RAPID COMMUNICATIONS

PHYSICAL REVIEW A **79**, 040304(R) (2009)

Reversible state transfer between superconducting qubits and atomic ensembles

David Petrosyan,[1,2] Guy Bensky,[1] Gershon Kurizki,[1] Igor Mazets,[3,4] Johannes Majer,[3] and Jörg Schmiedmayer[3]

[1]*Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel*

[2]*Institute of Electronic Structure and Laser, FORTH, 71110 Heraklion, Crete, Greece*

[3]*Atominstitut der Österreichischen Universitäten, TU-Wien, A-1020 Vienna, Austria*

[4]*A. F. Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia*

(Received 9 February 2009; published 14 April 2009)

We examine the possibility of coherent reversible information transfer between solid-state superconducting qubits and ensembles of ultracold atoms. Strong coupling between these systems is mediated by a microwave transmission line resonator that interacts near resonantly with the atoms via their optically excited Rydberg states. The solid-state qubits can then be used to implement rapid quantum logic gates, while collective metastable states of the atoms can be employed for long-term storage and optical readout of quantum information.

DOI: 10.1103/PhysRevA.79.040304 PACS number(s): 03.67.Lx, 74.50.+r, 37.30.+i, 32.80.Ee

I. INTRODUCTION

Solid-state superconducting (SC) qubits [1–3] are promising candidates for implementing quantum information (QI) processing in a scalable way [4]. Very fast and efficient quantum logic gates can be performed by SC qubits without significant loss of coherence. However, dephasing and decoherence hinders the long-term storage of QI in such qubits. It would therefore be desirable to reversibly transfer the QI from the rather fragile qubits to a longer-lived system for storage and retrieval purposes [5,6].

Appealing candidates for such storage are ground electronic (hyperfine) states of ultracold (UC) atoms having very long coherence times [7]. QI can then be stored for many seconds as a collective spin excitation of an atomic ensemble. Using stimulated Raman techniques, such as electromagnetically induced transparency [8], this QI can be optically read out by mapping the collective atomic state onto the generated photon, acting as traveling qubit [9], whose detection is possible with quantum efficiency approaching unity.

Here we put forward a proposal for reversible transfer of QI between SC qubits and UC atomic ensembles. In our scheme, the coupling between these systems is mediated by a near-resonant microwave transmission line resonator [10–12] employing optical excitations of atomic Rydberg states [13,14]. This hybrid scheme, despite considerable challenges, is predicted to be feasible and allow high-fidelity QI processing.

II. QUBIT-CAVITY COUPLING

Our solid-state qubit is represented by a SC Cooper pair box coupled to a SC electrode via two tunnel junctions at the rate E_J (charge qubit) in the superconducting quantum interference device (SQUID) configuration [3]. At the charge degeneracy point, the energy separation $\hbar\omega_{10}=2E_J\cos(\pi\Phi/\Phi_0)$ between the qubit states $|0\rangle$ and $|1\rangle$ can be dynamically controlled via an external magnetic field $B_\perp$ that induces flux $\Phi=AB_\perp$ through the SQUID area A ($\Phi_0=hc/2e$ is the flux quantum). Typical values for $E_J/\hbar$ are the microwave range (10–20 GHz). The dipole moment $\wp_{01}$ for the transition $|0\rangle\leftrightarrow|1\rangle$ is typically very large, $\wp_{01}\simeq 10^4 a_0 e$. Using resonant microwave fields, one can then perform many fast quantum logic gates within the qubit dephasing time $1/\gamma_q \gtrsim 1$ μs [15].

