

Classical light thermalization toward negative temperature equilibrium states in optical fibers and extension to the quantum regime

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Abstract.

We report the observation of classical light thermalization to the negative temperature Rayleigh-Jeans (RJ) equilibrium states. We extend theoretically these equilibrium states to the Bose-Einstein quantum regime (BE) through the analysis of the thermodynamic properties.

1 Introduction

In analogy with gas thermalization, classical optical waves propagating in multimode optical fibers (MMF) can exhibit a thermalization to a RJ equilibrium state. This thermalization process has been recently observed experimentally [1–3], in relation with the spatial beam-cleaning effect [4]. We report the observation of light thermalization to negative temperature RJ equilibrium states [5], and extend theoretically this study to the quantum regime [6].

2 Negative temperature equilibria

Contrary to a classical gas where the kinetic energy can increase freely, the kinetic energy of a speckle beam propagating in a MMF is bounded, due to the finite number of guided modes. By combining this property with the Kerr nonlinearity, we have reported the observation of light thermalization in graded-index MMFs to negative temperature equilibrium states [5]. Fig.1b,c report the experimental modal distributions for two different kinetic energies E (i.e. different initial modal occupations), keeping the total power N constant [5]. At variance with usual positive temperature equilibrium featured by a modal distribution peaked on the fundamental fiber mode (Fig.1b), for negative temperatures, the distribution is inverted – higher-order modes are more populated than low-order modes (Fig.1c).

Recent works indicate that the Bose-Einstein distribution (BE) can fit the experimental results obtained in multimode optical fibers [7]. We therefore have extended the thermodynamic equilibrium properties studied in the classical RJ regime to the quantum regime. We have obtained a general formulation of the thermodynamic equilibrium properties including the RJ and BE regimes as particular limit cases.

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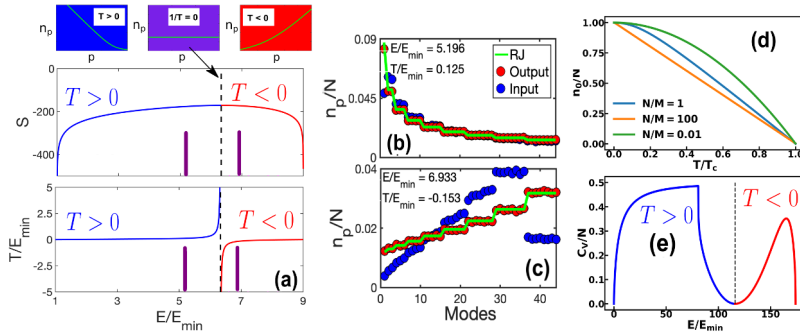


Figure 1. (a) Entropy S , and temperature T , vs kinetic energy E : the decrease of S with E implies negative temperatures, $1/T = (\partial S/\partial E)_N < 0$. (b)-(c) Experimental modal distributions averaged over realizations at the input (blue), and output (red), of the fiber, and the corresponding equilibrium RJ distribution (green), for $T > 0$ (b), and $T < 0$ (c). Panels (b,c) correspond to the two values of E indicated by purple lines in (a). The distribution peaked on the fundamental mode for $T > 0$ (b), gets inverted for $T < 0$ (c). The modes are sorted from the fundamental (mode 0) to the highest order one (mode 45). (d) Condensate fraction n_0/N versus T/T_c for RJ ($N \gg M$), BE ($N \ll M$), and intermediate regime $N \simeq M$, where M is the number of fiber modes, N the number of photons. (e) Specific heat C_V/N vs $E/E_{\min}$ for $N = M$, which exhibits hybrid properties from the BE and RJ regimes ($E_{\min}$ is the lowest energy level).

The specific heat C_V is known as an important quantity that characterizes the phase transition to BE condensation. Due to the quantum properties of frozen degrees of freedom, $C_V \rightarrow 0$ for $E \rightarrow 0$ (or $T \rightarrow 0$), which is in contrast with the classical RJ property of energy equipartition $C_V \rightarrow M$ for $E \rightarrow 0$, see [1]. Notice in Fig.1e the presence of a cusp on the slope of C_V at the condensation phase transition for $T = T_c > 0$. However, for $T < 0$, the singularity of C_V is smoothed out, because the inverted condensation toward a macroscopic population of the highest energy level is not a phase transition [6].

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