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Thermalization of light waves in multimode optical fibers: Negative temperatures equilibrium states and the role of disorder - INVITED

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Abstract. Nonlinear random waves exhibit a phenomenon of irreversible thermalization, in analogy with the thermalization of a classical gas system. This irreversible process of thermalization to the Rayleigh-Jeans equilibrium distribution has been recently observed experimentally in multimode optical fibers. Here we discuss a recent progress along two different directions. Firstly, we report the observation of thermalization to negative temperature equilibrium states, in which high-order fiber modes are more populated than low-order modes. Secondly, we analyze the impact of disorder inherent to light propagation in multimode fibers. We identify an unexpected regime in which strong random coupling among non-degenerate modes leads to a nonequilibrium process of Rayleigh-Jeans thermalization.

1 Introduction

Different studies on wave turbulence revealed that purely classical waves can exhibit a process of condensation that originates from the thermalization of the waves toward the Rayleigh-Jeans (RJ) equilibrium distribution [1]. Recently, the observation of RJ thermalization and condensation of light waves has been reported in multimode optical fibers (MMFs) [2-4], in relation with the discovery of the phenomenon of spatial beam cleaning [5-6]. More recently, RJ thermalization has been extended by including the conservation of orbital angular momentum [7].
In this contribution we present two recent developments: (i) The observation of RJ thermalization to negative temperatures equilibrium states [8]. (ii) The study of the impact of strong disorder (strong random mode coupling) on RJ thermalization [9].

2 Negative temperatures equilibriums

Because of the presence of a finite number of modes supported by the MMF, the propagation constants of the fiber exhibit both lower and upper bounds for the energy levels. Such a bounded spectrum, combined to the nonlinear four-wave interaction, are responsible for the process of RJ thermalization to negative temperature equilibrium states [10]. We report in Fig. 1 the experimental modal distributions for different values of

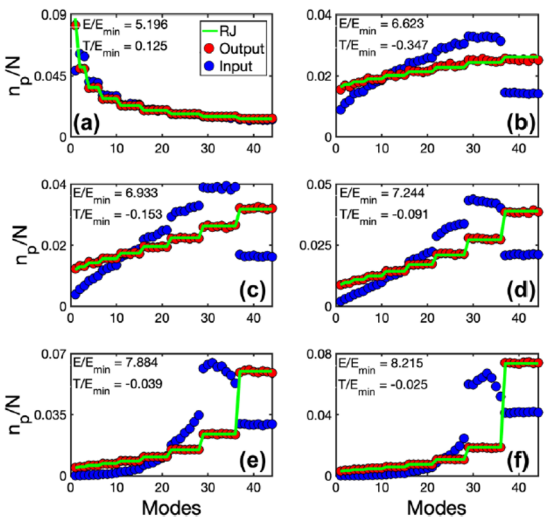

Fig. 1. Negative temperature equilibriums: Experimental modal distributions averaged over realizations at the fiber input (blue), at the fiber output (red). Corresponding RJ theoretical equilibrium (green). The six panels correspond to different values of kinetic energy (E), or equivalently different temperatures T. The modal distribution peaked on the lowest mode for $T > 0$ (a), gets inverted for $T < 0$ (b-f). The fiber modes are sorted from the fundamental one (β_0) to the highest mode group (nine-fold degenerate with $\beta_{max} = 9\beta_0$). Degenerate modes are equally populated at equilibrium, leading to a staircase distribution n_p^{RJ}. From Ref.[8].

the kinetic energy E (i.e., different amount of randomness of the injected speckle beam), while keeping

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constant the power N [8]. At variance with usual positive temperature equilibriums where the fundamental mode is the strongly populated (Fig. 1a), for negative temperatures the modal population is inverted, i.e., the high-order modes are more populated than low-order modes (Fig. 1b-f). Our experiments show that negative temperature speckle beams are featured, in average, by a non-monotonous radial intensity profile, see Fig. 2 [8].

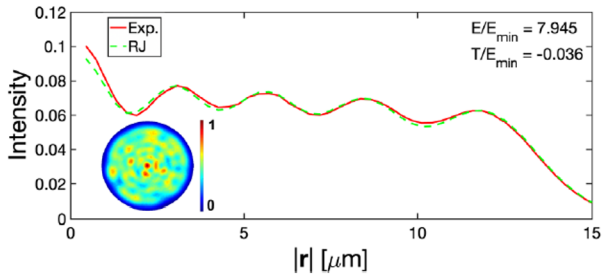

Fig. 2. Oscillating radial intensity distribution at negative temperatures. Experimental intensity distribution averaged over the realizations as a function of the radial distance (red). Note the quantitative agreement (without free parameters) with the theoretical RJ intensity distribution (dashed green). The oscillating behaviour of the intensity distribution is a signature of the negative temperature equilibrium. Inset: corresponding 2D intensity averaged over the realizations (the radius of the circle is the fiber radius). From Ref.[8].

3 Impact of strong disorder

Light propagation in MMFs is affected by a structural disorder of the material, i.e., linear random coupling among the modes [9,11,12]. While the impact of weak random mode coupling has been shown to accelerate the rate of thermalization [11], strong mode coupling has not been the subject of detailed investigations [9]. At variance with weak disorder, strong disorder involves a random coupling among non-degenerate modes, which prevents the conservation of the kinetic energy (Hamiltonian) through the propagation in the MMF. As a consequence, strong disorder prevents light thermalization to the RJ distribution, and, in this way, it should also prevent beam cleaning condensation.

In order to study the impact of strong disorder on light thermalization, we have extended the wave turbulence theory by including the impact of strong random mode coupling [9]. The derived kinetic equation unveils the interplay of disorder and nonlinearity. In particular, it unexpectedly reveals that a nonequilibrium process of condensation and thermalization can take place in the presence of strong disorder, see Fig. 3. We have validated the theory by numerical simulations of the nonlinear Schrödinger equation and the derived kinetic equation, which are found in quantitative agreement without adjustable parameters, see Fig. 3. Experiments realized in MMFs with an applied external stress evidence the process of thermalization in the presence of strong disorder [9].

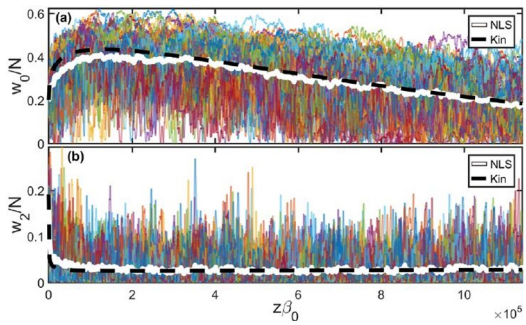

Fig. 3. Impact of strong disorder: Numerical simulations showing the evolution of the power fraction in the fundamental fiber mode (a) and the third fiber mode (b), during the propagation through the MMF (in units of $1/\beta_0$): for the NLS equation (64 realizations are reported with coloured lines; the bold white line is the corresponding average), and for the wave turbulence kinetic equation (dashed black line). The system exhibits an incipient process of RJ thermalization and nonequilibrium condensation characterized by a growth of the condensate amplitude for short propagation lengths. Disorder subsequently prevails, which induces a decay of the condensate amplitude and eventually brings the system to an equilibrium of power equipartition among the modes. From Ref.[9].

4 Conclusion

Bringing negative temperatures to MMFs opens the door to the investigation of fundamental issues of negative temperature states in a flexible experimental environment. In addition, extending wave turbulence to disordered systems sheds new light on complex systems and the interplay between disorder and nonlinearity.

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