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**Title**: Cavity quantum electrodynamics with rare-earth ions in solids
**Issue Date**: 2015-03-12

# Chapter 7

# Conclusions and outlook

This thesis presents both experimental and theoretical studies on a novel cavity QED system consisting of a high-Q $Si_3N_4$ ring resonator and implanted $Yb^{3+}$ ions, and reflects interesting physics and the potential of this system for quantum information applications. Sub-systems and enabling techniques were characterized and explored, which make the full-functional system be reliably operating at cryogenic temperatures. The Purcell factor and the homogeneous linewidth of $Yb^{3+}$ ions are the main themes of this thesis, because the former characterizes the quality of the cavity and the coupling between the cavity and the ions, while the latter characterizes the quantum properties of the ions.

A bare ring resonator was first studied in Chapter 2 by using two single-mode optical fibers coupled to the straight waveguide that couples via evanescent waves to the ring resonator. This configuration represents a general application scheme which involves couplings among the fibers, the straight waveguide, and the ring resonator. Their optical modes and the spatial overlaps among these modes play essential roles in the transmission properties of the system. The ring resonator, once hit on resonance, couples light from the modes of the waveguide into its resonant mode and vice versus leading to resonance behaviors of the system. In the experiment, the transmission of the system was measured while the relative positions of the fibers were varied and the frequency of the light was scanned. The results reveal information on the modes of the ring resonator and the waveguide especially the quality factors and free spectral ranges of the modes of the ring resonator. Asymmetric lineshapes—the Fano resonance were observed in the transmission spectra resulting from the interference between the modes in the waveguide. The Fano resonance has potential applications for sensing refractive index changes of the surrounding medium with a higher sensitivity compared with using symmetric lineshapes. To this end, the top cladding of the ring resonator should be thin such that the mode field overlaps with the medium of interest and on-chip mode couplers for the waveguide should be used to achieve a high coupling efficiency.

With the knowledge on the optical properties of the ring resonator and its coupling to the fibers, in Chapter 3 we designed and fabricated ring resonators doped with $Yb^{3+}$ ions and secured the fiber connections by using UV curing optical adhesive. The $Yb^{3+}$ ions form a thin lateral sheet in the $SiO_2$ cladding just above the $Si_3N_4$ core of the ring resonator. We carefully avoided doping $Yb^{3+}$ both in $SiO_2$ and in $Si_3N_4$, because to remove implantation defects in $Si_3N_4$ the required annealing temperature is so high that in $SiO_2$ $Yb^{3+}$ would aggregate into clusters and lose optical properties. Stable and high-efficiency fiber connections to the ring resonator are crucial to the experiments at cryogenic temperatures. Our techniques have been proven to maintain the coupling efficiency while cooled from room temperature down to 12 mK. In our sample, both the ring resonator and the straight waveguide were equally doped with $Yb^{3+}$. This might cause confusion about whether the emission from the ions in the waveguide contributed to the measurement results. We would argue that throughout the thesis the laser power in the waveguide was so low that the excitation of the ions in the waveguide was negligible, while the excitation level of the ions in the ring resonator was much higher due to the enhanced cavity field. However, the uniform doping of $Yb^{3+}$ prevents the use of strong, coherent laser pulse to excite the ions, because the emission from the ions in the waveguide will unnecessarily complicate the measurement results. For future work, the waveguide structures can be masked with photoresist before the ion implantation. This will produce doped ring resonators with clean waveguides suitable for coherent excitations.

In Chapter 4 we studied SE rate of $Yb^{3+}$ in a ring resonator in the temperature range of 5.5–295 K. At high temperatures, the Purcell factor $F \approx 0.8$ is dominated by its 1D (waveguide) component and is almost independent of temperature because the homogeneous linewidth of $Yb^{3+}$ is much larger than the cavity linewidth. At low temperatures, the 3D (cavity) component of the Purcell factor becomes dominant and increases with decreasing temperature due to the decreasing homogeneous linewidth of $Yb^{3+}$. We demonstrated a Purcell factor of 3.6 at 5.5 K. The experimental data are in good agreement with a theoretical model that includes the multi-dimensional Purcell effect and the dipole depolarization of $Yb^{3+}$. An important expression obtained from the experimental data is the temperature-dependent homogeneous linewidth of $Yb^{3+}$ in pure silica given by $5.0 \times T^{1.3}$ (MHz) for $T < 40$ K, which is useful to estimate the coherence time of $Yb^{3+}$ at different temperatures. The model predicts a Purcell factor of about 9 at the low temperature limit. This prediction was verified in Chapter 5.

In Chapter 5 the sample was further cooled from 4.7 K down to 12 mK by using a dilution refrigerator. The measured Purcell factor is in good agreement with the model as described in Chapter 4 and reaches about 9 at 50 mK.

The results prove that the expression for the homogeneous linewidth of $Yb^{3+}$ obtained in Chapter 4 is still valid at least down to about 100 mK. The Purcell factor at 12 mK is apparently lower than the value that the model predicts and also deviates from the trend of other data. This phenomenon still lacks a theoretical explanation and will be further studied in the future.

In the previous chapters the $Yb^{3+}$ ions were excited with weak and long (1 ms) laser pulses on a timescale that was much longer than the coherence time of $Yb^{3+}$. As a result, the $Yb^{3+}$ ions were in random superposition states before the start of the spontaneous emission. This incoherent initial state hindered the formation of correlation among the ions and validated the assumption of independent ions as always assumed in the previous chapters. On the other hand, the $Yb^{3+}$ ions will probably exhibit collective effects if they are coherently excited to the same quantum state. In Chapter 6, the collective effects of emitters in a cavity were theoretically studied by using the quantum Monte Carlo method with different initial states and pure dephasing rates. The parameters used in the simulation were typical values for $Yb^{3+}$ ions in our ring resonators at low temperature, but similar results should be anticipated also for other cavity QED systems. These collective effects can in principle be observed experimentally with different initial states by using coherent laser pulses through a clean waveguide that is coupled to a ring resonator doped with $Yb^{3+}$.