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Large cooperativity in strongly coupled chip-scale photonic-atomic integrated system

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The miniaturization of atomic quantum systems and their integration into silicon microchips paves the way for a wide variety of applications in quantum computing, metrology and magnetometry. A particular interest is found in the integration of quantum entities into the micro and nanoscale photonic resonators to implement chip scale cavity quantum electrodynamics. Here we demonstrate the interaction of a chip scale micro disc resonator with thermal rubidium atoms via the evanescent field of the mode. We observe high Rabi splitting of 4 GHz in the transmission spectrum of the coupled photonic-atomic system due to collective enhancement of the coupling rate by the ensemble of hot atoms and present a theoretical model to support the measured results. This result corresponds to atom-photon cooperativity of ~ 1 . Such cooperativity is the onset for quantum interference, needed for high-end chip scale quantum technologies, such as quantum manipulation, quantum information storage and processing, and few photon switching.

incorporating such atoms into the chip scale systems^{19–21}. These works mostly demonstrated the integration of atoms with silicon nitride waveguides^{22,23}, photonic crystals^{24–27} and diffractive elements^{28–30}.

1. Introduction

On-chip nanophotonics is a rapidly advancing platform which is already being used in diverse applications, offering miniaturization and integration of large number of optical elements into a single compact and efficient chip scale system. One of the key components of such on-chip optical systems is the optical resonator such as the whispering gallery mode (WGM) resonator which allows the confinement of light in a small volume for long periods of time. WGM resonators are key components for various use cases such as frequency comb generation^{1–4}, lasers^{5–7}, and sensing^{8–10} to name a few. In parallel to the progress in chip scale nanophotonics, the control and manipulation of atoms and atomic integrated systems is flourishing. Specifically, a great interest resides in atomic systems consisting of alkali atoms such as rubidium (Rb) or cesium. Using such systems, one can study phenomena ranging from quantum entanglement^{11–13}, and Rydberg excitation in atoms^{14,15}, to myriad of other quantum phenomena, from Bose Einstein condensation to Ramsey spectroscopy^{16–18}. A recent effort is geared towards

Figure 1 - a) The experimental setup which consists of: 780nm laser, BS - Beamsplitter 92% Transmission 8% reflection, NDF - Neutral density filter, REF - 71mm long natural Rb cell, DET - Photodetector, COL - Collimator, VOA - Variable optical attenuator, Lensed Fiber - 780nm 2 micron spot size lensed fiber, Heater - Homemade copper oven with resistive heaters, Chip - The device under test, F-DET - sensitive femtowatt photodetector. b) An image of the measurement setup including input and output lensed fibers, Copper oven, photonic chip with ^{87}Rb filled cell bonded on top of it.

A particular research field that can benefit from interfacing atoms with nanophotonics is that of the cavity quantum electrodynamics (CQED). The study of CQED is dated back to the revolutionary work of E. M. Purcell in 1946³¹ where he quantitatively described the modification of spontaneous emission rates of atoms in a cavity. Since then the field of CQED has seen many of important works shaping our understanding of the quantum realm and the interaction between light and matter, ranging from application driven research such as quantum memories^{32,33} and quantum computers^{34,35} to more fundamental concepts such as entanglement³⁶ and Anderson localization³⁷. For many years, the study of CQED was limited to the weak coupling regime, where the rate of spontaneous emission is considerably lower than the rate of dissipation within the cavity. In this regime the coherent energy exchange between the atom and the cavity is overshadowed by the incoherent process of dissipation, resulting in difficulty in maintaining the quantum state of the system long enough to be manipulated or extracted. However, starting from the 1980s³⁸ the technological advancement both in the fabrication process of optical cavities and in laser light sources has allowed scientists to reach the strong coupling regime, where the dissipation rate of the system is lower than the spontaneous emission rate and a coherent interchange of energy can be maintained. This has opened the door for numerous research groups to study the strongly coupled cavity-atom interaction of a single atom³⁹⁻⁴¹, an ensemble of cold atoms⁴²⁻⁴⁴, and up to millions of hot atoms⁴⁵⁻⁴⁷. These experiments, although substantial in their scientific contribution, have not scaled down to the micron sized cavity regime. In recent years an attempt was made to miniaturize the CQED systems in the form of photonic crystal cavities^{24,27} and micro ring resonators⁴⁸⁻⁵¹, yet, these experiments are mostly in the weak coupling regime. This is mainly due to either limited quality factor (less than 10^5) or low atomic

