Quantum dots in microcavities: from single spins to engineered states of light

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Summary

In this thesis, we explore foundational quantum optics experiments based on cavity quantum electrodynamics with a single self-assembled III-V quantum dot in an optical microcavity. This system has a number of exciting aspects, for instance, it enables high-fidelity single photon production for future quantum applications.

Semiconductor quantum dots (QDs) are nanometer-scale islands of one semiconductor embedded into a different semiconductor of a higher band gap. Due to their small size, QDs have discrete electronic levels, enabling the emission of single photons like in atoms. However, unlike in atoms, the QD energy levels can be fine-tuned by the composition and dimension of the quantum dot, and can afterwards be controlled via external fields. Our self-assembled InGaAs quantum dots were grown by molecular beam epitaxy in the intrinsic region of GaAs *p*-*i*-*n* junction, enabling tuning of the QD energy levels via the quantum confined Stark effect. We use this effect to bring a QD transition into resonance with the fundamental resonance of an optical microcavity in which the QD is embedded, or to trap an extra electron in the initially charge-neutral QD. The monolithic optical cavity is formed by two thin-film Bragg mirrors consisting of alternating layers of materials with different refractive indices. The light inside the high-quality optical cavity circulates around 40 000 times in the cavity before it is lost through a mirror, resulting in a near deterministic interaction with the QD and high-efficiency generation and extraction of single photons.

We discuss the quantum-dot devices used in this thesis and their optical characterization in Chapter 2. The device design inspired by samples originally developed for semiconductor lasers has an extra electron-blocking layer below the QDs. This layer supports deterministic and stable QD charging with an extra electron - a spin-based quantum memory. The extra electron in the QD significantly changes the optical selection rules connecting the photon polarization to the electron spin state. For example, if the singly-charged QD is optically excited to the trion state, energy-degenerate circularly polarized transitions emerge. Once placed in an in-plane (Voigt geometry) external magnetic field, electron and trion states are split by the Zeeman effect, and two pairs of orthogonally linearly polarized transitions appear, which we show in Chapter 4.

Studying the electron and trion states using resonant laser spectroscopy requires filtering out of the relatively strong excitation laser, for which we use the cross-polarization technique. The cross-polarization quality is quantified by the cross-polarization extinction ratio, which is limited by the quality of the optical elements. However, recently, it has been discovered that this ratio can be improved by spin-orbit coupling of light upon optical (Fresnel) reflection. In Chapter 3, we identify and explore these effects in our cryogenic confocal microscope and utilize it to improve the purity of the single photons produced by the trion transition of the QD. We find a unique polarization setting where the cross-polarization ratio exceeds the bare-polarizer extinction ratio by a factor 10. We prove that this enhancement is based on compensation of the small ellipticities of our polarizers, while spin-orbit coupling effects are mitigated by single-mode fiber filtering. In order to explore the use of the electron spin as a quantum memory, the spin states

need to be split by an external magnetic field. In Chapter 4, we develop a simple cold permanent magnet assembly delivering almost 0.5 T at cryogenic temperatures. Cooling down our singly-charged QD with this assembly allowed us to perform two-color laser spectroscopy and reveal the QD spin dynamics.

In Chapters 5 and 6, we use a high-quality single-photon source to perform quantum optics experiments that are impossible using classical fields. In our experiments, we use Hong-Ou-Mandel interference to bunch individual photons together and thus produce quantum states of light with a complex structure in photon statistics.

In Chapter 5, we theoretically study single-photon addition to coherent states on an unbalanced beam splitter. The quantum states emerging from one output port of the beam splitter have non-Gaussian properties. These states are interesting for continuous variable quantum computing and communication, however, are notoriously challenging to produce. We propose a simple method based on photon correlations to confirm successful single-photon addition. The two-photon correlations show a universal maximum enabling to maximize the fidelity of the single-photon addition.

Finally, in Chapter 6, we experimentally create artificial coherent states of light from scratch. In fact, we use Hong-Ou-Mandel interference repeatedly in an optical delay loop and manipulate a single-photon stream produced by our QD-cavity source. This allows us to engineer photon-by-photon complex photon-number superposition states with tunable photon number statistics, similar to Poissonian statistics of coherent states. The photon correlations and our models show that the artificial coherent states are more complicated than ordinary coherent states and contain multi-photon entanglement in the form of linear cluster states, a potential resource for universal quantum computing.