Multimode strong coupling of laser-cooled atoms to a nanofiber-based ring resonator

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Summary

An ensemble of laser-cooled Cesium (Cs) atoms is interfaced with an optical nanofiber, itself contained in a 30 m long fiber ring resonator [1] with a free spectral range (FSR) of 7 MHz. The collective coupling of the atomic cloud exceeds the FSR, leading to multimode strong coupling (or superstrong coupling) [2-4], a novel regime of light-matter interaction.

Introduction

Optical nanofibers have already successfully been used to investigate light-matter interaction at the single-photon level: emitters such as neutral atoms can be addressed with the guided field since a significant fraction of the propagating light is contained in an evanescent field surrounding the fiber [5, 6]. They offer a versatile platform where novel regimes are accessible. Their excellent transmissions exceeding 99% [5, 6] permits their integration into cavities to reach the strong coupling regime of CQED [7, 8]. In this work we include a nanofiber into a 30 meter-long fiber ring resonator. The inherent fiber integration makes the system very flexible and allows us to tune key parameters such as the free spectral range (FSR) and eigenpolarizations. Due to the strong enhancement of light-matter interaction in the optical nanofiber, several hundred atoms suffice to achieve a collective coupling strength that exceeds the FSR of 7 MHz of the cavity.

Discussion

The resonator consists of a long standard fiber section and a fiber beam splitter where the coupling into the cavity can be adjusted. A piezoelectric element allows to shift the resonator lines by slightly pulling on the fiber, in response to external perturbations to lock the cavity. A large part of the resonator is contained in a insulating box except the section connected to the nanofiber which is fed into the vacuum chamber. A magneto-optical trap (MOT) containing several 10^8 Cs atoms is formed around the tapered optical fiber with a 1 cm-long waist and a diameter of 400 nm (see Fig. 1). With the optical densities we previously measured without a resonator we expect to reach collective coupling strengths of the order of 10 MHz, thus larger than the FSR. The expected spectra are shown Fig. 2, according to a simple model where the output transmission is computed for a moderate finesse cavity (F = 14) containing a variable number of atoms. By letting the MOT fall for a given time before acquiring the transmission spectrum we can adjust the number of atoms coupling to the nanofiber and tune the collective coupling, to demonstrate the transition from "standard" single-mode coupling to multimode coupling, as illustrated theoretically figure 2.

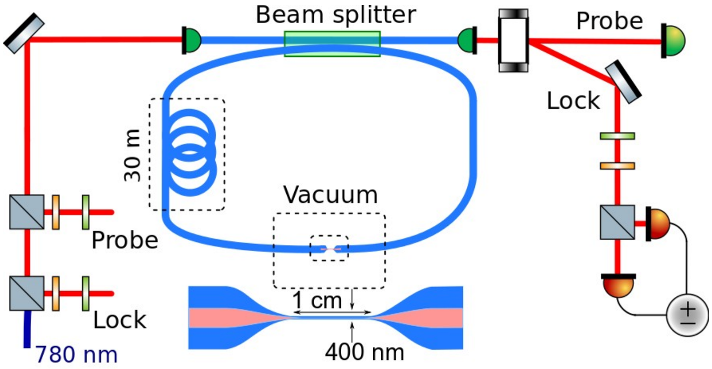

Fig.1 Schematic of the experimental setup. The resonator includes a nanofiber to couple atoms to the cavity. Weak (single-photon level) probe light as well as lock light and blue-detuned light (to repel the atoms from the nanofiber surface) are coupled into the resonator. The lock signal relies on the birefringence of the resonator, similar to [9].

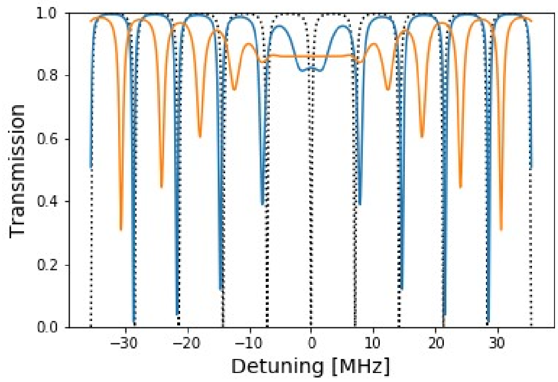

Fig.2: Expected spectra for N = 20 atoms (blue) and N = 200 (orange) compared to the empty cavity spectrum (dotted). The transmission dips are gradually shallower and shifted outwards as the coupling becomes multimode, and the central splitting increases.

Conclusions

In conclusion, we investigate the collective coupling of an ensemble of laser-cooled atoms with a fiber ring resonator. Both a small FSR and a strong collective enhancement of the coupling lead to g > FSR, *i.e* strong coupling of the atoms to several longitudinal resonator modes. In this novel regime of cQED atoms can mitigate interactions between photons in different resonator modes. We envision to make use of this to e.g., realize quantum annealing based quantum information processing [10].

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