density. The latter is important as the collective Rabi splitting is proportional to $\sqrt{n}$, n being the atomic density.

In this work, we demonstrate a chip scale hybrid atomic-nanophotonic system and show it can operate in the strong coupling regime. This is achieved by the integration of hot vapor of Rb atoms with a nanophotonic chip, consisting of a moderately high quality factor silicon nitride disk resonator ($Q \sim 10^5$) which is evanescently coupled to the thermal Rb vapor. The combination of high quality factor and relatively high atomic density makes it possible to clearly observe mode splitting which is a direct result of the strong coupling between the atoms and the optical cavity with collective Rabi splitting of $g \sim 4$ GHz. To the best of our knowledge, this is the largest splitting demonstrated to date in atomic CQED systems. Our results are supported by a theoretical model interfacing the classical coupled mode theory (CMT) with an atomic two-level system.

2. The experimental setup and results

Device fabrication

We have fabricated a chip scale WGM cavity which is evanescently coupled to a single mode bus waveguide. The cavity consists of a 250 nm thick silicon nitride microdisc of 80 μm radius and a rib thickness of 50 nm on top of a 2 μm thermal silicon oxide. The entire chip is covered by 2 μm of silicon oxide except for the region of the disc where the oxide is removed to allow the interaction of light residing in the microdisc to the ^{87}Rb vapor. The chip is then bonded with a vacuum compatible epoxy sealant to a small Pyrex glass cell. The bonded cell is baked out for 3 days to extract any solvents from the epoxy and water molecules. Finally, the device is

Figure 1 - Measured and simulated transmission spectrum of the integrated WGM-Rb vapor device around the D2 Rb vapor lines ($F_g = 1$ at the bottom of the graph and $F_g = 2$ at the top of the graph) as a function of thermal tuning for 2 different optical powers: a- measured spectrum for power of 24 nW. b- the measured spectrum at the anti-crossing points extracted from the dashed blue and pink lines of figure a. The gray line is the measured transmission through a reference free space vapor cell at room temperature. C, d – same as a, b for a higher power of 240 μ W. e- simulated spectrum for power of 24 nW . f. the simulated spectrum at the anti-crossing points extracted from the dashed blue and pink lines of figure e. g, h – same as e, f for a power level of 240 μ W . The horizontal gray bars in all the panels represent the frequency of the D2 transitions.

filled with ^{87}Rb , and the open end of the glass tube is pinched off. The chip with the cell on top is illustrated in Figure 1.a.

Experimental setup

To perform measurements, the glass cell is positioned in a miniaturized homemade copper oven with its top metal cover replaced by a glass window for the purpose of imaging of the experiment with a long working distance microscope (see Figure 1.b). Once the cell is positioned inside the oven, we gradually increase the temperature from room temperature up to $\sim 380\text{K}$ while constantly measuring the temperature by a thermocouple. Next, light emerging from a tunable laser (Velocity TLB6700) is coupled into the chip via butt coupling scheme using a lensed fiber. A single mode waveguide on the facet of the chip is used to deliver the light to the exposed region of the chip where it is then coupled evanescently to the disc resonator. At the other side of the chip light is out coupled to another lensed fiber and captured by a photodetector (Newport 2151). Tunable variable optical

attenuators (VOA) are connected to the fibers leading to and from the chip in order to control the incoming power from the one hand and avoiding saturating the photodetector on the other. By scanning the laser frequency, we can observe the spectrum of the WGM resonance having a quality factor of about 10^5 as well as the Rb_{87} D_2 , $5^2S_{1/2} \rightarrow 5^2P_{3/2}$ transitions. We then slowly increase the temperature by up to 6 degrees Kelvin to shift the resonance frequency of the WGM towards to Rb resonance by thermal tuning taking advantage of the thermo-optic effect while continuously measuring the transmission spectrum in 1 second intervals.

