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Approaching ultrastrong coupling in transmon circuit QED using a high-impedance resonator

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In this experiment, we couple a superconducting transmon qubit to a high-impedance 645 Ω microwave resonator. Doing so leads to a large qubit-resonator coupling rate $g$, measured through a large vacuum Rabi splitting of $2g \approx 910$ MHz. The coupling is a significant fraction of the qubit and resonator oscillation frequencies $\omega$, placing our system close to the ultrastrong coupling regime ($g/\omega = 0.071$ on resonance). Combining this setup with a vacuum-gap transmon architecture shows the potential of reaching deep into the ultrastrong coupling $g \sim 0.45$ with transmon qubits.

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I. INTRODUCTION

Cavity QED is a study of the light-matter interaction between atoms and the confined electromagnetic field of a cavity [1]. For an atom in resonance with the cavity, a single excitation coherently oscillates with vacuum Rabi frequency $g$ between the photonic and atomic degree of freedom if $g$ exceeds the rate at which excitations decay into the environment, which is known as the strong coupling condition [2]. Spectroscopically, this is observed as a modesplitting (vacuum Rabi splitting) with distance $2g$. If the coupling is small with respect to the resonator (atomic) frequency $\omega_a$ ($\omega_r$), $g \ll \omega_r, \omega_a$, and the frequencies respect the condition $|\omega_a - \omega_r| \ll |\omega_r + \omega_a|$, the interaction is faithfully described with the Jaynes-Cummings (JC) model [3]. As the coupling becomes a considerable fraction of $\omega_r$ or $\omega_a$, typically $g = g/\omega_r, a \sim 0.1$, the JC model no longer applies and the interaction is better described by the Rabi model [4–7]. This ultrastrong coupling (USC) regime shows the breakdown of excitation number conservation; however, excitation parity remains conserved for arbitrarily large $g$ [8]. The key prediction for the deep-strong coupling (DSC) regime, where $g \sim 1$, is a symmetry breaking of the vacuum (i.e., qualitative change of the ground state) similar to the Higgs mechanism [9]. The prospect of probing these new facets of light-matter interaction, in addition to potential applications in quantum information technologies [10,11], has spurred many experimental efforts to reach increasingly large coupling rates.

Experimentally, the only platform that observed ultrastrong or higher coupling rates with a single emitter uses a superconducting circuit with a flux qubit. Pioneered by the experiments of Refs. [12,13], experiments in the DSC regime have now been achieved with flux qubits coupled to resonators [14] as well as an electromagnetic continuum [15]. Additionally, the U/DSC coupling regime of the Rabi model was the subject of recent analog quantum simulations [16,17].

Here we explore coupling strengths at the edge of the USC regime in circuit QED using a superconducting transmon qubit [18] coupled to a microwave cavity that has a high characteristic impedance. Using a high-impedance $Z_0$ considerably increases coupling rates compared to typical 50 $\Omega$ implementations by increasing the voltage zero-point fluctuations of the cavity $V_{zpf} \propto \sqrt{Z_0}$ as exploited in cavity QED with quantum dots [19]. When the transmon and fundamental mode of the cavity are resonant, we spectroscopically measure a coupling $g/\Pi = 455$ MHz, corresponding to $g = 0.071$. With the prospect of maximizing the transmon analog of the dipole moment [20], we show how this system could approach its theoretical upper limit [21,22]

$$2g \lesssim \sqrt{\omega_r \omega_a}.$$ (1)

Exploring the ultrastrong coupling regime of the transmon has two main advantages with respect to using flux qubits. First, the transmon has become a standard in efforts to build a quantum processor [23–25]. Implementing USC in this system therefore paves the way to exploiting USC features in quantum computation to decrease gate times [10] and perform quantum error correction [11]. Secondly, due to the weak anharmonicity of the transmon we are exploring a different Hamiltonian than the one implemented with flux qubits. The higher excitation levels of the transmon become increasingly relevant with higher coupling rates and in the USC regime it cannot be considered a two-level system. The system studied here is therefore not a strict implementation of the Rabi model, yet is still expected to bear many of the typical USC features and a proposal has been made to measure them [26].