Charge qubits can be embedded in near-resonant SC transmission line resonators, such as a coplanar waveguide (CPW) cavity of Fig. 1(a) [10–12], having high quality factor $Q\approx 10^6$. The tight confinement of the cavity field in a small volume (see below) yields very large field per photon ε_c and strong coupling (vacuum Rabi frequency) $\eta_{qc} =(\wp_{01}/\hbar)\varepsilon_c u(\mathbf{r})\sim 2\pi\times 50$ MHz between the cavity field and the qubit located at position $\mathbf{r}$ near the field antinode where the cavity mode function $u(\mathbf{r})\lesssim 1$. In the frame rotating with the cavity field frequency ω_c, the Hamiltonian has the form

$$H_{qc}=\hbar\Delta_{qc}\hat{\sigma}^+\hat{\sigma}^- - \hbar\eta_{qc}(\hat{\sigma}^+\hat{c}+\hat{c}^\dagger\hat{\sigma}^-), \quad (1)$$

where $\Delta_{qc}=\omega_{10}-\omega_c$ is the externally controlled (via $B_\perp$) detuning, $\hat{\sigma}^-$ ($\hat{\sigma}^+$) is the qubit lowering (rising) operator, and $\hat{c}$ ($\hat{c}^\dagger$) is the cavity photon annihilation (creation) operator.

One can incorporate many SC qubits in the same CPW cavity, each qubit located near the cavity field antinode [Fig. 1(a)]. The cavity can then mediate long-range controlled interactions between pairs of resonant qubits [10–12], realizing, e.g., the two-qubit $\sqrt{\text{swap}}$ gate, which together with the single-qubit rotations form the universal set of logic gates in

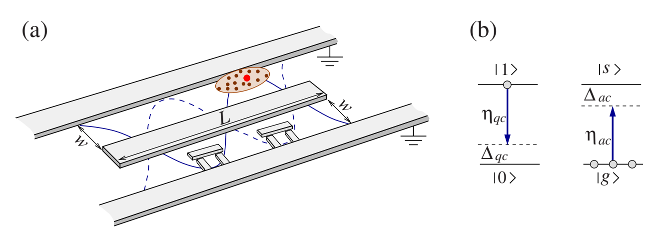

FIG. 1. (Color online) (a) CPW cavity with strip-line length L and electrode distance w. SC qubits are placed at the antinodes of the standing-wave field and ensembles of UC atoms are trapped near the CPW surface. (b) SC qubit (left) and ensemble qubit (right) can couple to a common mode of the CPW cavity.

such a quantum computer. However, due to rapid dephasing and relaxation, neither SC qubits nor the cavity mode can carry out reliable long-term storage of QI. In what follows, we show that this task can be accomplished by reversibly transferring the QI to the ground hyperfine states of UC atoms trapped near the surface of an integrated atom chip, incorporating the CPW cavity and SC qubits [16].

III. ATOMIC ENSEMBLE QUANTUM MEMORY

We envision a small trapping volume containing $N \simeq 10^6$ atoms of ^{87}Rb with the ground-state hyperfine splitting $\omega_{sg}/2\pi = 6.83$ GHz between $|F=1\rangle \equiv |g\rangle$ and $|F=2\rangle \equiv |s\rangle$. Let us choose the frequency of the CPW cavity to be near resonant with that of the atomic transition $|g\rangle \leftrightarrow |s\rangle$ [Fig. 1(b)]. When the atomic ensemble is near the field antinode, with the spatial dimension of the cloud being small compared to the mode wavelength, all the atoms couple symmetrically to the cavity field. The corresponding Hamiltonian can be expressed as

$$H_{ac} = \hbar \Delta_{ac} \hat{s}^\dagger \hat{s} + \hbar \eta_{ac} (\hat{s}^\dagger \hat{g} \hat{c} + \hat{c}^\dagger \hat{g}^\dagger \hat{s}), \tag{2}$$