Experimental results

The measured spectra are then combined to create a 2D surface map as can be seen in Figure 2.a-b. On top of the thermal tuning effect, the heating also results in an increase in vapor density due to the increased vapor pressure. In Figure 2.a one can observe the measured transmission spectrum of light propagating through our device for low

optical power of 24 nW within the waveguide. In fact, only $\sim 4.5\%$ of the optical power resides in the interaction region with the Rb vapor and thus ~ 1 nW optical power is involved in the light-vapor interaction. The gray line represents the measured transmission spectrum of a reference room temperature natural Rb cell while the pink and blue lines represent the spectrum at temperatures in which the WGM resonance frequency coincides with the Rb resonance frequencies for the D2 $F_g = 2$ (blue) and $F_g = 1$ (pink) transitions. These temperatures are marked as vertical dashed lines in Figure 2a. In an analogy to classical physics where two harmonic oscillators⁵² having the same resonance frequency will undergo mode splitting once coupled, our chip scale quantum photonic circuit demonstrates the same behavior as one can clearly observe from Figure 2.a-b. The two harmonic oscillators in our case are the WGM resonance and the Rb resonance. By thermal tuning, the WGM resonance frequency matches that of the Rb D2 line, resulting in mode splitting of up to 4 GHz due to the coupling between the resonators via the electromagnetic field. The evolution of the mode splitting and anti-crossing over time is also shown in video file which can be found in the supplementary material.

On top of the mode splitting and mode anti-crossing that are evident in Figure 2, one can clearly observe that the signal is accompanied by another resonance at the original frequency of the Rb transition. This is attributed to the coupling between the optical mode in the bus waveguide leading to and away from the resonator with the Rb vapor. Another clear observation is the significance difference between low power spectrum (Figure 2a,b) and high power spectrum (Figure 2c,d, where higher optical power of 240 μ W was used). For the latter, the splitting is effectively vanished, due to the effect of saturation of atomic transition. The effect of incident optical power will be discussed in more details later in the text.

Broadening mechanisms

By closely observing Figure 2.b, one can identify a considerable broadening of the Rb absorption lines in comparison with that of the reference cell. This is due to few major reasons. The first is the increase in Doppler broadening which is the result of the increase in photon momentum of light confined to the cavity, as evident by the higher value of wavenumber with respect to that of a photon propagating in free space. The Doppler broadening is given by⁴⁵ $\Delta\omega_D = \sqrt{\frac{8\ln(2)k_B T}{m} \frac{\omega \cdot n_{eff}}{c}}$, where k_B is the Boltzmann's constant, m is the mass of the Rb atom, T is the temperature, ω is the radial frequency of the photon, n_{eff} is the effective mode index of the optical mode in the cavity, and c is the speed of light in vacuum. From this equation we obtain Doppler broadening of $\Delta\omega_D/2\pi = 980$ [MHz]. The second factor which contributes to the line broadening is the transit time broadening due to the finite time it takes for the atoms to cross the confined optical mode. In order to extract the transit time broadening we perform a finite element simulation to attain the mode field distribution of light within the cavity (Figure 3). The electric field in the region exposed

Figure 2 – Electric field of the whispering gallery mode of the disc resonator with n_{eff} of 1.75 and TE polarization. The gray box represents the effective area of the mode outside the nitride which is exposed to the Rb vapor with 83% of the electromagnetic power within the box. The atoms demonstrate two possible atomic velocities: one parallel to the disc and one transverse to it.

