Acousto-optical preparation of exciton and biexciton states in quantum dots

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Recent years brought the idea of hybrid systems [1], in which quantum degrees of freedom of various kinds, allow the transfer of quantum information and may lead to the emergence of new generation devices. A hybrid system may include quantum information processing, storage, and transmission components. Optically active quantum dots (QDs) are at the forefront of systems for applications in quantum technologies. The wide tunability of optical properties, and the available interfaces with light, microwaves, and mechanical waves make QDs a great candidate for a component of hybrid systems.

QDs generate polarization-entangled photon pairs by exploiting indistinguishable emission paths within the biexciton-exciton cascade, but deterministic and high-fidelity preparation of the state is needed. There are various methods like resonant excitation or phonon-assisted schemes. However, all resonant schemes need cross-polarization filtering to distinguish emitted photons from the resonant excitation pulse, which limits the photon yield significantly, and phonon-assisted schemes strongly rely on an incoherent relaxation path. Thus, new methods of deterministic state preparation are needed. Recently, a novel and purely optical approach has been proposed, where the state is prepared by effectively periodically switching between two detunings [2].

In this contribution, we propose a hybrid acousto-optical extension of the swing-up state control method [3]. We take advantage of the acoustic modulation that allows state preparation with just one mode of vibration and one optical pulse or even continuous optical driving with a single acoustic pulse. In this approach, selectively exciting either exciton or biexciton state is possible. The results enable the protocol's operation for both single-photon or entangled photon sources.

We model the states in a QD using the two- and three-level Hamiltonians in the dipole and rotating wave approximations. Apart from directly finding the evolution for Gaussian optical pulses by numerically solving the Liouville-von Neumann equation, we provide analytical considerations for flat-top optical and acoustic pulses to understand the system's evolution better. Additionally, we estimate the impact of phonon-induced decoherence processes in a non-Markovian approach.

The only limitation of this method is caused by the availability of sufficiently high acoustic field frequencies, but already for those available currently, the scheme can be almost phonon decoherence-free even at elevated temperatures. More importantly, the scheme may pave the way for generating entanglement between an emitter and a quantum acoustic mode, leading to subsequent state transfer via an acoustic bus.

[1] G. Kurizki, et al., Proc. Natl. Acad. Sci. **112**, 3866 (2015).
[2] T. K. Bracht, et al., PRX Quantum **2**, 040354 (2021).
[3] M. Kuniej, et al., arXiv 2402.07887 (2024).