where $\Delta_{ac} = \omega_{sg} - \omega_c$ is the detuning and $\eta_{ac} = i(\wp_{sg}/\hbar)\varepsilon_c u(\mathbf{r})$ is the coupling rate between the cavity field and a (single) atom at position $\mathbf{r}$. Since $|F=1\rangle \leftrightarrow |F=2\rangle$ is a magnetic dipole transition, the corresponding matrix element is small, $\wp_{sg} \simeq \frac{1}{2}\alpha a_0 e$ with $\alpha = 1/137$, which yields $\eta_{ac} \sim 2\pi \times 20$ Hz [for $u(\mathbf{r}) \lesssim 1$]. The operators $\hat{g}$ ($\hat{g}^\dagger$) and $\hat{s}$ ($\hat{s}^\dagger$) annihilate (create) an atom in the corresponding state $|g\rangle$ and $|s\rangle$; these essentially bosonic operators live in a space of completely symmetrized states $|n_g, n_s\rangle$ with n_g atoms in state $|g\rangle$ and n_s atoms in state $|s\rangle$, while $n_g + n_s = N$.

Apparently [6], the most direct approach to state transfer from the SC qubit to the atomic ensemble would be to prepare all the atoms in state $|g\rangle$, the cavity field in vacuum $|0_c\rangle$, and choose the frequencies of the cavity mode and the atomic hyperfine transition to be the same, $\Delta_{ac} = 0$. Then, by tuning the SC qubit frequency to resonance with the cavity, $\Delta_{qc} = 0$, during time τ_{qc} such that $2\eta_{qc}\tau_{qc} = \pi$, an arbitrary quantum state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ will be transferred from the SC qubit to the CPW cavity field [cf. Eq. (1)]. Next, it follows from Eq. (2) that the collective coupling rate of the cavity field and the atomic ensemble via the transition $|n_g = N, n_s = 0; 1_c\rangle \to |n_g = N-1, n_s = 1; 0_c\rangle$ is given by $\sqrt{N}\eta_{ac} \sim 2\pi \times 20$ KHz. Thus, during time $\tau_{sg} = \pi/(2\sqrt{N}\eta_{ac}) \sim 12$ μs the cavity photon will be absorbed by the atoms and we will have achieved our goal. The time τ_{sg} is, however, comparable to the photon lifetime in the CPW cavity, $\kappa^{-1} = Q/\omega_c \sim 20$ μs. Thus the photon will be lost with high probability $P_{\rm loss} \approx \kappa\tau_{sg} \sim 0.5$ before being coherently absorbed by the atoms. It is therefore necessary to improve the CPW cavity by increasing its quality factor Q and thereby decreasing the photon decay rate κ.

In an alternative setup, the SC qubit and the atoms are tuned to be resonant with each other, $\Delta_{qc,ac} \simeq \Delta$, but detuned from the cavity mode frequency. For large detuning $\Delta \gg \eta_{qc}$, the adiabatic elimination of the cavity mode yields an effective photon decay rate $\kappa_{\rm eff} = \kappa \eta_{qc}^2/\Delta^2$, while the corresponding second-order interaction Hamiltonian,

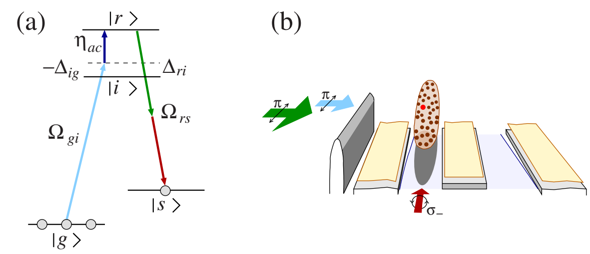

FIG. 2. (Color online) (a) Atomic Rydberg states $|i\rangle$ and $|r\rangle$ and relevant couplings for the excitation transfer from the CPW cavity to the atomic storage state $|s\rangle$. (b) Propagation geometry of the corresponding optical fields and the beam stop and metallic mirrors on top of the SC electrodes of the CPW cavity.

