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Superconducting atom chips : towards quantum hybridization

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ABSTRACT

Atomic-superconducting hybrid systems are of particular interest as they are combining the long coherence times of ultracold atoms and fast gate operation times of superconducting circuits. Here we discuss an experimental realization of an interface between cold Rydberg atoms and a transmon circuit embedded in a microwave cavity. We present numerical calculations showing a significant coupling of Rydberg atoms to a transmon. Here we place the atoms in the vicinity of the transmon shunting capacitor. Exciting them to the Rydberg states alters the dielectric constant of the medium inside the capacitor. This results in a dispersive shift of the transmon resonance frequency. Using the protocols developed in Ref. 1, 2 will allow the coherent transfer of quantum states between these two systems.

Keywords: Cold Atoms, Superconductivity, Hybrid Quantum Systems, Quantum Information

1. INTRODUCTION

Superconducting atom chips combine ultracold atoms and superconducting circuits in one platform. Interconnecting these distinct physical quantum technologies in a so called 'hybrid quantum system' offers potential for creating unique capabilities in quantum communication and information applications Ref. 3. Atomic qubits are well isolated from their environment and thus show long coherence times, making them ideal candidates for quantum storage Ref. 4. However, their isolation gives rise to inefficient coupling, making them ineffective for processing quantum information. In superconducting qubits the roles are reversed. They are very well controlled, but suffer from comparably short coherence times, making them ideal quantum processors, but not memories. Consequently, integrating both systems will allow efficient processing and storage of quantum states in one device. Furthermore, atoms can be coherently coupled to optical photons Ref. 5, enabling them to transmit quantum states to other devices.

Integrating ultracold atom with superconducting circuit technologies is a challenging experimental task Ref. 6, 7, 8, 9. In order to build a high-fidelity coherent interface, atoms need to be manipulated in cryogenic environments, in close proximity to superconducting circuits, using optical, magnetic and electric fields Ref. 10, 11. Generally, these will disturb the superconducting state, leading to strong perturbations in the superconducting qubit. Techniques that keep these perturbations as small as possible while allowing sufficient coupling for coherent exchange between both systems are currently under development.

Here we introduce a coherent interface between Rydberg atoms and a superconducting qubit. We analyze the possible scenario of coupling Rydberg atoms to superconducting circuits enclosed in a 3D microwave resonator. The unique properties of Rydberg atoms, namely that they possess microwave frequency transitions as well as high electrical dipole moments, can be used to achieve coherent coupling between both systems. We explore this interface doing numerical simulations of the electrical coupling of Rydberg atoms of ⁸⁷Rb to a transmon qubit.

2. A HYBRID QUANTUM PLATFORM

In the following we describe a hybrid platform of Rydberg atoms and superconducting qubits. After a general description of the coupling mechanism we will present a potential implementation of the system. Furthermore we present numerical simulations showing that both quantum systems can be coherently coupled.

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Figure 1. Diagram of hybrid atom-3D transmon setup. A 3D control cavity represented as a parallel LC resonator is capacitively coupled to a transmon qubit. The transmon consists of a Josephson junction and a shunting capacitor. Atoms are embedded inside the shunting capacitor of the transmon.

2.1 A Rydberg atom - Transmon hybrid

Atomic and superconducting qubits are readily compatible as they both share transition frequencies in the few GHz range. For atoms these transitions occur naturally, while for superconducting circuits the frequencies are by design and can even be tuned in-situ Ref. 12. The coupling between both systems is accomplished through electric or magnetic dipole interactions, where the interaction is either direct, or indirect via a quantum bus. Typically, a microwave resonator is used as a bus Ref. 13. Here we want to study the direct coupling of Rubidium Rydberg atoms with a superconducting transmon qubit embedded in a 3D microwave resonator, a so-called 3D transmon Ref. 14. The coupling in this case is accomplished via the electric field in the capacitive part of the transmon.

Superconducting qubits can be viewed as LC resonators that are made anharmonic by replacing the inductor with a Josephson junction, which introduces a non-dissipative nonlinearity at the single quantum level. This leads to a non-linear excitation spectrum of the resonator, allowing to single out the lowest states as a two level system. The resonance frequency of this qubit is determined by the inductance and capacitance of the circuit, which can be designed arbitrarily. In recent years the 3D transmon became a widely used circuit, as it shows long coherence times and is comparably easy to fabricate Ref. 15. This design consists of a Josephson junction connected to a microwave antenna, embedded in the center of a 3D cavity, which acts as a control and readout of the qubit. The microwave antenna of the transmon is the shunting capacitor. Atomic electric dipole moments can be coupled to a transmon through the local electric field of its capacitor to form a hybrid system Ref. 1, as depicted in Fig.1. Here the atoms act as a dielectric medium, tuning the capacitance and thus the frequency of the transmon. Vice versa, the electrical field of the capacitor will shift the states of the atoms Ref. 2. The interaction strength depends on two factors, the polarizability of the atoms and the coupling of the atoms to the capacitor. The polarizability of neutral atoms is increasing with the principle quantum number n and scales as n^7 for Rydberg states Ref. 16. To reach strong coupling it is therefore favorable to use Rydberg states as the density needed for ground state atoms are not attainable. The atom-capacitor coupling is technically challenging. Ideally, atoms should be placed inside the capacitor where the electric fields are strongest. As the transmon is a planar circuit on chip this is impractical. Instead, atoms need to be coupled via the fringe electric field of the capacitor that is protruding out of the chip.

