Cavity quantum electrodynamics with rare-earth ions in solids

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Cover: designed by Dapeng Ding, artist's impressions of an optical cavity that confines light (front) and a rare-earth ion in solids that emits light (back).

To my parents

Contents

Preface

In recent years there have been two parallel developments taking place with profound implications in the fields of optoelectronic engineering and quantum optics, respectively. The first one is the development of ultra-high-quality-factor (UHQ) optical ring resonators based on the integrated-optics approach [1, 2]. These UHQ ring resonators offer great controllability and stability for high demanding applications such as frequency comb generation [3] and gyroscopes [4]. The second development is the exploration of rare-earth ions in solids for quantum information applications such as quantum memories [5, 6] and quantum bits (qubits) [7, 8, 9]. These applications benefit from the exceptionally long coherence times of the $4f$ electronic states of rare-earth ions.

In this thesis, these two developments merge to form a coupled system that can be described in the theoretical framework of cavity quantum electrodynamics (QED). As a result, the inherently weak optical transition of rare-earth ions is enhanced by the cavity field of the ring resonator, and the rare-earth ions acquire the advantage of integrated optics and become scalable for future quantum networks. In close collaboration with the optoelectronics research group of Professor Bowers at the University of California, Santa Barbara, USA, and with the nuclear solid state group of Professor Vantomme at the KU Leuven, Belgium, solid-state cavity QED devices were designed and fabricated. This thesis presents the first results on such a system.

This thesis starts with an introduction to the quantum electrodynamical description of the interaction between light and matter. The role of optical cavities in the interaction is discussed and the basic properties of rare-earth ions are reviewed.

In Chapter 2 a bare ring resonator that is coupled to a straight waveguide via evanescent waves is studied by using two single-mode optical fibers coupled to the straight waveguide. Transmission spectra are measured through the two fibers, from which optical properties of the ring resonator and the waveguide are characterized. In particular the multimode property of the waveguide leads to asymmetric lineshapes in the transmission spectra, typically referred to as the Fano resonance.

Chapter 3 addresses two technical issues that have been essential for the research presented in this thesis. The first technique is the implantation of rare-earth ions into the ring resonator in combination with the device fabrication. The second technique is the permanent fiber connections to the waveguides that are coupled to the ring resonator. The fiber connections have to be robust against temperature cycling and be stable at cryogenic temperatures. The fiber connection technique applied to micro-pillar cavities with embedded quantum dots is also discussed.

Chapter 4 is devoted to the research on the enhancement of the spontaneous emission (SE) rate in an ytterbium-doped ring resonator in the temperature range of 5.5–295 K as a result of the Purcell effect. The Purcell factor that characterizes the enhancement of the SE rate is obtained from the experimental data. A theoretical model that includes the multi-dimensional effect, the dipole depolarization of the ions, and the temperature-dependent homogeneous linewidth of the ions is proposed.

Chapter 5 presents the results of measurements performed on an ytterbium-doped ring resonator in a dilution refrigerator in the temperature range of 12 mK–4.7 K. The measured Purcell factor is compared with the theoretical model as presented in Chapter 4.

In previous chapters the rare-earth ions are treated as independent emitters because of the incoherent excitation used in the experiment. On the other hand, the ions will probably exhibit collective effects if they are coherently excited to the same quantum state. In Chapter 6 collective effects of an ensemble of emitters in a cavity are theoretically studied with different initial states and pure dephasing rates by using the quantum Monte Carlo method.

Chapter 7 concludes the thesis and presents an outlook for future work.