Limitations of two-level emitters as nonlinearities in two-photon controlled-PHASE gates

We investigate the origin of imperfections in the fidelity of a two-photon controlled-PHASE gate based on two-level-emitter nonlinearities. We focus on a passive system that operates without external modulations to enhance its performance. We demonstrate that the fidelity of the gate is limited by opposing requirements on the input pulse width for one- and two-photon-scattering events. For one-photon scattering, the spectral pulse width must be narrow compared with the emitter linewidth, while two-photon-scattering processes require the pulse width and emitter linewidth to be comparable. We find that these opposing requirements limit the maximum fidelity of the two-photon controlled-PHASE gate to 84% for photons with Gaussian spectral profiles.

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Few-photon Non-linearities in Nanophotonic Devices for Quantum Information Technology

In this thesis we investigate few-photon non-linearities in all-optical, on-chip circuits, and we discuss their possible applications in devices of interest for quantum information technology, such as conditional two-photon gates and single-photon sources. In order to propose efficient devices, it is crucial to fully understand the non-equilibrium dynamics of strongly interacting photons. Employing both numerical and analytical approaches we map out the full scattering dynamics for two photons scattering on a two-level emitter in a one-dimensional waveguide. The strongest non-linear interaction arise when the emitter is excited the most, which occurs for incoming photon pulses with a spectral bandwidth comparable to the emitter linewidth. For two identical, counter-propagating photons, the emitter works as a non-linear beam splitter, as the emitter induces strong directional correlations between the scattered photons. Even though the non-linearity also alters
the pulse spectrum due to a four-wave mixing process, we demonstrate that input pulses with a Gaussian spectrum can be mapped to the output with up to 80% fidelity. Using two identical two-level emitters, we propose a setup for a deterministic controlled-phase gate, which preserves the properties of the two incoming photons with almost 80%, limited by spectral changes induced by the non-linearity and phase modulations upon scattering. Another setup for a controlled-phase operation is suggested with two coupled ring resonators exploiting a strong second-order material non-linearity. By dynamically trapping the first of two temporally separated photons in the non-linear resonator, the scattering of the second photon is altered. Due to the trapping, the undesired aforementioned non-linear effects are avoided, but the gate performance is now limited by the capturing process. Semiconductor quantum dots (QDs) are promising for realizing few-photon non-linearities in solid-state implementations, although coupling to phonon modes in the surrounding lattice have significant influence on the dynamics. By accounting for the commonly neglected asymmetry between the electron and hole wavefunction in the QD, we show how the phonon-assisted transition rate to a slightly detuned optical mode may be suppressed. This is achieved by properly matching the electrical carrier confinement with the deformation potential interaction, where the suppression only occurs in materials where the deformation potential interaction shifts the electron and hole bands in the same direction. We demonstrate also how the phonon-induced effects may be altered by placing the QD inside an infinite slab, where the confinement of the phonons is modified instead. For a slab thickness below ~ 70 nm, the bulk description of the phonon modes may be insufficient. The QD decay rate may be strongly increased or decreased, depending on how the detuning between the QD and the optical mode matches the phonon modes in the slab.

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Scattering of two photons on a quantum emitter in a one-dimensional waveguide: exact dynamics and induced correlations
We develop a wavefunction approach to describe the scattering of two photons on a quantum emitter embedded in a one-dimensional waveguide. Our method allows us to calculate the exact dynamics of the complete system at all times, as well as the transmission properties of the emitter. We show that the nonlinearity of the emitter with respect to incoming photons depends strongly on the emitter excitation and the spectral shape of the incoming pulses, resulting in transmission of the photons which depends crucially on their separation and width. In addition, for counter-propagating pulses, we analyze the induced level of quantum correlations in the scattered state, and we show that the emitter behaves as a nonlinear beam-splitter when the spectral width of the photon pulses is similar to the emitter decay rate.

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Strong nonlinearity-induced correlations for counterpropagating photons scattering on a two-level emitter
We analytically treat the scattering of two counterpropagating photons on a two-level emitter embedded in an optical waveguide. We find that the nonlinearity of the emitter can give rise to significant pulse-dependent directional correlations in the scattered photonic state, which could be quantified via a reduction in coincidence clicks in a Hong–Ou–Mandel measurement setup, analogous to a linear beam splitter. Changes to the spectra and phase of the scattered photons, however, would lead to reduced interference with other photons when implemented in a larger optical circuit. We introduce suitable fidelity measures which account for these changes and find that high values can still be achieved even when accounting for all properties of the scattered photonic state.

