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$\mathbb{Z}_2$ quantum memory implemented on circuit quantum electrodynamics

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ABSTRACT

We present a technique to store and retrieve single- and two-qubit states into a parity-protected quantum memory implemented on a state-of-the-art superconducting circuit architecture. Our proposal relies upon a specific superconducting circuit design that permits a tunable qubit-resonator coupling strength. The latter allows us to adiabatically tune from the weak coupling to the ultrastrong coupling regime of light-matter interaction, where a controllable and well-protected effective two-level system is defined due to the $\mathbb{Z}_2$ parity symmetry. Storage and retrieval time of the qubit are in a few nanoseconds timescale, which is far below the effective qubit coherence time.

Keywords: flux qubit, $\mathbb{Z}_2$ parity protected memory, adiabatic evolution, ultrastrong coupling regime

1. INTRODUCTION

Recent advancements in quantum technologies significantly empower the development of a practical quantum computer.¹ In particular, proof-of-principle experiments in circuit quantum electrodynamics (cQED)²⁻⁴ have shown quantum speed-up⁵ over their classical counterparts. Equipped with this speed-up, a quantum central processing unit⁶ would eventually need to store valuable quantum bits (qubits) in terms of a scalable quantum random-access memory.⁷⁻⁹ Thus, quantum memory (QM) devices such as solid-state based QMs,¹⁰⁻¹² topological QM¹³ and $\mathbb{Z}_2$ QMs implemented on one- and two-dimensional spins array¹⁴ become essential components in implementing the quantum Von Neumann architecture.

Among all the known quantum computing architectures, cQED is one of the most promising candidates to attain a scalable quantum computer. Furthermore, recent experiments in cQED^{15,16} have demonstrated the ultrastrong coupling (USC) regime of light-matter interaction.¹⁷ In this regime, the qubit-resonator coupling strength Ω_0 is comparable to or larger than some fractions of the resonator frequency ω_{res} , i.e., $\Omega_0/\omega_{\text{res}} \gtrsim 0.1$. Here, the system dynamics exhibit a $\mathbb{Z}_2$ parity symmetry which is governed by the Rabi Hamiltonian.¹⁸ In particular, when the ratio $\Omega_0/\omega_{\text{res}}$ approaches unity, it has been shown that the ground and first excited states of the system can be approximated^{19,20} by

$$|\Psi_{\text{G/E}}\rangle \simeq \frac{1}{\sqrt{2}} [|-\alpha\rangle|+\rangle^{\otimes N} \pm (-1)^N |\alpha\rangle|-\rangle^{\otimes N}], \quad (1)$$

where $|\alpha\rangle$ is a coherent state of the resonator field with $\alpha = \Omega_0/\omega_{\text{res}}$, $|\pm\rangle = (|e\rangle \pm |g\rangle)/\sqrt{2}$ are eigenstates of the Pauli operator σ_x , $|g\rangle$ ($|e\rangle$) stands for the ground (excited) state of the qubit, and N is the number of qubits embedded inside the resonator. The states in Eq. 1 form the basis of a robust qubit¹⁹ in the deep strong coupling (DSC) regime,²¹ that is $\Omega_0/\omega_{\text{res}} \gtrsim 1$, reaching coherence times of about $\tau_{\text{coh}} \gtrsim 10^5/\omega_{\text{eg}}$, where ω_{eg} is the qubit frequency. Thus, it may give rise to a good quantum memory within the framework of cQED setup.

In the present work, we propose a technique to store and retrieve unknown single- and two-qubit states to and from a $\mathbb{Z}_2$ quantum memory operating at the USC regime. We use the specific superconducting circuit design [see Fig. 1] that permits a tunable qubit-resonator coupling strength Ω . In particular, the storage and retrieval of a qubit is achieved by adiabatically switching the qubit-resonator coupling back and forth between the weak coupling and the ultrastrong coupling. We show that the whole process can be operated in a few nanoseconds timescale, which is much shorter than the effective qubit coherence time. In the following Sec. 2, we discuss our superconducting circuit design and numerical results for the storage and retrieval of single-qubit states are discussed in Sec. 3. At last, in Sec. 4, we conclude with summarizing remarks along with future practical implications arisen from our proposal.

