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Experimental investigation of light-matter interaction when transitioning from cavity QED to waveguide QED

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Abstract. Cavity quantum electrodynamics (cavity QED) is conventionally described by the Jaynes- or Tavis-Cummings model, where quantum emitters couple to a single-mode cavity. The opposite scenario, in which an ensemble of emitters couples to a single spatial mode of a propagating light field, is described by waveguide QED, where emitters interact with a continuum of frequency modes. Here we present an experiment where an ensemble of cold atoms strongly couples to a fiber-ring resonator with variable length containing an optical nanofiber. By changing the length of the resonator we can tailor the density of frequency modes and thus explore the transition from cavity QED to waveguide QED. We analyse the response of the ensemble–cavity system after the sudden switch-on of resonant laser light and find that for progressively longer resonators, the Rabi oscillations typical of cavity QED disappear and the single-pass dynamics of waveguide QED appear. Our measurements shed light on the interplay between the single-pass collective response of the atoms to the propagating cavity field and the ensemble–cavity dynamics.

In waveguide QED, emitters couple to a propagating light field via a continuum of frequency modes. Conceptually, the waveguide QED case can be interpreted as a cavity with mirrors at infinite distance. As the cavity is shortened progressively, the frequency spacing or free spectral range of the cavity modes increases until the emitters finally couple only to a single mode of the cavity. This regime is usually described in the framework of the Jaynes- or Tavis-Cummings model where a single or multiple emitters couple to a single mode of an optical cavity.

Here we experimentally and theoretically study light-matter interaction for emitters placed in a fiber-ring cavity with variable length where emitters interact with one, few or multiple resonator modes [1]. Systems in the transition region between cavity and waveguide QED, where the roundtrip time of the resonator is approximately as long as the lifetime of the excited state of the emitter, cannot correctly be described by the Jaynes- or Tavis-Cummings model, nor by the standard waveguide QED approach. This situation can, however, be described by a cascaded interaction model [2–4], which applies to cavities with arbitrary length and encompasses the cavity QED and waveguide QED limits. Based on this model, we study the temporal dynamics of the field transmitted through the resonator for different cavity lengths after the rapid switch-on of light that show typical features of cavity and waveguide QED, where in the intermediate cases features from both regimes are present simultaneously.

In Figure 1 (a), the experimental setup is sketched [1, 5]. A fiber-ring resonator with variable length is coupled to an input fiber via a fiber coupler. We prepare an ensemble of cold cesium atoms in a magneto-optical trap and interface it with the resonator field via the evanescent field of a tapered optical nanofiber (waist diameter $\approx$ 400 nm, waist length $\approx$ 1 cm) which is part of the fiber-ring.

In Figure 1 (b), we present the frequency response of our system for a resonator length of 45 m for an ensemble of cesium atoms corresponding to an optical density of 6. In this case, we are in the multimode strong coupling regime [1, 3], as the free spectral range of the cavity is smaller than the linewidth of cesium ($\nu_{\mathrm{FSR}} = 4.4$ MHz, $\Gamma/2\pi = 5.2$ MHz). As resonator modes are being pushed outwards compared to the reference spectrum, the atoms interact with multiple modes simultaneously. The cascaded interaction model fits the experimental data well and proves that it is well suited to describe the resonator response.

To measure the time domain dynamics, we record the response of the ensemble–cavity system after the sudden switch-on of light resonant with the D2 line of cesium ($6^2S_{1/2}$, $F = 4 \rightarrow 6^2P_{3/2}$, $F = 5$) using a single photon counting module (SPCM). To quickly turn on the laser, we use an electro-optic modulator with a rise time that is much shorter ($\approx$ 0.8 ns) than the lifetime of the exited state of cesium ($\approx$ 30.4 ns).

Figures 1 (c) - (e) show the predicted temporal response for three different resonator lengths using the cascaded interaction model and an optical density of 6. The resonator lengths we consider are (c) 5 mm, (d) 5 m and (e) 50 m which correspond to roundtrip times, t_{rt}, that are much smaller, comparable or much larger than the lifetime, τ_{at}, of the excited state of cesium. When $t_{\mathrm{rt}} \ll \tau_{\mathrm{at}}$ as in (c), the transmission shows the typical damped Rabi oscillation predicted by cavity QED. On the other hand,

