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A quantum photonic dissipative transport theory

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ABSTRACT

In this paper, a quantum transport theory for describing photonic dissipative transport dynamics in nanophotonics is developed. The nanophotonic devices concerned in this paper consist of on-chip all-optical integrated circuits incorporating photonic bandgap waveguides and driven resonators embedded in nanostructured photonic crystals. The photonic transport through waveguides is entirely determined from the exact master equation of the driven resonators, which is obtained by explicitly eliminating all the degrees of freedom of the waveguides (treated as reservoirs). Back-reactions from the reservoirs are fully taken into account. The relation between the driven photonic dynamics and photocurrents is obtained explicitly. The non-Markovian memory structure and quantum decoherence dynamics in photonic transport can then be fully addressed. As an illustration, the theory is utilized to study the transport dynamics of a photonic transistor consisting of a nanocavity coupled to two waveguides in photonic crystals. The controllability of photonic transport through the external driven field is demonstrated.

1. Introduction

With the rapid development of nanotechnology, all-optical photonic circuits embedded in nanoscale photonic crystals have received tremendous attention [1,2]. The on-chip all-optical integrated circuits are considered as the promising nanophotonic devices for robust interconnect networks used in optical communication. Photonic crystals are artificial nanomaterials with periodic refractive index. The photonic band gap (PBG) structures together with characteristic dispersion properties make the light manipulation and transmission much more efficient. For examples, strong light

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confinement can be realized by introducing point defect (nanocavity) in photonic crystals [3], slow lights can be generated by waveguide structures with controllable dispersion properties, which can be implemented by introducing line defects or series of coupled point defects in photonic crystals [4,5]. Various novel nanophotonic devices have been constructed or proposed by the combinations of different defects with PBG structures, such as optical switches [6], filters [7], memory devices [8] and on-chip single photon guns [9]. Furthermore, with the new development of the semiconductor nanofabrication techniques, many tunable functional nanophotonic devices have also been proposed and modeled recently. Different techniques are utilized to characterize various physical properties in these nanophotonic devices. In particular, properties such as the resonance frequency of a nanoresonator or the band structure of a waveguide can be tuned by changing the refractive index of the photonic crystal through thermooptic effect [10], electrooptical effect [11], fluid insertion [12], or even by mechanically changing the structure of the photonic crystal [13]. Couplings between different elements in a photonic circuit can be controlled by nanoelectromechanical systems [14]. These dynamical tunable nanodevices greatly expand their applications in photonic integrated circuitry and further stimulate the potential application in quantum information processing.

To achieve the goal of quantum information processing in terms of all-optical processing, information carriers should be individual photons. Photonic transmission processes in nanophotonics should be performed in an ultrafast and well-controllable way. In such a situation, the nanophotonic devices are far away from equilibrium, then the non-Markovian memory and quantum decoherence dynamics dominate the photonic transport. Thus, a fundamental quantum transport theory that can incorporate with the non-Markovian memory structure and quantum decoherence dynamics for photonic transmission is highly demanded.

In fact, non-Markovian dynamics in quantum optics has been extensively studied for a few-level atom placed inside photonic crystals [15,16]. The typical features of the non-Markovian dynamics include atomic population trapping (inhibition of spontaneous emission), strong localization of light, formulation of atom–photon bound states, and collective switching behavior in the vicinity of the PBG [17–21]. These features can be determined exactly from the Schrödinger equation of an atomic-photon state contains only a single photon, or using a perturbative expansion to the Heisenberg equation of motion in the weak coupling limit of the atom-field interacting with the reservoir. When the number of photon increases or the perturbation break down, the problem becomes intractable. The general non-Markovian dynamics involving arbitrary number of photons at arbitrary temperature for a structured reservoir has not been fully understood. Recently, we have utilized the exact master equation of a micro/nano cavity coupled to a general thermal reservoir or a structured reservoir in photonic crystals to study non-perturbatively various non-Markovian processes involving arbitrary number of photons at an arbitrary temperature [22,23]. However, a quantum photonic transport theory describing photonic transmission dynamics in all-optical nanophotonic circuits has not yet been established.

A fundamental quantum transport theory should be treated in a fully nonequilibrium way. Modern nonequilibrium physics was developed based on the Schwinger–Keldysh nonequilibrium Green function technique [24,25] and the Feynman–Vernon influence functional approach [26]. The nonequilibrium Green function technique allows a systematic perturbative [27] and also a non-perturbative [28] study for various nonequilibrium phenomena in many-body electronic systems. It has become a very powerful tool in the study of quantum electron transport in mesoscopic physics [29]. However, such an approach has not been utilized to investigate photonic transport in all-optical processing. Besides, the non-Markovian memory structure and the quantum decoherence dynamics have not been well explored in terms of the nonequilibrium Green functions in the transient quantum transport. On the other hand, the Feynman–Vernon influence functional approach [26] has been widely used to study the dissipation dynamics in quantum tunneling problems [30] and the decoherence dynamics in quantum measurement theory [31]. It is particularly useful in the derivation of the exact master equation for the quantum Brownian motion (QBM), achieved by completely integrating out the environmental degrees of freedom through the functional integral [32,33]. The QBM is modeled as a central harmonic oscillator linearly coupled to a thermal bath simulated by a set of harmonic oscillators. Applications of the QBM exact master equation cover various topics, such as quantum decoherence, quantum-to-classical transition, and quantum measurement theory,