2. CIRCUIT QED ARCHITECTURE

We show our superconducting circuit design in Fig. 1. It consists of a standard flux qubit composed of three Josephson junctions labelled 1 – 3, surrounded by additional four junctions labelled 4 – 7 while the whole configuration is galvanically coupled²² to an inhomogeneous coplanar waveguide resonator (CWR) that supports a single bosonic mode. The flux qubit design exhibits three main features arising from the external fluxes ϕ_ℓ ($\ell = 1, \dots, 5$). Firstly, it provides a tunable qubit-resonator coupling strength via the external fluxes ϕ_4 and ϕ_5 . Secondly, it allows us to manipulate the qubit energy via the external flux ϕ_1 , which is independent of the qubit-resonator coupling strength. Thirdly, it reaches the USC regime via the coupling junction 8 shared by the qubit and the resonator.¹⁵

Following from the cQED design of Fig. 1, we naturally arrive at the flux qubit potential energy by adding the corresponding Josephson potential energy terms $\mathcal{E}(\varphi_\ell) = -E_{J\ell} \cos(\varphi_\ell)$, where $E_{J\ell}$ and φ_ℓ represent the Josephson energy and the superconducting phase across the ℓ th junction, respectively. We assume $E_{J1} = E_{J2} = E_J$, $E_{J3} = \alpha E_J$ and $E_{J4} = E_{J5} = E_{J6} = E_{J7} = \beta E_J$, where dimensionless parameters $\alpha, \beta < 1$. In addition, the flux quantization criterion has to be satisfied, i.e., the total flux across any closed loop has to be an integer multiple of the fundamental flux quantum $\Phi_0 = h/2e$. In another words, $\sum_\ell \varphi_\ell = 2\pi f_\ell + 2\pi n$, where $f_\ell = \phi_\ell/\Phi_0$ is a frustration parameter. With this quantization criterion and the condition $f_4 = f_5$, the potential energy, containing both the qubit and the qubit-resonator interaction energy terms, reads

$$\begin{aligned} \frac{U}{E_J} = & -[\cos \varphi_1 + \cos \varphi_2 + \alpha \cos(\varphi_2 - \varphi_1 + 2\pi f_1)] + 2\beta(f_4)[\cos(\varphi_2 - \varphi_1 + 2\pi(f_1 + f_2 + f_4/2) + \Delta\psi) \\ & + \cos(\varphi_2 - \varphi_1 + 2\pi(f_3 + f_4/2))], \end{aligned} \quad (2)$$

where $\beta(f_4) = \beta \cos(\pi f_4)$, and $\Delta\psi$ stands for the phase slip shared by the resonator and the ϕ_2 loop, [see Fig. 1]. We also note that the junction 8 at the CWR introduces an extra boundary condition modifying the mode

Figure 1. Schematic of the circuit QED design for storage and retrieval of an unknown quantum state. (a) An incoming flying qubit with an unknown quantum state (red colored left arrow) impinges upon the resonator (light blue). When necessary, the stored qubit is released as a outgoing flying qubit (red colored right arrow). (b) The zoomed-in flux qubit with a tunable qubit-resonator coupling strength, attained from the external fluxes ϕ_4 and ϕ_5 .

structure of the resonator but not the potential term, Eq. 2. The latter is guaranteed by assuming majority of the superconducting current flows through the resonator.¹⁷ A detailed analysis of an inhomogeneous CWR can be found elsewhere.^{17,23} In particular, it has been shown that the phase slip takes the form $\Delta\psi = \Delta\psi_1(a + a^\dagger)$ where $\Delta\psi_1 = (\delta_1/\varphi_0)(\hbar/2\omega_r C_r)^{1/2}$ and $a^\dagger(a)$ corresponds to creation (annihilation) operator of the resonator bosonic mode. Here, $\delta_1 = u_1(x_1) - u(x_2)$ is the difference between two first-order spatial modes evaluated at the two points shared by the resonator and the ϕ_2 loop, $\varphi_0 = \Phi_0/2\pi$ is the reduced flux quantum, ω_r is the frequency of the first resonator mode, and $C_r = C_{\text{res}} + C_{J8}$ is the total geometric capacitance of the resonator, respectively.