to the Rb atoms accounts for $\sim 4.5\%$ of the total electric field of the cavity mode and it resides very closely to the surface of the micro disc. A small region, 1.5 microns wide and up to 100nm above the microdisc as denoted by the gray box in Figure 3, contains 83% of the light outside the disc. We thus treat this region as the effective area of the mode interacting with the Rb vapor, and denote it as $A_{interaction}$. A simplistic way to treat the transit time broadening is by dividing the average velocity of an atom by the distance it travels within the mode. In our model there are two extremum cases: One considers atoms that travel perpendicular to the top surface of the microdisc whereas the other is that of atoms travel in parallel to the surface. The distance an atom travels in the beam for each of the cases is: $\Delta x_{\perp} = 100$ nm, $\Delta x_{\parallel} = 1500$ nm. The broadening corresponding to each of these values is:

$$\frac{\Delta\omega_{tt}^{\perp}}{2\pi} \cong \frac{\langle v \rangle}{2\pi\Delta x_{\perp}} = \frac{\sqrt{\frac{2K_B T}{m}}}{2\pi\Delta x_{\perp}} = 414 \text{ MHz} \quad (1)$$

$$\Delta\omega_{tt}^{\parallel}/2\pi \cong \frac{\langle v \rangle}{2\pi\Delta x_{\parallel}} = \frac{\sqrt{\frac{2K_B T}{m}}}{2\pi\Delta x_{\parallel}} = 27.6 \text{ [MHz]} \quad (2)$$

Where $\langle v \rangle = \sqrt{2K_B T/m}$ is the most probable velocity of the atoms according to Maxwell-Boltzmann distribution. From this rough calculation we obtain the limit of transit time broadening $\Delta\omega_{tt}^{\parallel} < \Delta\omega_{tt} < \Delta\omega_{tt}^{\perp}$. A more accurate value can be extracted from a more rigorous simulation model taking all velocity probabilities into account. However, our somewhat simplified model still provides a good estimation for the different atom groups and their respective broadening mechanism. In our numerical calculations that

Figure 4 a,b) Left: Measured and simulated normalized transmission spectrum of the D2 $F_g=2$ transition as a function of input power ranging from 20nW up to 600 μ W. The dashed blue and green lines denote the case of low input power (24nW) and higher input power ($\sim$ 400 μ W). Right: Transmission spectrum for 24nW input power (blue) and 400 μ W input power (green).

will follow we will use the transit time broadening $\Delta\omega_{tt}$ as a fit parameter and verify that the obtained values falls within these limits.

Model

The challenge in adequately describing the coupled Rb-nanophotonic system resides mostly in the nonlinearity of the Rb vapor due to the effect of saturation, as well as in its nonlocal properties in the momentum space (broadening effects depend on the photon momentum, which in turn depends on the mode properties). To cope with this challenge, we have developed a model that accounts for this nonlinearity and it takes into account our specific device geometry. Detailed description of the model is given in the supplementary.

Simulation results

Based on the above mentioned model, we have simulated the transmission spectrum of light propagating through our device using incident power levels that are similar to the power levels used in the experiment. The simulation results for the low power case (24 nW) are shown in Figure 2.e-f. Mode splitting similar to that observed in the experimental results can be witnessed between temperature offset of 1-3K and the same holds true also for the $F_g = 1$ transition for temperature offset between 3-5K. In Figure 2.g-h a simulation of the scan with higher power (240 μ W) is shown, demonstrating the same behavior as the experimental results (Figure 2c-d) where no mode splitting is visible. This is due

to the effect of saturation of atomic transition, manifesting the nonlinear nature of our system.