Measuring the effective phonon density of states of a quantum dot in cavity quantum electrodynamics
We employ detuning-dependent decay-rate measurements of a quantum dot in a photonic-crystal cavity to study the influence of phonon dephasing in a solid-state quantum-electrodynamics experiment. The experimental data agree with a microscopic non-Markovian model accounting for dephasing from longitudinal acoustic phonons, and the analysis explains the difference between nonresonant cavity feeding in different nanocavities. From the comparison between experiment and theory we extract the effective phonon density of states experienced by the quantum dot in the nanocavity. This quantity determines all phonon dephasing properties of the system and is found to be described well by a theory of bulk phonons.
Proposed Quenching of Phonon-Induced Processes in Photoexcited Quantum Dots due to Electron-Hole Asymmetries

Differences in the confinement of electrons and holes in quantum dots are shown to profoundly impact the magnitude of scattering with acoustic phonons. Using an extensive model that includes the non-Markovian nature of the phonon reservoir, we show how the effect may be addressed by photoluminescence excitation spectroscopy of a single quantum dot. We also investigate the implications for cavity QED, i.e., a coupled quantum dot-cavity system, and demonstrate that the phonon scattering may be strongly quenched. The quenching is explained by a balancing between the deformation potential interaction strengths and the carrier confinement and depends on the quantum dot shape. Numerical examples suggest a route towards engineering the phonon scattering.

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Non-Markovian phonon dephasing of a quantum dot in a photonic-crystal nanocavity

Single quantum dots (QDs) can be embedded in nanocavities in order to enhance the interaction with a single mode of the electromagnetic field, thereby making them candidates for applications in quantum information systems. In this work [1], we investigate the coupling between single QDs and localized modes in photonic crystal (PC) cavities. From measurements of the detuning-dependent decay rate of a QD embedded in an L3 PC cavity we find a surprisingly broadband enhancement of the decay rate, cf. Fig. 1, which cannot be explained using the standard approach of a dissipative Jaynes-Cummings (JC) model. Similar measurements on a single QD tuned through an Anderson localized (AL) mode [2] in a PC waveguide show that in this system the decay rates closely follow the JC model.

We introduce a novel microscopic model taking the interaction with longitudinal-acoustic (LA) phonons into account. Using this model, we are able to explain the broadband enhancement in an L3 cavity, and the quantitative difference compared to the AL-cavity arises from a larger background decay rate in the AL-cavity due to the presence of leaky radiation modes.
The concept of the effective phonon density of states (DOS) is introduced, which determines the rate of phonon-assisted spontaneous emission. If, e.g., the QD is blue-detuned from the cavity mode, the QD can emit a photon into the cavity mode by emitting the residual energy as a phonon [3]. Our microscopic model allows us to extract the effective phonon DOS, that turns out to agree with a model for bulk phonons.

Reducing dephasing in coupled quantum dot-cavity systems by engineering the carrier wavefunctions

We demonstrate theoretically how photon-assisted dephasing by the electron-phonon interaction in a coupled cavity-quantum dot system can be significantly reduced for specific QD-cavity detunings. Our starting point is a recently published theory, which considers longitudinal acoustic phonons, described by a non-Markovian model, interacting with a coupled quantum dot-cavity system. The reduction of phonon-induced dephasing is obtained by placing the cavity-quantum dot system inside an infinite slab, assuming spherical electronic wavefunctions. Based on our calculations, we expect this to have important implications in single-photon sources, allowing the indistinguishability of the photons to be improved.

Suppressing electron-phonon interactions in semiconductor quantum dot systems by engineering the electronic wavefunctions

It is well-known that decoherence deteriorates the efficiency of cavity QED systems containing quantum dots (QDs), and that a major contribution stems from the coupling between the electrical carriers in the QD and acoustic phonons [1]. Employing a recently published model [2], we demonstrate how a proper matching between the electronic wavefunction and the phonon-induced energy shift of valence and conduction band may be exploited to change the decoherence and
decay properties of the QD by suppressing the phonon-induced processes. This effect may be addressed in a photoluminescence experiment, where a CW laser excites a two-level QD which interacts with a non-Markovian reservoir of acoustical phonons, see Fig. 1a. We assume a simple harmonic confinement of the electronic carriers, resulting in Gaussian wavefunctions, \((r) / \exp[-r^2/(2W^2)]\), with \(W_e\) (\(W_h\)) being the width of the electron (hole) wavefunction. In Fig. 1b we plot the stationary QD population vs. the laser frequency. We observe that for non-equal electron and hole wavefunction, the phonon-induced effect on the population surprisingly is fully suppressed at specific detunings. In a coupled QD–cavity system [2, 3], see Fig. 2a, this effect causes the QD lifetime to be unaffected by phonon processes at specific QD-cavity detunings. Furthermore, as shown in Fig. 2b, a proper choice of the QD wavefunction minimizes the phonon-induced pure dephasing rate, both in terms of the short-time magnitude and the long-time constant value. Furthermore we show, that even for realistic QDs, where \(W_e\) and \(W_h\) are determined by the QD shape and material composition, a significant suppression of phonon-induced processes is possible. Thus, more efficient quantum systems may be obtained if the QD wavefunctions are properly matched with the phononic properties of the surroundings.

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