$V_{qa}^{(2)} = \hbar\eta_{\rm eff}(\hat{s}^\dagger \hat{g}\hat{\sigma}^- + \hat{\sigma}^+ \hat{g}^\dagger \hat{s})$ with $\eta_{\rm eff} = \eta_{qc}\eta_{ac}/\Delta$, describes an effective swap of an excitation between the SC qubit and atomic ensemble with the rate $\sqrt{N}\eta_{\rm eff}$ mediated by virtual photon exchange in the cavity [17]. Thus the effective coupling is reduced by a factor of Δ/η_{qc}, while the decoherence rate is reduced by a factor of $(\Delta/\eta_{qc})^2$. For $\Delta = 10\eta_{qc}$ we then have $\sqrt{N}\eta_{\rm eff} \sim 2\pi \times 2$ KHz while $\kappa_{\rm eff} \simeq 2\pi \times 100$ Hz, which yields a low probability of photon decay during the excitation swap, $P_{\rm loss} \approx \kappa_{\rm eff}\pi/(2\sqrt{N}\eta_{\rm eff}) = 0.08$.

Recall, however, that the SC qubit dephasing $\gamma_q \lesssim 1$ MHz is much larger than $\sqrt{N}\eta_{\rm eff}$, hampering the foregoing scheme. In turn, γ_q is much smaller than the coupling η_{qc}; hence, this decoherence does not pose a problem during the resonant excitation exchange between the SC qubit and CPW cavity. This rapid stage may therefore be accomplished with high fidelity, as opposed to the much slower stage of excitation transfer from the cavity to the atoms with weak magnetic dipole transition.

IV. ATOM-CAVITY COUPLING VIA RYDBERG STATES

Very strong atom-cavity field coupling can be achieved at microwave frequencies for electric dipole transitions between highly excited Rydberg states [18,19]. Let us therefore select a pair of Rydberg states $|i\rangle$ and $|r\rangle$ such that the frequency ω_{ri} of transition $|i\rangle \leftrightarrow |r\rangle$ is close to the cavity mode frequency ω_c, with the corresponding detuning being $\Delta_{ri} = \omega_{ri} - \omega_c$. We envision a level scheme sketched in Fig. 2(a), where the transition $|g\rangle \leftrightarrow |i\rangle$ is driven by an external optical field with Rabi frequency Ω_{gi} and detuning Δ_{ig}. The Hamiltonian reads

$$H_{ac} = \hbar\Delta_{ig}\hat{i}^\dagger\hat{i} + \hbar(\Delta_{ig} + \Delta_{ri})\hat{r}^\dagger\hat{r} - \hbar(\Omega_{gi}\hat{i}^\dagger\hat{g} + \eta_{ac}\hat{r}^\dagger\hat{i}\hat{c} + \text{H.c.}), \tag{3}$$

where $\eta_{ac} = (\wp_{ir}/\hbar)\varepsilon_c u(\mathbf{r})$ is the atom-cavity field coupling rate, with $\wp_{ir}$ being the corresponding dipole matrix element, while operators $\hat{i}$ ($\hat{i}^\dagger$) and $\hat{r}$ ($\hat{r}^\dagger$) annihilate (create) an atom in state $|i\rangle$ and $|r\rangle$, respectively.

