Trapping a single atom in the evanescent field of a WGM-resonator

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Abstract. We demonstrate the trapping of single atoms in the evanescent field of a whispering-gallery-mode (WGM) resonator with a standing wave optical dipole trap. We present our progress towards an improved trap loading scheme.

1 Introduction

WGM resonators are monolithic structures that guide light by total internal reflection. They exhibit ultra-high Q-factors combined with a small optical mode volume, and are conveniently tunable. They also provide lossless in- and out-coupling of light via tapered optical fibers, and allow one to reach the strong coupling regime of cavity-QED when coupling a single atom to their evanescent field. Furthermore, these resonators exhibit chiral (i.e. direction dependent) light-matter interaction [1], which makes them attractive atom-photon interfaces for novel quantum information processing devices [2]. However, so far, only free falling atoms have been coupled to WGM resonators, which severely limits the atom-resonator interaction time and results in a probabilistic operation. Here we describe a trapping scheme that led us, for the first time, to trapping of single ^{85}Rb atoms in the evanescent field of a WGM resonator [3]. With use of a two-colour magic wavelength trapping scheme, we are able to observe a vacuum Rabi splitting in the coupled atom-resonator spectrum. Furthermore, we present our ongoing implementation of a second generation trapping scheme, which will enable deterministic trap loading with improved trap lifetimes in addition to a well-defined coupling strength.

2 Experimental details

2.1 Dipole Trap Scheme

The trapping setup is sketched in Fig. 1. We use a bottle microresonator (BMR), i.e. a fiber-based WGM resonator with a quasi-cylindrical geometry, stabilized to the unperturbed D2 transition of ^{85}Rb. A tapered fiber is interfaced with the BMR to couple light into and out of it. A cloud of cold ^{85}Rb atoms is delivered from a magneto-optical trap (MOT) to the BMR's evanescent field by an atomic fountain. The system is set to critical coupling such that, when an atom enters the evanescent field, an increase in the coupling fiber's transmission is measured. This signal triggers an FPGA-based real time detection scheme, which switches on our dipole trap in ~250 ns, i.e. much less than the transit time of the atom in the evanescent field (~1-2 μs). The trap consists of a red-detuned light field tightly focused on the resonator surface [4]. A standing wave pattern results from the interference between the incident and back-reflected beams, such that an atom can probabilistically be trapped at the first potential minimum, at a distance of ~200 nm from the BMR's surface.

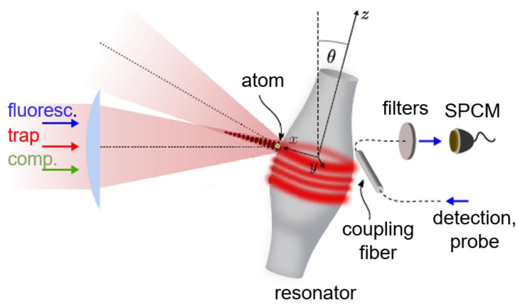

Figure 1. Simplified scheme of the setup for trapping single atoms close to the WGM resonator ssurface.

2.2 Light Shift Compensation and Atom Detection

The trapping field induces a position-dependent AC-Stark shift of the atomic transition, which impairs the atom-resonator coupling. In order to compensate for this effect, a dual-colour magic wavelength trapping scheme is employed: a second light beam, with proper power and detuning with respect to a higher atomic transition, is complementarily focused on the trapping position, with the ultimate effect of shifting the excited level back into resonance to remove the atom-resonator detuning. Furthermore, a fluorescence detection scheme is used to inspect

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the trap loading: short resonant pulses are sent through the trap optics, a fraction of the scattered light is coupled to the resonator and collected through the coupling fiber, in order to detect the presence of a trapped atom at variable time delays. In this way, we can infer a trap loading efficiency of $\eta_0 \approx 0.7$ % and a trapping lifetime of $\tau \approx 2$ ms. This represents a 1000-fold increase in the atom-resonator interaction time. In Fig. 2, transmission spectra of the atom-resonator system with and without the Light-Shift Compensation (LSC) field are shown in comparison with the spectrum of the empty resonator. The spectrum with LSC shows a symmetric vacuum Rabi splitting, which agrees well with the theoretical prediction curve based on our setup parameters. From the latter, we estimate the coupling strength of the atom-resonator system to be $g = 2\pi \times 9.3$ MHz.

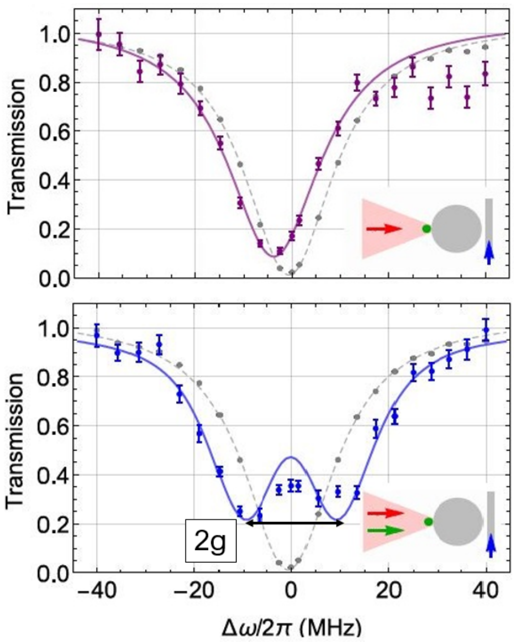

Figure 2. Transmission spectra of the coupled atom-resonator system. In violet (above): without LSC. In blue (below): with LSC. In grey: transmission spectrum of the empty resonator. The solid lines represent the theoretical predictions.

2.3 Outlook

We are currently working on the implementation of a second generation trapping setup. In this novel scheme, the dipole trap is directly focused into the MOT region, which is located at a short distance from the BMR (~1 mm). Once the trap is loaded, the atom is delivered to the resonator surface with a moveable optical tweezer, generated by a Focus Tuneable Lens (FTL), whose focal length is adjustable by an externally applied electric field. However, this poses a further complication: while moving to the resonator, the interference of the incoming and reflected beam builds up a high contrast standing wave potential, which inhibits transport to the evanescent field of the WGM. The envisaged solution is based on the use of a Spatial Light Modulator (SLM) to generate a superposition of higher-order Laguerre-Gaussian modes, to enable the suppression of the interference fringes of the standing wave potential [5]. With the prospected upgrades, our setup will allow trapping of colder atoms, which will result in a better control of the atomic position and, thus, on an even longer trapping lifetime with a better definition of the coupling strength g.

3 Summary

We have successfully implemented an experimental protocol that led, for the first time, to trapping of a single atom in the evanescent field of a WGM resonator. The trap-induced light shift of the atomic transition was overcome by employing a dual-colour magic wavelength trapping scheme, based on the addition of a second beam to restore the atomic resonance. This resulted on a 1000-fold increase of the atom-field interaction time in the strong coupling regime. The ongoing upgrades of the setup will enable us to reach a longer trapping lifetime and a better-defined coupling strength g.

References

[1] P. Lodahl et al., Nature **541**, 473 (2017)
[2] M. Scheucher et al., Science **354**, 1577 (2016)
[3] J. D. Thompson et al., Science **340**, 1202 (2013)
[4] E. Will et al., Phys. Rev. Lett. **126**, 233602 (2021)
[5] J.-B. Beguin et al., PNAS **117/42**, 26109 (2020)