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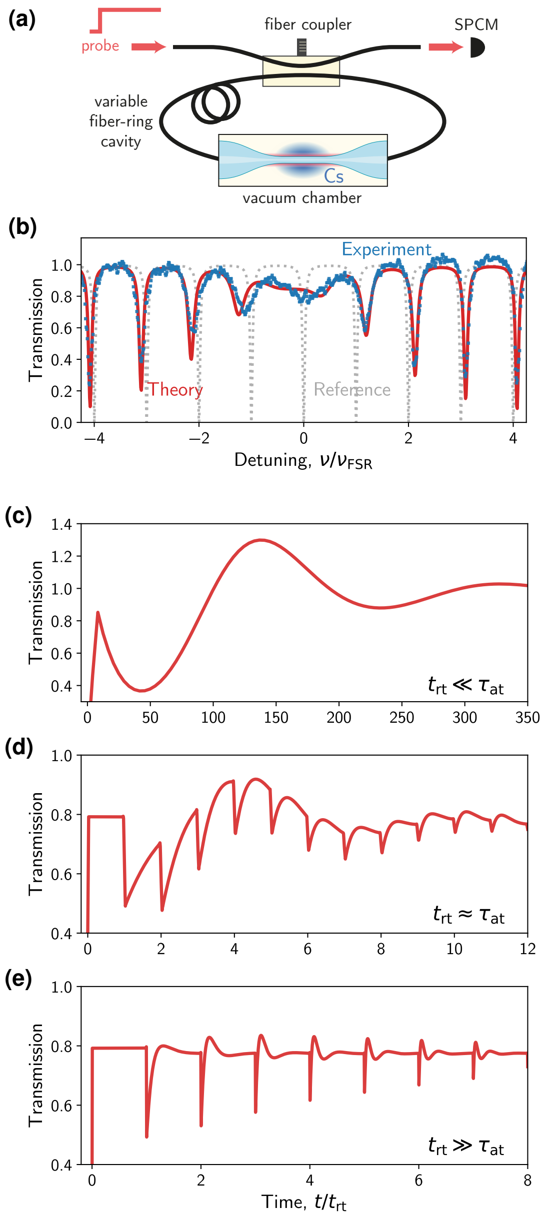

Figure 1: **(a)** Experimental setup of our fiber-ring cavity system. **(b)** Frequency scan of the cavity transmission for a 45-m-long cavity with frequency normalized to the free spectral range ν_{FSR} of the resonator. Experimental data is represented as blue dots, theory as a red solid line and reference cavity as a grey dotted line. In this case, the atomic ensemble interacts with multiple resonator modes at the same time. **(d)**-**(e)** The transmission through cavities with increasing lengths as predicted by the cascaded interaction model with time normalized to the roundtrip time of the resonator. The longer the resonator and the longer its roundtrip time, t_{rt}, is compared to the lifetime of the atoms, τ_{at}, the more the typical Rabi oscillations of cavity QED disappear and the more the repeating single-pass dynamics of waveguide QED dominate.

when $t_{rt} \gg \tau_{at}$ as in (e), the transmission is characterized by sharp features that repeat every roundtrip time, which result from the consecutive single-pass waveguide-QED-like response of the atomic ensemble to the light pulse propagating in the resonator. For $t_{rt} \approx \tau_{at}$ as in (d), the system is in a transition region between cavity QED and waveguide QED. In this case, the transmission displays a slowly oscillating envelope, which corresponds to a Rabi oscillation typical of cavity QED, while simultaneously showing the sharp, repeating features of the single-pass dynamics of waveguide QED. These predicted dynamics agree well with preliminary measurement results.

Our work is the first detailed experimental and theoretical study of the transition regime between cavity and wavguide QED. It improves the understanding of the response of emitters to a propagating cavity field for arbitrary resonator lengths and has the potential to enable new protocols and experiments in new regimes of light-matter interaction.

References

[1] A. Johnson, M. Blaha, A.E. Ulanov, A. Rauschenbeutel, P. Schneeweiss, J. Volz, Physical Review Letters **123**, 243602 (2019)
[2] J.T. Shen, S. Fan, Physical Review A **79**, 023837 (2009)
[3] M. Blaha, A. Johnson, A. Rauschenbeutel, J. Volz, Physical Review A **105**, 013719 (2022)
[4] R. Pennetta, D. Lechner, M. Blaha, A. Rauschenbeutel, P. Schneeweiss, J. Volz, arXiv:2112.10806 (2021)
[5] R. Pennetta, M. Blaha, A. Johnson, D. Lechner, P. Schneeweiss, J. Volz, A. Rauschenbeutel, Physical Review Letters **128**, 073601 (2022)