We set the detunings as $\Delta_{ri} \simeq -\Delta_{ig} = \Delta$. Then, given a photon in the cavity, the external field Ω_{gi} and the cavity field induce a two-photon transition from the ground state $|g\rangle$ to the Rydberg state $|r\rangle$ via nonresonant intermediate Rydberg state $|i\rangle$. If $\Delta \gg \eta_{ac}, \sqrt{N}\Omega_{gi}$, state $|i\rangle$ is never populated, and we obtain an effective interaction Hamiltonian $V_{ac}^{(2)} = \hbar \eta_{\text{eff}}(\hat{r}^\dagger \hat{g}\hat{c} + \hat{c}^\dagger \hat{g}^\dagger \hat{r})$ with $\eta_{\text{eff}} = \Omega_{gi}\eta_{ac}/\Delta$ [20]. Thus, starting from the initial state of the system $|n_g = N, n_{i,r,s} = 0; 1_c\rangle$, by pulsing Ω_{gi} for time $\tau_{gr} = \pi/(2\sqrt{N}\eta_{\text{eff}})$, the cavity photon will be coherently absorbed and a single atom from the ensemble will be excited to the Rydberg state $|r\rangle$. Next, another (bichromatic) external field with Rabi frequency Ω_{rs} pulsed for a time $\tau_{rs} = \pi/(2\Omega_{rs})$ can resonantly transfer the single collective Rydberg excitation of the atomic ensemble to the storage state $|s\rangle$: this process is described by $H_{rs} = -\hbar\Omega_{rs}\hat{s}^\dagger\hat{r} + \text{H.c}$. At a later time, when required, the reverse process can add a single photon in the cavity while all the atoms will end up in state $|g\rangle$. This single photonic excitation can then be quickly transferred to the SC qubit, as described above.

A. System parameters

Before proceeding, we survey the relevant experimental parameters. An elongated trapping volume $V_a \sim d \times d \times l$ with $d \simeq 5$ μm and $l \simeq 1$ mm contains $N \simeq 10^6$ atoms at density $\rho_a \sim 4 \times 10^{13}$ cm^{-3}. The atomic lower states $|g\rangle$ and $|s\rangle$ correspond to the $|F=1, M_F=-1\rangle$ and $|F=2, M_F=1\rangle$ sublevels of the ground electronic state $5s_{1/2}$ of ^{87}Rb. We choose the Rydberg states $|i\rangle \equiv |np_{1/2}, F=2, M_F=-1\rangle$ and $|r\rangle \equiv |(n+1)s_{1/2}, F=1, M_F=0\rangle$ with $n=68$ as the principal quantum number. The quantum defects for the $s_{1/2}$ and $p_{1/2}$ Rydberg states of Rb are $\delta_s = 3.131$ and $\delta_p = 2.6545$ [18], with which the corresponding transition frequency is $\omega_{ri} = 2\pi \times 12.2$ GHz. Calculation of the relevant transition dipole matrix element involving the radial and angular parts gives $\wp_{ir} \simeq 1520 a_0 e$.

With the strip-line length $L \simeq 1$ cm and effective dielectric constant $\epsilon_r \sim 6$, the frequency of the mth standing-wave mode of the cavity is $\omega_c = \pi mc/L\sqrt{\epsilon_r}$ [Fig. 1(a)]. The grounded SC electrodes at distance $w \simeq 10$ μm confine the cavity field within the effective volume $V_c = \int d^3 r |u(\mathbf{r})|^2 \simeq \frac{\pi}{2} w^2 L$ yielding $\varepsilon_c = \sqrt{\hbar\omega_c/2\epsilon_0 V_c} \gtrsim 0.5$ V/m. Taking the full-wavelength ($m=2$) linearly polarized cavity mode with $\omega_c/2\pi \simeq 12.16$ GHz, we estimate [6] that at the position of atomic cloud about 10 μm above the CPW surface the mode function $u(\mathbf{r}) \simeq e^{-1}$ which yields the vacuum Rabi frequency $\eta_{ac} = (\wp_{ir}/\hbar)\varepsilon_c u(\mathbf{r}) \simeq 2\pi \times 3.85$ MHz and appropriately large detuning $\Delta_{ri} \simeq 10\eta_{ac}$.