II. SETUP

Our device, depicted in Fig. 1, consists of a high-impedance superconducting $\lambda/2$ microwave resonator [27] capacitively overcoupled to a 50 $\Omega$ feedline on one end and coupled to a transmon qubit on the other. The resonator is a 1 $\mu$m wide, 180 nm thick, and $\sim 6.5$ mm long meandering conductor. It is capacitively connected to a background plane through the 275 $\mu$m silicon substrate as well as through vacuum/silicon to the side ground planes.

The transmon is in part coupled to ground through a vacuum gap capacitor; see Fig. 1(b). Its bottom electrode constitutes one island of the transmon; the other plate is a suspended 50 $\mu$m thick graphite flake. The diameter of this capacitor is 15 $\mu$m with a gap of 150 nm. This device was designed to couple the mechanical motion of the suspended graphite to the transmon qubit, where the coupling is mediated by a dc voltage offset [28,29]. In this experiment, the graphite flake is
Following circuit quantization [33], we find that the dynamics of the qubit to ground. From room temperature resistance we stamp a graphite flake on the 15 μm wide stripline on one end and a transmon qubit on the other end. From a vector network analyzer we send a microwave tone that is heavily attenuated before being launched on the feedline of the chip. The transmitted signal is send back to the vector network analyzer through a circulator and a low-noise high-electron-mobility transistor amplifier. This setup is detailed in the Supplemental Material [21]. It allows us to probe the absorption of our device and thus the energy spectrum of the Hamiltonian (2). At high driving power we measure the bare cavity resonance [34] to have a total linewidth of 51 fF and its coupling capacitor is $C_c = 9 fF$. The parameters of other circuit elements will be extracted from the data. We will denote the lowest three eigenstates of the transmon by $|g\rangle$, $|e\rangle$, and $|f\rangle$ with increasing energies.

We characterize our device at a temperature of 15 mK, mounted in a radiation-tight box. From a vector network analyzer we send a microwave tone that is heavily attenuated before being launched on the feedline of the chip. The transmitted signal is send back to the vector network analyzer through a circulator and a low-noise high-electron-mobility transistor amplifier. This setup is detailed in the Supplemental Material [21]. It allows us to probe the absorption of our device and thus the energy spectrum of the Hamiltonian (2). At high driving power we measure the bare cavity resonance [34] to have a total linewidth of $\kappa = 2 \pi \times 29.3$ MHz and a coupling coefficient of $\eta = \kappa_c/\kappa = 0.96$, giving the ratio between the coupling rate $\kappa_c$ and total dissipation rate $\kappa = \kappa_c + \kappa_i$, where $\kappa_i$ is the internal dissipation rate.

### III. RESULTS

With a current biased coil, we can control the magnetic field and tune the effective $E_J$ to bring the qubit in resonance with the cavity. Where the transmon and resonator frequencies cross, we measure a vacuum Rabi splitting which gives an estimate of the coupling rate $2g/2\pi \approx 910$ MHz as shown in Fig. 2.

In Fig. 3, we show the result of performing two-tone spectroscopy to probe the qubit frequency [35,36]. When the qubit is detuned from the cavity, the resonator acquires a frequency shift which is dependent on the state of the qubit. Hence probing the transmission of the feedline at the cavity resonance (shifted by the qubit in the ground state), while exciting the qubit with another microwave tone, will cause the transmission to change by a value $\delta|S_{21}|$ due to the qubit-state dependent shift. In Fig. 3(a) we measure the spectral response of the qubit for different magnetic fields. As the magnetic flux through the SQUID loop tunes the qubit frequency we track the ground to first excited state transition as a function of magnetic field. Since the probe power is kept constant during this experiment a clear power broadening of

![Circuit Diagram](image-url)
the qubit is visible, because more of the power is delivered to the qubit as it is closer to the cavity in frequency. The secondary faint resonance corresponds to the spectral response of the first to second exited state transition of the transmon due to some residual occupation of the first excited state. The difference in frequency between both transitions provides an estimate of the residual occupation of the first excited state. The difference 

$$g = \frac{\hbar}{\pi Z_r}$$

is related to the characteristic impedance of the transmon line through 

$$Z_0 = \pi Z_r/2$$

yielding a value $Z_0 = 645 \, \Omega$.