Figure 2. 3D transmon design. Left : a transmon circuit on a sapphire substrate (blue) is embedded in a 3D microwave cavity. The circuit consists of a Josephson junction and a shunting capacitor with the following dimensions: $L = 400, \mu\text{m}$, $W = 300 \mu\text{m}$ and $G = 30 \mu\text{m}$, where L , W and G are the length, width and gap of the capacitor. The 3D microwave cavity is used for control and readout of the transmon. Right : numerical simulation of the TE_{101} mode surface current distribution.

2.2 Trapping atoms in the vicinity of a transmon qubit

Trapping neutral atoms close to a superconducting qubit is a challenging task. Atoms are routinely trapped using strong magnetic or optical fields, which are detrimental to superconductors. Magnetic fields applied to superconductors create Meissner currents and can create vortices, which leads to changes in the complex conductivity of the material and therefore to shifts in resonance frequencies and increased dissipation. Magnetic trapping of atoms requires field gradients on the order of 10 mT/cm , which would produce field strengths in the range of 1 mT/cm at the position of the superconducting circuits. However, it was shown Ref. 17 that even fields of $100 \mu\text{T}$ and below have significant influence on the circuit properties. Therefore it is unfeasible to use magnetic traps.

Here we propose to use an optical dipole trap to bring atoms close to a superconducting qubit. The main concern in this approach is direct irradiation of the superconducting components. It was found Ref. 11 that absorption of photons is a significant mechanism for decoherence in qubits. Therefore direct irradiation and scattered light coming from the atoms need to be avoided.

We consider a transmon that is placed in the center of a 3D cavity. Fig.2 left displays a schematic of the setup. Shown are the cavity that is capacitively coupled via SMA connectors to the control and readout electronics, as well as a piece of substrate, depicted in blue, supporting the transmon. The cavity dimensions are $31 \times 6 \times 31 \text{ mm}$, which results in a simulated resonance frequency and Q-factor of the fundamental TE_{101} mode of $f_0 = 6.90 \text{ GHz}$ and $Q_L = 1.45 \cdot 10^4$ respectively. The TE_{101} mode is chosen for maximum coupling of the cavity and the qubit. To bring atoms close to the qubit, openings in the cavity are needed for allowing atoms to enter. These openings should be placed on spots that carry no surface current so the Q-factor and frequency are minimally influenced. In order to determine these spots we simulate the surface current density of the TE_{101} mode, which is shown in Fig.2 on the right side. It can be seen that for this mode the current density is negligible in the center of the z-x plane. This permits to add circular openings on both sides of the cavity, which we choose to have a diameter of 5 mm , running parallel to the y-axis with an z-offset of $50 \mu\text{m}$ above the transmon chip. Preliminary measurements of such a setup showed that there is no influence of the openings on the cavity parameters. The openings in the 3D cavity allow a focused gaussian laser beam to pass through the cavity. Choosing a beam waist of $30 \mu\text{m}$, the beam can enter and leave the cavity through optical viewports of a dilution refrigerator without directly illuminating any surface inside the refrigerator. Consequently, there will be no direct heating of any surface by the laser light.

Transporting atoms inside the 3D cavity works in two steps. First an atomic cloud is prepared in a dipole

Figure 3. Transport of atoms in the vicinity of the transmon. An atomic cloud (green) is prepared in an optical dipole trap with a total beam power of 7 W and a beam waist of 30 μm outside the cavity. Through translation of the trap focus the atoms are moved inside the cavity.

trap outside the cavity. Fig.3 shows a schematic of this setup. Atoms (green) are held in the focus of a gaussian laser beam (red) which is passing through the cavity. In the next step the focus of the beam is translated linearly into the cavity, transporting the atoms inside. The beam waist of $w_0 = 30 \mu\text{m}$ ensures that the atomic cloud can be brought close to the transmon chip. Furthermore, we set the wavelength of the trapping light to $\lambda = 1064 \text{ nm}$ and the optical power to $P = 7 \text{ W}$. The chosen beam waist and wavelength result in a Rayleigh length of $R_L = \pi \cdot w_0^2 / \lambda = 2.7 \cdot 10^{-3} \text{ m}$. This ensures that the atomic cloud will be distributed over the whole length of the transmon.