The transition $|g\rangle \to |i\rangle$ is driven by linearly π-polarized UV field with wavelength $\lambda_{ig} \simeq 297$ nm and detuning $\Delta_{ig} = -\Delta_{ri}$. To optimize the transition rate, its Rabi frequency is chosen as $\sqrt{N}\Omega_{gi} \simeq \eta_{ac}$, with which the transfer time is $\tau_{gr} \simeq 0.65$ μs. The required UV field intensity at the atomic cloud is $I_{gi} = 0.46$ W cm^{-2}. Next, $|r\rangle \to |s\rangle$ is a two-photon transition via nonresonant intermediate state $|5p_{1/2}, F=2, M_F=0\rangle = |e\rangle$. The wavelengths are $\lambda_{re} \simeq 474$ nm (linearly π-polarized field) and $\lambda_{es} \simeq 795$ nm (circularly σ_--polarized field). With the corresponding intensities $I_{re} = 440$ W cm^{-2} and $I_{es} = 2.25$ mW cm^{-2} and intermediate detuning $\Delta_{es} = 2\pi \times 25$ MHz, the two-photon Rabi frequency is $\Omega_{rs} = 2\pi \times 250$ KHz leading to the transfer time of $\tau_{rs} \simeq 1$ μs. Note that τ_{gr} and τ_{rs} are short compared to the lifetimes of cavity photon $1/\kappa \sim 10$ μs and Rydberg states $1/\Gamma_R \sim 100$ μs [18].

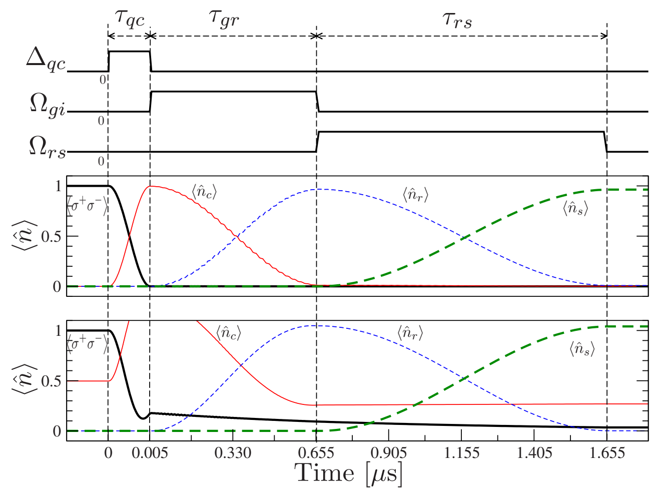

FIG. 3. (Color online) Numerical simulations of the three-step excitation transfer from the SC qubit to the UC atomic ensemble. Top panel illustrates the sequence of (π–) pulses: first the SQ qubit is brought to resonance with the CPW cavity, by pulsing $\Delta_{qc}(t)=0$ for time τ_{qc}; next, the $\Omega_{gi}(t)$ field is pulsed for time τ_{gr}; and finally, the $\Omega_{rs}(t)$ field is pulsed for time τ_{rs}. Central and lower panels show the dynamics of occupation numbers for the qubit exited state $\langle\hat{\sigma}^+\hat{\sigma}^-\rangle$, the cavity field $\langle\hat{n}_c\rangle \equiv \langle\hat{c}^\dagger\hat{c}\rangle$ and the collective atomic states $\langle\hat{n}_r\rangle \equiv \langle\hat{r}^\dagger\hat{r}\rangle$, and $\langle\hat{n}_s\rangle \equiv \langle\hat{s}^\dagger\hat{s}\rangle$. Initially, the mean thermal photon number is $\langle\hat{n}_c(0)\rangle = 0$ in the central panel and $\langle\hat{n}_c(0)\rangle = 0.5$ in the lower panel.

B. Numerical simulations

Employing a master equation approach [4], we have simulated the dynamics of transfer process in the system with above parameters and temperature-dependent initial population $\langle\hat{n}_c(0)\rangle$ of the CPW cavity photon field. Figure 3 shows the results of numerical integration of the equations for density operator $\hat{\rho}(t)$ whose evolution is governed by Hamiltonians H_{qc}, H_{ac} of Eq. (3), and H_{rs}. As seen, in the case of $\langle\hat{n}_c(0)\rangle = 0$, the state transfer is nearly ideal, with the small final error probability $P_{\text{err}} \lesssim 0.04$ due to relaxation of the qubit, the cavity field, and the atoms. However, in the case of finite temperature, $\langle\hat{n}_c(0)\rangle = 0.5$, during the transfer, as expected, the cavity field and the collective atomic state occupation numbers $\langle\hat{n}_c\rangle$ and $\langle\hat{n}_{r,s}\rangle$ exceed unity and the resulting error probability $P_{\text{err}} \simeq 0.3$ is large.

