Cavity-waveguide interplay in optical resonators and its role in optimal single-photon sources

Interfacing solid-state emitters with photonic structures is a key strategy for developing highly efficient photonic quantum technologies. Such structures are often organized into two distinct categories: nanocavities and waveguides. However, any realistic nanocavity structure simultaneously has characteristics of both a cavity and waveguide, which is particularly pronounced when the cavity is constructed using low-reflectivity mirrors in a waveguide structure with good transverse light confinement. In this regime, standard cavity quantum optics theory breaks down, as the waveguide character of the underlying dielectric is only weakly suppressed by the cavity mirrors. By consistently treating the photonic density of states of the structure, we provide a microscopic description of an emitter including the effects of phonon scattering over the full transition range from waveguide to cavity. This generalized theory lets us identify an optimal regime of operation for single-photon sources in optical nanostructures, where cavity and waveguide effects are concurrently exploited.
Driving-induced population trapping and linewidth narrowing via the quantum Zeno effect

We investigate the suppression of spontaneous emission from a driven three-level system embedded in an optical cavity via a manifestation of the quantum Zeno effect. Strong resonant coupling of the lower two levels to an external optical field results in a decrease of the decay rate of the third upper level. We show that this effect has observable consequences in the form of emission spectra with subnatural linewidths, which should be measurable using, for example, quantum dot-cavity systems in currently obtainable parameter regimes, and may find use in applications requiring the control of single-photon arrival times and wave-packet extent. These results suggest an underappreciated link between the Zeno effect, dressed states, and Purcell enhancement.
Intrinsic and environmental effects on the interference properties of a high-performance quantum dot single-photon source

We report a joint experimental and theoretical study of the interference properties of a single-photon source based on an In(Ga)As quantum dot embedded in a quasiplanar GaAs microcavity. Using resonant laser excitation with a pulse separation of 2 ns, we find near-perfect interference of the emitted photons, and a corresponding indistinguishability of $I = (99.6 \pm 0.4 \pm 1.4)\%$. For larger pulse separations, quasiresonant excitation conditions, increasing pump power, or with increasing temperature, the interference contrast is progressively and notably reduced. We present a systematic study of the relevant dephasing mechanisms and explain our results in the framework of a microscopic model of our system. For strictly resonant excitation, we show that photon indistinguishability is independent of pump power, but strongly influenced by virtual phonon-assisted processes which are not evident in excitonic Rabi oscillations.

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We investigate the role of phonons on the emission properties of solid-state single photon sources. We demonstrate a fundamental trade-off between indistinguishability and efficiency of sources based on both cavity and waveguide architectures.

**Phonon limit to simultaneous near-unity efficiency and indistinguishability in semiconductor single photon sources**

We investigate the role of phonons on the emission properties of solid-state single photon sources. We demonstrate a fundamental trade-off between indistinguishability and efficiency of sources based on both cavity and waveguide architectures.

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Phonon scattering inhibits simultaneous near-unity efficiency and indistinguishability in semiconductor single-photon sources

Semiconductor quantum dots (QDs) have recently emerged as a leading platform to generate highly indistinguishable photons efficiently, and this work addresses the timely question of how good these solid-state sources can ultimately be. We establish the crucial role of lattice relaxation in these systems in giving rise to trade-offs between indistinguishability and efficiency. We analyse the two source architectures most commonly employed: a QD embedded in a waveguide and a QD coupled to an optical cavity. For waveguides, we demonstrate that the broadband Purcell effect results in a simple inverse relationship, in which indistinguishability and efficiency cannot be simultaneously increased. For cavities, the frequency selectivity of the Purcell enhancement results in a more subtle trade-off, in which indistinguishability and efficiency can be increased simultaneously, although not arbitrarily, which limits a source with near-unity indistinguishability (> 99%) to an efficiency of approximately 96% for realistic parameters.
Probing Electron-Phonon Interaction through Two-Photon Interference in Resonantly Driven Semiconductor Quantum Dots

We investigate the temperature dependence of photon coherence properties through two-photon interference (TPI) measurements from a single quantum dot (QD) under resonant excitation. We show that the loss of indistinguishability is related only to the electron-phonon coupling and is not affected by spectral diffusion. Through these measurements and a complementary microscopic theory, we identify two independent separate decoherence processes, both of which are associated with phonons. Below 10 K, we find that the relaxation of the vibrational lattice is the dominant contribution to the loss of TPI visibility. This process is non-Markovian in nature and corresponds to real phonon transitions resulting in a broad phonon sideband in the QD emission spectra. Above 10 K, virtual phonon transitions to higher lying excited states in the QD become the dominant dephasing mechanism, this leads to a broadening of the zero phonon line, and a corresponding rapid decay in the visibility. The microscopic theory we develop provides analytic expressions for the dephasing rates for both virtual phonon scattering and non-Markovian lattice relaxation.
Protocol for generating multiphoton entangled states from quantum dots in the presence of nuclear spin fluctuations

Multiphoton entangled states are a crucial resource for many applications in quantum information science. Semiconductor quantum dots offer a promising route to generate such states by mediating photon-photon correlations via a confined electron spin, but dephasing caused by the host nuclear spin environment typically limits coherence (and hence entanglement) between photons to the spin $T_2$ time of a few nanoseconds. We propose a protocol for the deterministic generation of multiphoton entangled states that is inherently robust against the dominating slow nuclear spin environment fluctuations, meaning that coherence and entanglement is instead limited only by the much longer spin $T_2$ time of microseconds. Unlike previous protocols, the present scheme allows for the generation of very low error probability polarization encoded three-photon GHZ states and larger entangled states, without the need for spin echo or nuclear spin calming techniques.

