Cavity quantum electrodynamics with rare-earth ions in solids
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Summary

Rare-earth elements are seventeen chemical elements in the periodic table. They are usually unknown to most non-scientists because there is no object entirely made out of these elements in our daily life and because they do not seem to play a role in biological processes—our body does not need them. Perhaps most of the people have never heard of their names such as Europium, Holmium, Thulium, Ytterbium, etc. Nevertheless, each rare-earth element turns out to be of particular importance for technological applications widely ranging from lasers, magnets, lamps, alloys, catalysts to nuclear batteries and superconductors. They are typically added in small quantities to other materials, for example during glass formation, during material growth, by implantation or through diffusion, and significantly influence the properties of the resulting materials. Unlike the name implies, rare-earth elements are not so rare in earth's crust with the abundances similar to that of copper and thousands times higher than gold and platinum. The name refers to the fact that these elements are mostly not concentrated in the form of minerals, a fact that makes exploitation somewhat difficult.

What makes rare-earth atoms so special and why are they used in numerous applications, and in particular in optical applications? All atoms in the gas phase have clear optical properties that typically provide direct information about the outermost electronic orbits. Because the electronic orbits have discrete well-determined energy values, an outer electron excited to a higher energy level will decay to a lower level by emitting the difference in energy in the form of light quanta. When the atoms condense to a piece of material the outer electronic orbits typically play an important role in binding the atoms together and they can no longer participate in the optical processes typical for atoms in the gas phase. Now the exceptional property of rare-earth atoms is that they maintain their optical properties to a large extend even when embedded in a piece of material. The reason for this is that rare-earth atoms have certain electronic orbits that are not fully filled with electrons and that are surrounded by other fully-filled electronic orbits. This means that optical transitions take place inside a "protected cage". Therefore, from an optics point of view, rare-earth atoms in a solid can be seen as "free" atoms with

clean optical properties trapped at a fixed place inside the solid. This special feature provides great advantages over other chemical elements. In gas phase atoms travel randomly with very high speeds and also collide with each other. The motion shifts the transition frequency (Doppler effect) and also makes tracking individual atoms almost impossible, while the collision undermines the quantum properties. Although controlling individual atoms is possible by laser trapping and cooling, this technique requires complicated equipment and cannot be scaled to many atoms at the same time, which is necessary for future applications in the field of quantum information science. The fact that rare-earth elements remain functional even in solids such as glass and crystals is therefore of particular interest to this field. In this thesis we consider the rare-earth atom Ytterbium. This atom loses three electrons to form an ion (charged atom) in solids, but the electrons that are responsible for the atomic properties are still safely protected inside the ion. The position of the ion in the solid is fixed, but at finite temperatures there is still some thermal motion that should be taken into account. Furthermore, it is promising to fabricate an integrated circuit on a small chip based on individual rare-earth ions as quantum bits just like the CPU in our normal computer.

A quantum computer can be seen as the ultimate goal of the research initiated in this thesis. To reach this goal, both the quantum states of individual rare-earth ions and the interactions among the ions should be well under control. Because the atomic transitions among the quantum states are associated with absorption or emission of light, light can be used to initialize the quantum states of the ions, to mediate the interactions among the ions (quantum operations), and eventually to readout the quantum states (computation results). Therefore understanding the light-ion interaction becomes a crucial first step in building a quantum information processing device based on rare-earth ions in solids. The main challenge lies in the fact that the interaction between rare-earth ions and light is so weak by their nature, about one million times weaker than the interactions in neon lamps or mercury-vapor lamps. This weak interaction reflects on their long excited-state lifetime—the typical time that it takes for the atom to decay from the excited state to the ground state via spontaneous emission. The excited-state lifetime of rare-earth ions is on the order of milliseconds (one thousandth of a second), while it is on the order of nanoseconds (one millionth of a millisecond) for neon and mercury atoms. In other words, the spontaneous emission rate (the inverse lifetime describing how fast the spontaneous emission occurs) of rare-earth ions is one million times smaller than that for neon and mercury atoms. With such a small spontaneous emission rate, it is extremely difficult to detect a single rare-earth ion, let alone to control its quantum state and to use it as a quantum bit.

This thesis aims to tackle this problem by using optical cavities to enhance the light-ion interaction. This effect is known as the Purcell effect after the physicist Edward Purcell and can be understood within the theoretical framework of cavity quantum electrodynamics. Generally speaking, an optical cavity is a device which traps light for a certain time within a certain volume. The longer the trapping time and the smaller the cavity volume, the stronger the light field can build up inside the cavity. Because the light-ion interaction strength is proportional to the local light field strength, the light-ion interaction is enhanced if an ion is placed at the field maximum in the optical cavity. In this thesis, the optical cavity is made of a waveguide in a ring shape on a silicon chip. A waveguide is an optical microstructure that guides light to travel along its body. Once bent into a ring shape, called a ring resonator, light is guided to travel in the ring and is effectively trapped in it. On the chip the ring resonator is coupled to other waveguides that guide light in and out of the ring resonator. This architecture resembles an electric circuit where transistors (ring resonator and rare-earth ions here) are connected with electrical wires (waveguides here). The difference is that we have light running on the chip instead of electric current. As a matter of fact, the fabrication procedures for the ring resonator and waveguides are similar to that of integrated circuits and can be easily scaled up to many ring resonators interconnected with waveguides. This feature shows potentials of our devices in the context of quantum computers.

With rare-earth ions implanted in a high-quality-factor (equivalent to long trapping time) and relatively-small-volume ring resonator at hands, we are still one step short from seeing the enhanced light-ion interaction. A key factor is temperature because thermal fluctuations at room temperature significantly reduce the quantum properties of the ions which are crucial to the Purcell effect. We have to cool the device down to low temperature to observe the Purcell effect. In the experiment, we first cooled the device to 5 K (5 degrees above absolute zero, or −268°C) and indeed observed an enhancement of the interaction by a factor of 4 (4 times higher spontaneous emission rate). In the subsequent experiment, we further cooled the device down to 50 mK (0.05 degrees above absolute zero, or −273°C) and observed an enhancement by a factor of 9. The results indicate that a fully optimized ring resonator with a higher quality factor and a smaller volume can eventually enable optical detection and quantum state control of a single rare-earth ion.

This thesis covers the details of my research activities on the rare-earth ions and ring resonators during my PhD. In the first introductory chapter, background knowledge that is required to understand this thesis is presented and the current status of this research field is surveyed. In the second chapter a bare ring resonator is measured and its properties are fully characterized. Especially we observe the Fano resonance (asymmetric lineshapes) in the transmission spectra. The third chapter presents the techniques that make the research on the light-ion interaction possible. In particular rare-earth ion implantation and fiber coupling to the waveguides on a chip are discussed. Chapter 4 is devoted to the theory, experiments, and results of rare-earth-ion-doped ring resonators at temperatures ranging from room temperature down to about 5 K. In Chapter 5, the measurement is extended down to 50 mK. Chapter 6 presents theoretical investigations on the collective effects of rare-earth ions in a cavity. Chapter 7 concludes this thesis and provides an outlook to future research.