We can characterize the transfer process for a given initial state $|\psi\rangle_q$ of the SC qubit by the conditional fidelity $F_\psi = \text{Tr}(\hat{\rho}|\psi\rangle_{aa}\langle\psi|)$, where $|\psi\rangle_a$ denotes the final state stored in the UC atomic ensemble for an ideal transfer. The mean transfer fidelity $\bar{F}$ is obtained by averaging F_ψ over all possible $|\psi\rangle$. The dependence of F_ψ and $\bar{F}$ on the CPW cavity temperature T, or the mean thermal photon number $\langle\hat{n}_c\rangle = (e^{\hbar\omega_c/k_B T} - 1)^{-1}$, is shown in Fig. 4. Below $k_B T/\hbar\omega_c \simeq 0.2$, corresponding to $\langle\hat{n}_c\rangle \lesssim 0.01$, the transfer fidelity is fairly high, $\bar{F} > 98\%$, but then it quickly degrades due to the detrimental effect of even a small number of thermal photons. For the above parameters, this critical temperature is $T \sim 0.1$ K necessitating cryogenic conditions. We note that the temperature of atomic cloud is much smaller, $T_a \lesssim 1$ μK, resulting in the lifetime of atomic hyperfine coherence in excess of 1s [7].

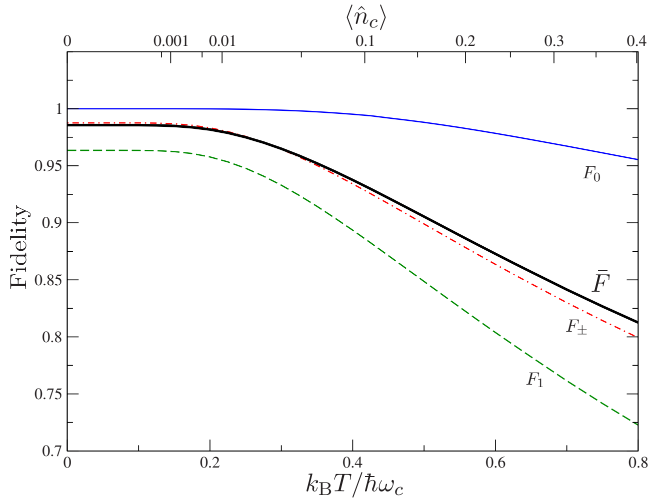

FIG. 4. (Color online) Conditional F_ψ and mean $\bar{F}$ transfer fidelities vs temperature $k_B T$ (lower horizontal axis) or mean thermal photon number $\langle \hat{n}_c \rangle$ (upper horizontal axis). In F_ψ, $\psi = 0, 1, \pm$ correspond to states $|0\rangle$, $|1\rangle$, and $\frac{1}{\sqrt{2}}[|0\rangle \pm (i)|1\rangle]$.