By considering the condition $\Delta\psi_1 \ll 1$ with realistic resonator parameters^{17,23} and expanding up to the second order in Eq. 2, the potential energy U can further be approximated as

$$\frac{U}{E_J} = -[\cos\varphi_1 + \cos\varphi_2 + \alpha\cos(\varphi_2 - \varphi_1 + 2\pi f_1)] + 2\beta(f_4) \left[\cos\varphi \left(1 - \frac{1}{2!}(\Delta\psi)^2 \right) + \Delta\psi \sin\varphi + \cos\theta \right], \quad (3)$$

where $\varphi = \varphi_2 - \varphi_1 + 2\pi(f_1 + f_2 + f_4/2)$, and $\theta = \varphi_2 - \varphi_1 + 2\pi(f_3 + f_4/2)$. From Eq. 3, we obtain the flux qubit potential energy $U_q = -E_J(\cos\varphi_1 + \cos\varphi_2 + \alpha\cos(\varphi_2 - \varphi_1 + 2\pi f_1))$ and the tunable qubit-resonator interaction strength via the frustration parameter f_4 . An interesting feature of Eq. 3 is that $\cos(\varphi)$ term disappears such that there is no renormalization on the qubit energy when $f_3 = f_1 + f_2 + 0.5$.²³ The potential U_q can be diagonalized numerically as a function of the frustration parameter f_1 . In particular when $f_1 \sim 0.5$, the two lowest levels are well separated from other higher level excited states, thus defining the two-level system. After projecting the qubit-resonator interaction term onto the qubit basis, the system Hamiltonian reads

$$H = \frac{\hbar\omega_{eg}}{2}\sigma_z + \hbar\omega_{\text{res}}a^\dagger a + H_{\text{int}}, \quad (4)$$

with the effective interaction Hamiltonian

$$H_{\text{int}} = -2E_J\beta\cos(\pi f_4) \sum_{n=1,2} (\Delta\psi)^n \sum_{\mu=x,y,z} c_\mu^n(\alpha, \beta, f_1, f_2)\sigma_\mu. \quad (5)$$

It has been shown²⁴ that the second order coefficient of the above interaction Hamiltonian can be suppressed by an appropriate choice of parameters α , β , f_1 and f_2 , thus producing a linear qubit-resonator interaction described by the single-mode spin-boson model with a tunable coupling strength $\Omega = 2E_J\beta\cos(\pi f_4)\Delta\psi_1/\hbar$, which allows us to adiabatically switch on/off the coupling. Therefore, it provides a on-chip circuit platform for the storage and retrieval of an unknown quantum state.

