Light condensation in multimode fibers

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Abstract: We report the observation of the transition to condensation of optical waves propagating in multimode fibers: below a critical value of the energy, the fundamental mode gets macroscopic populated, in agreement with the equilibrium theory. © 2019

OCIS codes: 190.0190; 030.0030; 060.4370.

1. Introduction

Recent studies on wave turbulence revealed that a purely classical system of random waves can exhibit a process of condensation with thermodynamic properties analogous to those of quantum Bose-Einstein condensation. Classical wave condensation finds its origin in the natural thermalization of the wave system toward the Rayleigh-Jeans (RJ) equilibrium distribution, whose divergence is responsible for the macroscopic occupation of the fundamental mode of the system [1,2].

Different forms of condensation-like effects have been identified in optical cavity systems, which are inherently forced-dissipative systems operating *far from thermal equilibrium*. On the other hand, the observation of condensation mediated by the RJ equilibrium statistics requires a (cavity-less) free propagation of the optical beam in a nonlinear medium. However, as a consequence of the ultraviolet catastrophe inherent to ensemble of classical waves, the RJ condensation is not properly defined in free propagation, so that only a nonequilibrium transient process of condensation is accessible experimentally [2,3]. This problem is circumvented in a waveguide configuration of the optical beam, in which the finite number of modes introduces an effective frequency cut-off [4,5]. In this framework, a remarkable effect of spatial beam self-cleaning has been recently discovered in multimode optical fibers (MMFs) [6-9]. As was pointed out by different approaches [10-13], spatial beam cleaning is characterized by a transfer of power toward the fundamental mode of the MMF. Yet despite experimental progress, there is still no clear-cut demonstration of the process of condensation of classical optical waves.

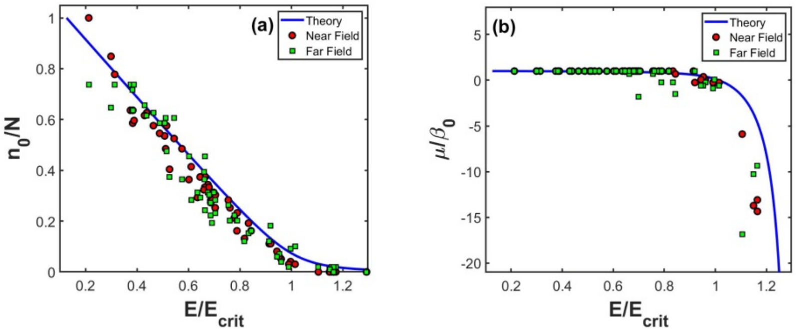

Fig. 1. Experimental measurements of the condensate fraction n_0/N vs energy E/E_{crit} (a), and chemical potential μ vs energy E/E_{crit} (b). Condensation arises when $\mu \to \beta_0$: for $E < E_{\text{crit}}$ the fundamental mode gets macroscopically populated. The solid lines report the theoretical predictions at thermal equilibrium for the considered MMF.