With the given beam parameters the trap depth U and scattering rate R for the atomic trap are given by Ref. 18 :

$$U = \frac{3\pi c^2}{2w_0^3} \left(\frac{\Gamma}{\Delta} \right) \cdot I, \quad R = \frac{3\pi c^2}{2\hbar w_0^3} \left(\frac{\Gamma}{\Delta} \right)^2 \cdot I \quad (1)$$

, where I , Δ are the light intensity and detuning, Γ is the decay rate of the atomic transition and $\hbar$, c are the reduced Planck's constant and speed of light. Using ^{87}Rb with a transition wavelength of $\lambda_0 = 780 \text{ nm}$ and a decay rate of $38.11 \cdot 10^6 \text{ s}^{-1}$ we find a trap depth of $U = 640 \mu\text{K}$ and a scattering rate of $R = 5 \text{ s}^{-1}$.

The scattering from the atoms inside the 3D cavity corresponds to a power of $2.5 \cdot 10^{-19} \text{ W}$. The total inner surface of the 3D cavity is $A = 29 \text{ cm}^2$. Assuming the cavity is cooled to $T = 20 \text{ mK}$ inside a dilution refrigerator, the total blackbody radiation emitted from the cavity wall is $P_{BB} = A \cdot \sigma \cdot \epsilon \cdot T^4 = 2.6 \cdot 10^{-18} \text{ W}$, where we used the Stefan-Boltzmann constant $\sigma = 5.67 \cdot 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$ and a emissivity of Aluminum of $\epsilon = 0.1$. We conclude that the total power irradiated by black body radiation is one order of magnitude larger than the total power emitted by the atoms. The fraction of the photons from the atoms scattered onto the superconducting circuits can be neglected.

2.3 Design of the 3D transmon qubit

The transmon qubit geometry offers a suitable platform for our proposal due to the large shunting capacitance to be coupled to the Rydberg atoms. To study the coupling between the systems through the frequency shift of the artificial two-levels atom, we choose to use two capacitive pads in parallel with a single Josephson junction. To simulate the transmon qubit one can model the Josephson junction as an RLC lumped element resonator in between the shunting capacitor and extract the resonance from the S_{21} scattering parameter of the whole system, chosen to be $f_0 = 5.5 \text{ GHz}$ here. In this particular scenario we are studying the coupling of the electric dipole moment of the Rubidium cloud to the electric field of the capacitor. In Fig.4 a sample qubit used in the simulations is represented, with the following dimensions: $\mathbf{L} = 400 \mu\text{m}$, $\mathbf{W} = 300 \mu\text{m}$ and $\mathbf{G} = 30 \mu\text{m}$, giving a capacitance of $C_0 = 38.249 \pm 0.004 \text{ fF}$. The atomic cloud must be parallel to the capacitor gap to

Figure 4. Top view of the transmon qubit. Atoms (green) are brought close to the center gap. $\mathbf{L}$ is the length of the pads, $\mathbf{W}$ the width and $\mathbf{G}$ the gap between them where the junction is patterned.

have a homogeneous coupling to the fringe field, similar to a macroscopic dielectric filled capacitor, providing a maximized frequency shift of the transmon Fig.4. The dielectric atomic medium has been modeled as a parallelepiped to reduce the computational cost. The length of the cloud is taken equal to $\mathbf{L}$ while the diameter of $\mathbf{d} = 60 \mu\text{m}$ is compatible with the focused laser beam waist. The atomic density is assumed to be $\rho = 10^{16} \text{ m}^{-3}$ as in our actual experimental setup. The correction to the vacuum environment is calculated from Ref. 19 using the Rydberg state $80S$, which corresponds to a scalar polarizability $\alpha_0 = 8.87884 \cdot 10^{-29} \text{ F} \cdot \text{m}^2$ and a correction to the dielectric constant equal to $\epsilon_r = 1.100278$. Our degree of freedom in the simulation is the vertical movement of the atoms, meaning the distance between the qubit and the dielectric medium. By moving it in small steps in an electrostatic computation we observe a capacitance shift as well as a corresponding frequency shift of the artificial atom transition, e.g. we can achieve a 1.1MHz resonance shift with the cloud at $50 \mu\text{m}$ height from the surface Fig.5.

2.4 Conclusion

In conclusion, we studied the experimental parameters required to couple a Rydberg atom ensemble to a transmon system. Using currently attainable experimental parameters we showed the feasibility of trapping an atomic cloud close to a 3D transmon qubit. In addition we performed numerical simulations of the transmon resonance, showing a significant shift in the resonance frequency in the presence of Rydberg atoms. Nevertheless, the experimental

Figure 5. Effects of the atomic cloud in proximity of the superconducting chip surface. Left: change in the transmon capacitance for different values of the Rydberg cloud distance. Right: transmon resonance frequency shift for varying Rydberg cloud distance.

effort required for this task is considerable. One needs to merge ultracold atom technology with a cryogenic environment suitable for superconducting quantum circuits. This technology is currently under development in our laboratory. It has been shown in Ref. 2 that in such a atom-superconductor hybrid system a bilateral transfer of quantum states between both systems is possible. This paves the way for a quantum computational platform combining the advantages of ultracold atoms and superconducting quantum circuits.

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