3. STORAGE AND RETRIEVAL OF QUANTUM INFORMATION

The storing of a single qubit into the $\mathbb{Z}_2$ memory involves two steps. Firstly, the qubit-resonator coupling strength at initial time $t = 0$ is tuned to be at the Jaynes-Cummings (JC) regime, i.e., $\Omega/\omega_{\text{res}} \ll 1$ while the resonator is decoupled from the qubit, i.e., $\omega_{\text{res}} > \omega_{eg}$ such that the ground and excited states of the total system are $|\psi_0\rangle = |g\rangle \otimes |0\rangle$ and $|\psi_1\rangle = |e\rangle \otimes |0\rangle$, respectively. Here, $|0\rangle$ stands for the vacuum state in the resonator. Suppose the qubit is prepared in its ground state $|g\rangle$ such that the state of the total system is at $|\psi_0\rangle$ initially. When a flying qubit in an unknown quantum state $|\psi_F\rangle = \alpha_F|0_F\rangle + \beta_F|1_F\rangle$ enters the resonator [see Fig. 1(a)], due to the presence of the JC interaction, the information is then transferred to the flux qubit such that the state of the total system eventually becomes $|\psi_S\rangle = (\alpha_F|g\rangle + \beta_F|e\rangle) \otimes |0\rangle$. Secondly, we adiabatically switch on the qubit-resonator coupling strength until it reaches the USC regime. For our purpose, we apply a linear adiabatic switching-on routine $\Omega(t) = (\cos(f) - \Delta f \sin(f)t/T)\Omega_0$, where T is total evolution time, $f = \pi f_4$ and Ω_0 is the coefficient factor seen in Eq. 5. As a result, the ground $|\psi_0\rangle$ and excited $|\psi_1\rangle$ states adiabatically follow the instantaneous system eigenstates such that $|\psi_0\rangle \rightarrow |\Psi_G\rangle$ and $|\psi_1\rangle \rightarrow |\Psi_E\rangle$ [refer to Eq. 1], thus codifying the incoming flying qubit $|\psi_F\rangle$ onto the parity protected basis state $|\psi\rangle = \alpha_F|\Psi_G\rangle + \beta_F|\Psi_E\rangle$.

The retrieving process is the reverse process of the storing protocol. That means the qubit-resonator coupling strength is adiabatically switched off, starting from the USC to the JC regime. As a consequence, the stored state $|\psi\rangle$ is mapped back to the initial prepared state $|\psi_S\rangle$.

Figure 2. Storage and retrieval processes. (a) Storage processes for a quantum state $|\psi_S\rangle = (\alpha_F|g\rangle + \beta_F|e\rangle) \otimes |0\rangle$ and (b) retrieval processes for a range of total evolution time $T \in [25/\omega_{\text{res}}, 105/\omega_{\text{res}}]$. In both plots, the fidelity between the initial state $|\psi_S\rangle$ and instantaneous state $|\psi(t)\rangle$, i.e., $\mathcal{F} = |\langle\psi_S|\psi(t)\rangle|^2$ is shown. Here, the system parameters are $\omega_{\text{res}} = 1$, $\omega_{eg} = 0.1\omega_{\text{res}}$, $\Omega_0 = \omega_{\text{res}}$.

In Fig. 2, we show numerical results of the storage and retrieval processes of an arbitrary superposed state $|\psi_S\rangle = (\alpha_F|g\rangle + \beta_F|e\rangle) \otimes |0\rangle$. We plot the fidelity between the initial state $|\psi_S\rangle$ and the instantaneous state $|\psi(t)\rangle$, i.e., $\mathcal{F} = |\langle\psi_S|\psi(t)\rangle|^2$ for each value of total evolution time T . As seen in the figure, the total evolution time T plays an important role in the storage and retrieval processes. With proper T 's, we achieve a unit fidelity while the initial information is lost with inappropriate T 's. In addition, the Berry's phase²⁵ plays an important role in obtaining unit fidelity since an extra geometric phase can be incurred depending on the total evolution time T . This issue has been thoroughly addressed in Ref. 9.

4. SUMMARY

To sum up, the $\mathbb{Z}_2$ memory implemented here uses the robust qubit at the USC regime whose coherence time is expected to be about $T_{\text{coh}} \sim 40 \mu\text{s}$ for a coupling strength $\Omega_0/\omega_{eg} \sim 1.5$.¹⁹ If we consider a qubit gap $\Delta/h \sim 2 \text{ GHz}$ and the resonator frequency $\omega_{\text{res}}/2\pi \sim 5 \text{ GHz}$, it implies the system reaches the USC regime with $\Omega_0/\omega_{\text{res}} = 0.6$. We estimate total time for storage/retrieval of a qubit is about 2 – 8 ns. Our proposal can also be generalized to consider entangled two-qubit processes.⁹ Thus, we believe that our proposal might be used as a building block in the development of scalable and robust quantum memory devices that can be interfaced together with a quantum central processing unit.

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