**IV. TOWARDS HIGHER COUPLING IN TRANSMON SYSTEMS: A PROPOSAL**

In the circuit of Fig. 1(d), the coupling rate is limited following

$$g = \frac{1}{\sqrt{\omega_a \omega_r}} \leq \frac{1}{2}.$$  

(5)
The highest couplings are therefore achieved by maximizing two capacitance ratios: $C_c/C_J$ and $C_c/C_r$. In the language of cavity QED with natural atoms, maximizing the first ratio is equivalent to increasing the dipole moment of the atom which is done by using Rydberg atoms [1]. Maximizing the second ratio increases the vacuum fluctuations of the cavities electric field as performed in alkali-atom experiments in a very small optical cavity [41].

In the regime $C_c/C_J,C_c/C_r \gg 1$ the effective capacitances of Eq. (4) are approximated by

$$C_{I,\text{eff}} = C_{r,\text{eff}} \simeq C_J + C_r,$$

these capacitances being the quantities to minimize to increase the coupling. Maximizing the coupling while keeping the resonator and transmon frequencies constant therefore requires a large increase in the inductances. In other words, the higher the impedance of the resonator and the higher the ratio $E_r/E_J$ in the transmon, the higher the coupling.

The highest ratio of $E_r/E_J$ for which we remain in the transmon regime is $\sim 1/20$ [18]. Combined with a typical choice of the transmon frequency $\omega_D/2\pi = 6$ GHz, compatible with most microwave experimental setups, we obtain a value of the transmons total capacitance $C_{I,\text{eff}} = C_{r,\text{eff}} \simeq C_J + C_r \simeq 20$ fF. Choosing $C_J = C_r = 10$ fF maximizes Eq. (5). Fixing the resonator frequency to $\omega_J = \omega_r$ leads to a value for resonators characteristic impedance: $722$ $\Omega$ if a $\lambda/4$ resonator is used, 1.44 k$\Omega$ for a $\lambda/2$ resonator, and 918 $\Omega$ for a lumped element resonator. The coupling achieved now depends on the value of the coupling capacitor. For $C_c = 200$ fF, for example, $\tilde{g} = 0.45$ and the system is deep in the USC regime.

In Ref. [20], the USC regime was reached by increasing the first capacitance ratio of Eq. (5), $C_c/(C_J + C_r) \simeq 0.9$, through the use of a vacuum-gap coupling capacitor. In this work, the large coupling is reached by increasing the second ratio $C_c/(C_J + C_r) \simeq 0.136$ above the usual values through the use of a high-impedance resonator while the first capacitance ratio remains modest $C_c/(C_J + C_r) \simeq 0.15$. Combining both approaches into a single device represented schematically in Fig. 4 would allow experimentally reaching deep into the USC regime $\tilde{g} = 0.45$ by matching the circuit parameters presented previously. The values $C_J = 10$ fF and $C_r = 200$ fF can be easily achieved experimentally reproducing the vacuum-gap transmon architecture of Ref. [20] with a smaller gap and larger capacitive plate, maybe even by replacing the vacuum gap by a dielectric. The use of a $\lambda/4$ resonator rather than a $\lambda/2$ is preferable as it decreases the impedance needed as well as increases the frequency spacing between the fundamental and higher modes. Moving to a $\lambda/4$ resonator makes the current architecture sufficient in terms of resonator impedance. The impedance could be further increased using a high kinetic inductance based resonator [42] or by using an array of Josephson junctions [43].

This proposal is however limited by the underlying assumption that only a single mode of the resonator participates in the dynamics of the system. However, for larger coupling rates, the higher modes no longer play a weak perturbative role [45]. Exploring the exact consequences of this fact on the observable USC phenomena that can be observed is outside the scope of this work, as is determining alternatives to probing the system spectroscopically to show for example the nontrivial ground state that one would expect in this regime. For a detailed study of these topics, we refer the reader to Ref. [26].

V. CONCLUSION

We have shown that it is possible to enhance the coupling between a microwave resonator and a transmon qubit by increasing the impedance of the resonator to 645 $\Omega$ compared to typical 50 $\Omega$ implementations. In doing this we reach a coupling rate of $g/2\pi = 455$ MHz at resonance, which is close to the ultrastrong coupling regime ($\tilde{g} = 0.071$). We have shown that by optimizing this strategy through sources of high inductance, combined with a vacuum-gap transmon architecture, we have the potential of reaching far into the ultrastrong coupling regime.

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