Power dependency of the cavity-atom interaction

In order to obtain a clearer view on the power dependency of the system and in particular to learn more about the transition process from the strong coupling regime observed at low power levels to the saturated regime at higher power levels, where no strong coupling is observed, we have conducted a power dependent experiment. The cavity mode has been aligned with the $F_g = 2$ transition via thermal tuning and the input optical power was varied from values as low as 20 nW and up to 600 μ W via two electrically controlled variable optical attenuators (VOAs), one at the input to the chip for the power control and one at its output to prevent the photodetector from saturating as can be seen in Figure 1.a. We have conducted 60 continues measurements of the spectrum with different values of input power at intervals of 1 second between consecutive measurements. The results can be seen in Figure 4.a. A 2D graph and a more detailed plot can be seen on the right for the low-power and high-power spectrum. As one can see the mode splitting occurs over almost 3 orders of magnitude without any change in the Rabi splitting. As the power reaches few microwatts an interesting phenomenon appears where the middle peak (which is due to the waveguide mode), vanishes as the power increased. This occurs due to the enhanced coupling between the atoms

and the waveguide mode which is 3 times higher than for the cavity mode resulting in lower saturation power for the waveguide mode. (A better view on this phenomenon can be seen in the attached video file showing the power scan frame by frame) As the power increased to around 10 μ W and above we are able to see the Rabi splitting decreases until both resonances completely merge into one reaching the saturation regime. The same can be seen in the simulation in Figure 4.b. where the power was varied in the same manner as for the experimental data and a very good fit is obtained over the entire power scan up to the saturation regime. When the power is increased beyond 100 μ W the simulation model begins to deviate from the experimental result in the form of broader resonance and higher contrast in the experimental results. This can be explained by the basic limitations of the model which is valid mostly for weak electromagnetic power since it is based on the dipole approximation and the two level system approximation neglecting most of the nonlinearities which occur in high electromagnetic fields, leaving the saturation regime outside its validity limits.

Discussion

A measure for strong coupling is the collective cooperativity, given as $C = Ng^2/(\kappa\gamma)$, where 2κ is the cavity power decay rate, γ is the atomic homogenous decay rate, and N is the effective number of atoms participating in the transition. Given a Q factor of $\sim 10^5$, $\kappa = 2\pi \cdot 3.8$ GHz. The atomic homogenous decay rate is determined by the transit time broadening, which in our system is estimated to be $\gamma \sim 2\pi 100$ MHz. Based on the measured splitting, $\sqrt{N}g = 2\pi 4$ GHz. Thus, the collective cooperative is found to be $C \sim 42$. From this value one can estimate the atom-photon cooperativity $C_0 = \frac{C}{N}$. N is given by $N_0 \cdot \Delta\omega_D/\gamma$, where N_0 is the number of atoms in the interaction volume (~ 70 μ m³) and $\Delta\omega_D$ is the Doppler linewidth, as defined above. With these definitions, one obtains atom-photon cooperativity $C \sim 1$. Such cooperativity is the onset for quantum interference, needed for high-end quantum technologies. This signifies a clear path towards atom-photon cooperativities on the order of hundred, simply by reducing the radius of the disk towards the 10 microns' regime, while simultaneously increasing its Q factor to 10^6 and above.

Conclusions

We have demonstrated a chip scale nanophotonic-atomic system reaching immense rabi splitting of 4GHz which to the highest value as to the authors knowledge and has not been observed before in atomic vapor systems. Furthermore, we have used the Bloch-Maxwell equations combined with CMT to implement a simple model of the cavity-atoms system. The validity of the model was tested by comparing with the measured data both for the temperature driven scan of the device and for the case where the cavity and the Rb resonances are co-aligned and the incoming power is swept over. The model has shown a very good agreement with the measured data, mostly in the weak driving regime where the power is below saturation. The small number of interactivity atoms which is less than 700 atoms in the cavity mode for any given time allows one to interact with a very small group of atoms in

particularly if one chooses to implement ensemble selective measurement such as velocity selection⁵³ or saturated absorption spectroscopy⁵⁴ for example. Which might allow to study strong coupling interactions of only few atoms in a compact and a robust on-chip platform. The work presented here opens the possibility to utilize hot atoms for applications in the quantum domain such as magnetometry⁵⁵ or Rydberg electrometry⁵⁶ and especially in the CQED⁵⁷ field.

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