2. Chemical potential and condensate fraction at the transition to condensation

We report in this work experimental evidence of the phase transition to condensation driven by the thermalization to the RJ equilibrium statistics. The experiments are performed in a graded-index MMF (fiber radius R = 26μm). Subnanosecond pulses delivered by a Nd:YAG laser (1.06 μm) are passed through a diffuser before injection of the speckle beam into the MMF. After propagation through a fiber length L = 12m, the near-field (NF) and the far-field (FF) intensity patterns are recorded on a camera. This allowed us to retrieve a measurement of the two conserved quantities during the propagation of the speckle through the MMF: the power $N = \Sigma_p n_p$, and the energy $E = \Sigma_p \beta_p n_p$, where n_p denotes the power in the mode $\{p\}$ and β_p the corresponding eigenvalue of the parabolic potential. The experiment is realized in the weakly nonlinear regime, where the linear length scale $L_{\mathrm{lin}} \sim 1/\beta_0 \sim 0.2$mm is much smaller than the nonlinear length $L_{\mathrm{nl}} \sim 0.5$m, which validates the applicability of the wave turbulence theory [10,11]. Accordingly, during the propagation of the speckle beam, the nonlinearity combined to the structural disorder of the fiber are responsible for an irreversible process of thermalization toward the RJ spectrum $n_p^{\mathrm{eq}} = T/(\beta_p - \mu)$ [10,11], where T and μ are the temperature and the chemical potential. At variance with experiments of photon condensation [14,15], in our case there is no thermostat (heat bath), i.e., we deal with a microcanonical statistical ensemble where the energy E plays a role analogous to the temperature. By decreasing the energy below a critical value E_{crit}, the system exhibits a phase transition to condensation that arises when $\mu \to \beta_0$, which leads to a macroscopic population of the fundamental mode of the MMF. Fig. 1 reports the measurements of μ vs E, and the corresponding fraction of condensed power into the fundamental mode n_0/N vs E. The experimental results are compared to the theory (solid lines) for the considered MMF without using adjustable parameters.

We report in Fig. 2 some examples of the recorded intensity patterns, as well as the corresponding *coherent* contribution from the condensate (fundamental mode $p = 0$), and the incoherent contribution from all the other modes $p \neq 0$. Above threshold ($E > E_{\mathrm{crit}}$), there is no condensation $n_0/N = 0$ and the speckle beam relaxes toward the RJ equilibrium distribution, as revealed by the good agreement with the theoretical FF spectrum.

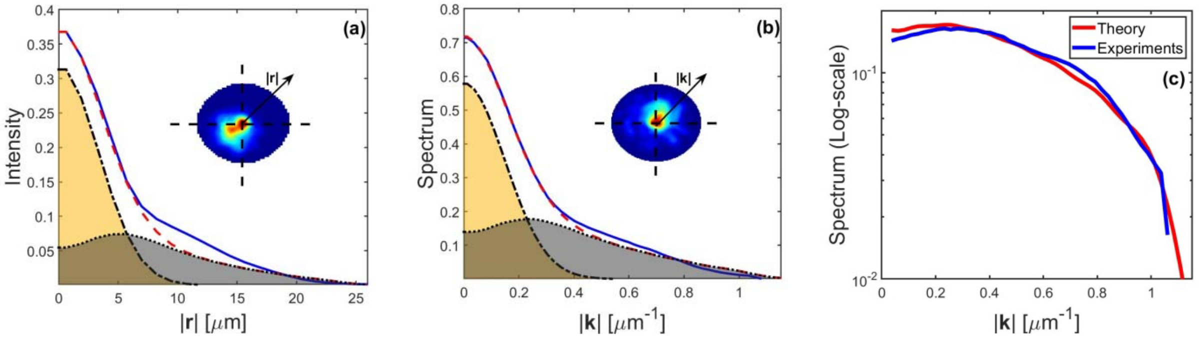

Fig. 2. Examples of experimental profiles in the near-field (n_0/N=0.31) (a), and far-field (n_0/N=0.26) (b), showing the intensity distributions (blue line) averaged over the polar angles (r, k). Corresponding theory showing the condensate contribution from the fundamental mode $p = 0$ (yellow region), the incoherent contribution from $p \neq 0$ (grey region), and their sums (dashed red). (c) Above the transition to condensation ($E > E_{\mathrm{crit}}$, n_0=0), the FF spectrum (blue) is in agreement with the RJ equilibrium distribution (red) – an average over five realizations has been taken (frequency cut-off of the MMF $k_c = 1.15\ \mu\mathrm{m}^{-1}$).

3. Conclusion

We have reported the observation of condensation of classical optical waves. The experiment provides the demonstration of a coherent phenomenon of self-organization that is driven by statistical thermodynamic equilibrium properties of purely classical waves.

4. References

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