulence revealed that a purely classical system of random waves can exhibit a process of condensation, whose thermodynamic properties are analogous to those of Bose-Einstein condensation [1-3]. Classical wave condensation finds its origin in the natural thermalization toward the Rayleigh-Jeans equilibrium distribution, whose divergence is responsible for the macroscopic occupation of the fundamental mode of the system. The experimental study of condensation in a conservative (cavity-less) configuration constitutes a major challenge, because of the prohibitive large propagation lengths required to achieve thermalization. In contrast with this commonly accepted opinion, a remarkable phenomenon of spatial beam self-cleaning has been recently discovered in graded-index multimode optical fibers (MMFs) [4-7]. This phenomenon is due to a purely conservative Kerr nonlinearity [7] and its underlying mechanism still remains debated.

Light propagation in MMFs is known to be affected by a structural disorder of the material due to inherent imperfections and external perturbations. On the basis of the wave turbulence theory, we formulate a nonequilibrium kinetic description of the random waves that accounts for the impact of disorder. The theory reveals that a structural disorder is responsible for a dramatic acceleration of the process of condensation by several orders of magnitudes. This counterintuitive mechanism of condensation acceleration provides a natural explanation for the effect of spatial beam self-cleaning: As a consequence of the fast condensation process, the beam power rapidly flows toward the fundamental mode of the MMF, which becomes macroscopically populated to the detriment of the other modes that exhibit energy equipartition, as predicted by the Rayleigh-Jeans distribution [1]. The simulations of the nonlinear Schrödinger equation (NLSE) are in quantitative agreement with those of the derived kinetic equation, and thus confirm the validity of the theory and the effect of acceleration of condensation mediated by disorder (see Fig. 1). Furthermore, the derived kinetic equation also explains *why spatial beam self-cleaning has not been observed in step-index MMFs*.

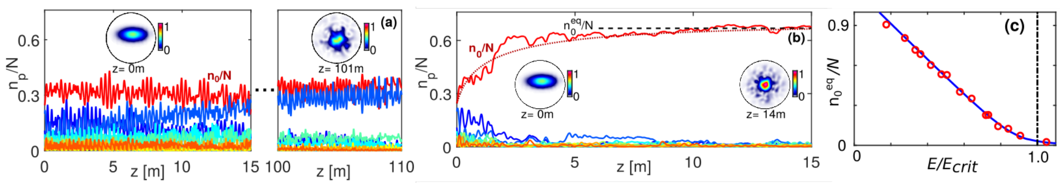

Fig. 1 Disorder-induced spatial beam self-cleaning: Evolutions of the power in the modal components $n_p(z)$ obtained by simulation of the NLSE in the absence of disorder (a), and in the presence of disorder (b), starting from the same initial condition ($p = 0$ red, $p = 1$ dark blue, $p = 2$ blue, $p = 3$ light blue...). The dotted red line in (b) shows the result of the simulation of the derived kinetic equation (same initial condition). (c) Equilibrium condensate fraction n_0^{eq}/N vs kinetic energy E: A phase transition to condensation occurs for $E < E_{\mathrm{crit}}$ (blue line: theory, red circles: NLSE simulations). Parameters: 120 modes of the graded-index MMF, beam power 47.5 kW.

We performed experiments in a MMF to evidence the transition to light condensation by varying the coherence of the input beam (as described in Fig. 1c). When a large number of modes are excited, the output intensity distribution tends to relax toward the thermal Rayleigh-Jeans distribution, i.e., the 'temperature' is above the critical value for condensation ($E > E_{\mathrm{crit}}$ in Fig. 1c) and spatial beam self-cleaning is not observed. By reducing the excitation of modes ($E < E_{\mathrm{crit}}$ in Fig. 1c), the power gradually condenses into the fundamental mode of the MMF, leading to a cleaned beam with a measured condensate fraction as large as $\sim$60%.

Example References

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