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Towards strongly correlated photons in arrays of dissipative nonlinear cavities under a frequency-dependent incoherent pumping

Gaz de photons fortement interagissant dans un réseau de cavités, en présence de pertes et de pompage incohérent dépendant de la fréquence

José Lebreuilly [a,b,*], Michiel Wouters [c], Iacopo Carusotto [b,1]

[a] *Département de physique de l'École normale supérieure, 24, rue Lhomond, 75231 Paris, France*
[b] *INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, via Sommarive 14, 38123 Povo, Italy*
[c] *TQC, Universiteit Antwerpen, Universiteitsplein 1, B-2610 Antwerpen, Belgium*

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ABSTRACT

We report a theoretical study of a quantum optical model consisting of an array of strongly nonlinear cavities incoherently pumped by an ensemble of population-inverted two-level atoms. Projective methods are used to eliminate the atomic dynamics and write a generalized master equation for the photonic degrees of freedom only, where the frequency-dependence of gain introduces non-Markovian features. In the simplest single cavity configuration, this pumping scheme gives novel optical bistability effects and allows for the selective generation of Fock states with a well-defined photon number. For many cavities in a weakly non-Markovian limit, the non-equilibrium steady state recovers a Grand-Canonical statistical ensemble at a temperature determined by the effective atomic linewidth. For a two-cavity system in the strongly nonlinear regime, signatures of a Mott state with one photon per cavity are found.
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RÉSUMÉ

Nous présentons l'étude d'un modèle d'optique quantique consistant en un réseau de cavités fortement non linéaires en présence de pompage incohérent induit par un ensemble d'atomes à deux niveaux, avec inversion de population. Nous appliquons une méthode projective afin d'éliminer les degrés de liberté atomiques, et dérivons une équation maîtresse généralisée contenant uniquement les degrés de liberté photoniques, dans laquelle le pompage dépendant de la fréquence induit des effets non markoviens. Dans le cas simple d'une cavité, cette méthode de pompage induit de nouveaux effets de bistabilité et permet la création d'états de Fock avec un nombre défini de photons. Dans le cas de plusieurs cavités dans un régime faiblement non markovien, l'état stationnaire hors équilibre prend la forme d'un ensemble grand-canonique, dont la température effective est définie

* Corresponding author at: INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, via Sommarive 14, 38123 Povo, Italy.
E-mail addresses: jose.lebreuilly@unitn.it (J. Lebreuilly), carusott@science.unitn.it (I. Carusotto).
[1] Fax: +39 0461 282014.

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par la largeur du spectre d'émission des atomes. Dans une configuration à deux cavités, en régime fortement non linéaire, nous observons la signature d'un état de Mott avec un photon par site.

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1. Introduction

The study of quantum many-body systems is one of the most active fields of modern condensed-matter physics. Among the most celebrated effects, we can mention frictionless flows in superfluid and superconducting systems and the geometrical quantization features of the fractional quantum Hall effect. While this physics was traditionally studied in liquid Helium samples [1,2], in atomic nuclei [3], in quark–gluon plasmas [4,5], or in electron gases confined in solid-state devices [6–9], the last two decades have witnessed impressive advances using ultra-cold atomic gases trapped in magnetic or optical traps [10–12].

In the last few years, a growing community has started investigating many-body effects in the novel context of the so-called quantum fluids of light [13], i.e. assemblies of many photons confined in suitable optical devices, where effective photon–photon interactions arise from the optical nonlinearity of the medium. After the pioneering studies of Bose–Einstein condensation [14] and superfluidity [15] effects in dilute photon gases in weakly nonlinear media, a great interest is presently being devoted to strongly nonlinear systems, where even single photons are able to appreciably affect the optical properties of the system.

The most celebrated example of such physics is the photon blockade effect [16], where the presence of a single photon in a cavity is able to detune the cavity frequency away from the pump laser, so that photons behave as effectively impenetrable particles. Experimental realizations of this idea have been reported by several groups using very different material platforms, from single atoms in macroscopic cavities [17] to single quantum dots in photonic crystal cavities [18,19] or to single Josephson qubits in circuit QED devices for microwaves [20,21].

Scaling up to arrays of many cavities coupled by photon tunneling is presently a hot challenge in experimental physics, as it would realize a Bose–Hubbard model for photons where the photon blockade effect may lead to a rich physics, including the superfluid to Mott-insulator phase transition at a commensurate filling or Tonks–Girardeau gases of impenetrable photons in one-dimensional continuum models. The first works on strongly correlated photons were restricted to quasi-equilibrium regimes where the photon loss rate is much slower than the internal dynamics of the gas so that the system has time to thermalize and/or be adiabatically transferred to the desired strongly correlated state [22,23]. While this assumption might be satisfied in suitably designed circuit-QED devices in the microwave domain, radiative losses are hardly negligible in realistic optical cavities in the infrared or visible domain, so that thermalization is generally far from being granted [13,21].

As a result, a very active attention has been recently devoted to the peculiar non-equilibrium effects that arise for realistic loss rates. Starting from the pioneering work on photon blockade in non-equilibrium photonic Josephson junctions [24], the interest has been focused on the study of schemes to generate strongly correlated many-body states in the very non-equilibrium context of photon systems, where the steady state is not determined by a thermal equilibrium condition, but by a dynamical balance of driving and losses.

The first such scheme proposed in [25] was based on a coherent pumping: provided the different many-body states are sufficiently separated in energy, many-photon processes driven by the coherent external laser are able to selectively address each many-body state as done in optical spectroscopy of atomic levels. In this way, the non-equilibrium condition is no longer just a hindrance, but offers new perspectives, as it allows one to individually probe each excited state. Furthermore, the appreciable radiative losses make microscopic information on the many-body wavefunction be directly encoded in the quantum coherence of the secondary emission from the device [26–28]. While this coherent pumping scheme offers a viable way to generate and control few photon states in small arrays, its efficiency is restricted to mesoscopic systems where the different states are well separated in energy. Moreover, this scheme intrinsically leads to coherent superpositions of states of different photon number: while this feature is intriguing in view of observing many-body braiding phases [28], it is not ideally suited to generate states with a well-defined photon number such as Mott-insulator states.

The identification of new schemes that do not suffer from these limitations is therefore of great importance in view of experiments. In the present work, we study the potential of frequency-dependent gain processes to selectively generate strongly correlated states of photons in arrays of strongly nonlinear cavities. The frequency-dependence of amplification is a well-known fact of laser physics and is often exploited to choose and stabilize a desired lasing mode [29]. In the last years, a series of works by our groups [30,31] have explored its effect on exciton-polariton Bose–Einstein condensation experiments, in particular questioning the apparent thermalization of the non-condensed fraction [32–36]. All these works were however restricted to the weakly interacting regime where quantum fluctuations can be treated in the input–output language by means of a Bogoliubov-like linearized theory around the mean field. Here we tackle the far more difficult case of strong nonlinearities, which requires including the non-Markovian features due to the frequency-dependent gain into the

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