Few-photon transport in low-dimensional systems: Interaction-induced radiation trapping

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(Dated: November 1, 2018)

We present a detailed analysis of the dynamics of photon transport in waveguiding systems in the presence of a two-level system. In these systems, quantum interference effects generate a strong effective optical nonlinearity on the few-photon level. We clarify the relevant physical mechanisms through an appropriate quantum many-body approach. Based on this, we demonstrate that a single-particle photon-atom bound state with an energy outside the band can be excited via multi-particle scattering processes. We further show that these trapping effects are robust and, therefore, will be useful for the control of photon entanglement in solid-state based quantum optical systems.

PACS numbers: 42.50.Nn, 42.50.-p, 42.50.Gy, 42.70.Qs

Over the past years, the conception and development of solid-state based quantum optical functional elements have received steadily increasing interest [1–3]. As compared to other approaches, solid-state-based systems offer an obvious scalability and handling advantage of the resulting devices as well as the utilization of modified light-matter interactions through judicious designs of the corresponding waveguides' dispersion relations and/or mode profiles.

However, since high-quality samples such as coupled-optical-resonator-waveguide arrays (CROWs) [4, 5] have become available only recently, there is limited theoretical work regarding the potential of utilizing modified light-matter interaction in (effectively) low-dimensional quantum-optical systems. The basic underlying problem, i.e., that of a system with discrete levels that is coupled to a continuum of states has attracted attention for a long time [6]. For single photons, quantum interference effects in one-dimensional waveguides with an embedded quantum impurity allow the realization of effective energy-dependent mirrors [7–9]. For two or more photons, this system induces an effective photon-photon interaction and even bound photon-photon states that may be exploited for efficient control of photon-entanglement [12–14]. Except for our work on the one-photon case [9], all of the above calculations have been carried out in the stationary regime. In particular, the more challenging few-photon case has been addressed with sophisticated Bethe-Ansatz [12, 13] and Lehmann-Symanzik-Zimmermann reduction techniques [14] that allow one to determine the corresponding scattering matrices for such systems. However, these field-theoretical approaches employ linearized dispersion relations without band edges.

In the present Letter, we apply our computational framework of time-domain simulations using Krylov-subspace-based operator-exponential methods [9, 10] to the case of few-photon transport through a quantum impurity in a one-dimensional waveguiding system similar to wave packet dynamics in electronic systems [10, 11]. This allows us to analyze the scattering of two or more photons at the quantum impurity in a very general way. In particular, for a cosine-type dispersion relation, we are able to confirm the existence of two bound photon-atom states [14]. Furthermore, we show how these states can be excited and controlled through the photon-nonlinearity that is induced by the quantum impurity. This elucidates the mechanism through which the quantum impurity can be utilized for controlling photon-entanglement. In the field-theoretical approaches discussed above [12–14], the photon-atom bound states are (due to the absence of band edges) energetically shifted to infinity and are thus removed from the physically accessible Hilbert space.

Starting from the well-known Dicke-Hamiltonian [15], we can derive a tight-binding Hamiltonian that describes photon propagation in an effectively one-dimensional waveguide with cosine-type dispersion relation (such as the CROWs of Refs. [4, 5]) that is coupled to a quantum impurity as [9]

$$\begin{aligned} \hat{H} \;&=\; -J \sum_{x=1}^{N-1} \left(a_x^\dagger a_{x+1} + a_{x+1}^\dagger a_x \right) + \frac{\Omega}{2}\sigma_z \\ &\quad + V \left(a_{x_0}\sigma_+ + a_{x_0}^\dagger \sigma_- \right). \end{aligned} \tag{1}$$

Here, $a_x^\dagger$ and a_x denote, respectively, bosonic (photon) creation and annihilation operators at lattice site x and J