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Energy transfer in structured and unstructured environments: Master equations beyond the Born-Markov approximations

We explore excitonic energy transfer dynamics in a molecular dimer system coupled to both structured and unstructured oscillator environments. By extending the reaction coordinate master equation technique developed by Iles-Smith et al. [Phys. Rev. A 90, 032114 (2014)], we go beyond the commonly used Born-Markov approximations to incorporate system-environment correlations and the resultant non-Markovian dynamical effects. We obtain energy transfer dynamics for both underdamped and overdamped oscillator environments that are in perfect agreement with the numerical hierarchical equations of motion over a wide range of parameters. Furthermore, we show that the Zusman equations, which may be obtained in a semiclassical limit of the reaction coordinate model, are often incapable of describing the correct dynamical behaviour. This demonstrates the necessity of properly accounting for quantum correlations generated between the system and its environment when the Born-Markov approximations no longer hold. Finally, we apply the reaction coordinate formalism to the case of a structured environment comprising of both underdamped (i.e., sharply peaked) and overdamped (broad) components simultaneously. We find that though an enhancement of the dimer energy transfer rate can be obtained when compared to an unstructured environment, its magnitude is rather sensitive to both the dimer-peak
resonance conditions and the relative strengths of the underdamped and overdamped contributions. (C) 2016 AIP Publishing LLC.

**General information**

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Fundamental Limits to Coherent Scattering and Photon Coalescence from Solid-State Quantum Emitters [arXiv]

The desire to produce high-quality single photons for applications in quantum information science has lead to renewed interest in exploring solid-state emitters in the weak excitation regime. Under these conditions it is expected that photons are coherently scattered, and so benefit from a substantial suppression of detrimental interactions between the source and its phonon environment. Nevertheless, we demonstrate here that this reasoning is incomplete, and phonon interactions continue to play a crucial role in determining solid-state emission characteristics even for very weak excitation. We find that the sideband resulting from non-Markovian relaxation of the phonon environment leads to a fundamental limit to the fraction of coherently scattered light and to the visibility of two-photon coalescence at weak driving, both of which are absent for atomic systems or within simpler Markovian treatments.

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Phonon limit to simultaneous near-unity efficiency and indistinguishability in semiconductor single photon sources

Semiconductor quantum dots have recently emerged as a leading platform to efficiently generate highly indistinguishable photons, and this work addresses the timely question of how good these solid-state sources can ultimately be. We establish the crucial role of lattice relaxation in these systems in giving rise to trade-offs between indistinguishability and efficiency. We analyse the two source architectures most commonly employed: a quantum dot embedded in a waveguide and a quantum dot coupled to an optical cavity. For waveguides, we demonstrate that the broadband Purcell effect results in a simple inverse relationship, where indistinguishability and efficiency cannot be simultaneously increased. For cavities, the frequency selectivity of the Purcell enhancement results in a more subtle trade-off, where indistinguishability and efficiency can be simultaneously increased, though by the same mechanism not arbitrarily, limiting a source with near-unity indistinguishability (> 99%) to an efficiency of approximately 96% for realistic parameters.

Quantum correlations of light and matter through environmental transitions

One aspect of solid-state photonic devices that distinguishes them from their atomic counterparts is the unavoidable interaction between system excitations and lattice vibrations of the host material. This coupling may lead to surprising departures in emission properties between solid-state and atomic systems. Here we predict a striking and important example of such an effect. We show that in solid-state cavity quantum electrodynamics, interactions with the host vibrational environment can generate quantum cavity-emitter correlations in regimes that are semiclassical for atomic systems. This behavior, which can be probed experimentally through the cavity emission properties, heralds a failure of the semiclassical approach in the solid state, and challenges the notion that coupling to a thermal bath supports a more classical description of the system. Furthermore, it does not rely on the spectral details of the host environment under consideration and is robust to changes in temperature. It should thus be of relevance to a wide variety of photonic devices.

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Projects:

**Photonic quantum technologies in structured environments**
Denning, E. V., PhD Student, Department of Photonics Engineering
Mark, J., Main Supervisor, Department of Photonics Engineering
Iles-Smith, J., Supervisor, Department of Photonics Engineering
Willatzen, M., Supervisor, Department of Photonics Engineering
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Joanesarson, K. B., PhD Student, Department of Photonics Engineering
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