V. EXPERIMENTAL CHALLENGES AND CONCLUSIONS

The practical realization of our scheme can be hindered by absorption of optical fields, driving the atomic transitions, by the SC electrodes of the CPW cavity. If not eliminated, the photon absorption would break up many Cooper pairs and produce quasiparticles resulting in drastic reduction in the cavity Q factor. Consider a geometry where the strong π-polarized fields propagate in the direction parallel to the CPW surface and perpendicular to the electrodes, in front of which an opaque barrier of height ~ 10 μm serves as a beam stop [Fig. 2(b)]. Due to the Fresnel diffraction on the barrier edge, some light will still reach the shade area behind the barrier, but we estimate that the light intensity at the SC electrodes, each about 10 μm wide, will be reduced by a factor of 300. However, even after such significant reduction in intensity, the residual absorption would remain too large. To completely eliminate the absorption, the SC electrodes can be covered by a few μm thick layer of dielectric followed by a thin metallic mirror. A moderate reduction in the cavity Q factor up to 10 times is tolerable, since the photon lifetime still remains long compared to the transfer times $\tau_{qc} + \tau_{gr} \sim 0.7$ μs, but the resulting fidelity will decrease to $\bar{F} \gtrsim 70\%$, which is still above the classical limit of 66%.

To conclude, we have proposed a promising approach for realizing efficient quantum state transfer between superconducting charge qubits and mesoscopic ultracold atomic ensembles coupled to a microwave coplanar waveguide cavity via optically excited Rydberg transitions. Our scheme is scalable to many superconducting qubits, whose merit is very high flipping rates, coupled to atomic ensembles serving as reliable storage qubits. We are currently working on the experimental implementation of the proposed techniques and demonstration of hybridization of solid-state and atomic quantum devices.

ACKNOWLEDGMENTS

This research was supported by the EC (MIDAS STREP, FET Open). D.P. was also supported by the EC Marie Curie RTN EMALI. I.M. acknowledges helpful discussions with P. Pillet and D. Comparat.

[1] M. H. Devoret and J. M. Martinis, Quantum Inf. Process. **3**, 163 (2004).
[2] J. Q. You and F. Nori, Phys. Today **58**(11), 42 (2005).
[3] Y. Makhlin, G. Schön, and A. Shnirman, Rev. Mod. Phys. **73**, 357 (2001).
[4] M. Nielsen and I. Chuang, *Quantum Computation and Quantum Information* (Cambridge University Press, Cambridge, England, 2000); P. Lambropoulos and D. Petrosyan, *Fundamentals of Quantum Optics and Quantum Information* (Springer, Berlin, 2006).
[5] P. Rabl *et al.*, Phys. Rev. Lett. **97**, 033003 (2006); K. Tordrup and K. Molmer, Phys. Rev. A **77**, 020301(R) (2008).
[6] J. Verdu *et al.*, e-print arXiv:0809.2552.
[7] P. Treutlein, P. Hommelhoff, T. Steinmetz, T. W. Hansch, and J. Reichel, Phys. Rev. Lett. **92**, 203005 (2004).
[8] M. Fleischhauer, A. Imamoglu, and J. P. Marangos, Rev. Mod. Phys. **77**, 633 (2005).
[9] A. Kuzmich *et al.*, Nature (London) **423**, 731 (2003); C. H. van der Wal *et al.*, Science **301**, 196 (2003).
[10] A. Blais, R. S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, Phys. Rev. A **69**, 062320 (2004); A. Wallraff *et al.*, Nature (London) **431**, 162 (2004).
[11] J. Majer *et al.*, Nature (London) **449**, 443 (2007); M. A. Sillanpää, J. I. Park, and R. W. Simmonds, *ibid.* **449**, 438 (2007).
[12] R. J. Schoelkopf and S. M. Girvin, Nature (London) **451**, 664 (2008).
[13] A. S. Sørensen, C. H. van der Wal, L. I. Childress, and M. D. Lukin, Phys. Rev. Lett. **92**, 063601 (2004).
[14] D. Petrosyan and M. Fleischhauer, Phys. Rev. Lett. **100**, 170501 (2008).
[15] A. A. Houck *et al.*, Phys. Rev. Lett. **101**, 080502 (2008).
[16] R. Folman *et al.*, Adv. At., Mol., Opt. Phys. **48**, 263 (2002); R. Grimm, M. Weidemuller, and Y. B. Ovchinnikov, *ibid.* **42**, 95 (2000); J. Fortagh and C. Zimmermann, Rev. Mod. Phys. **79**, 235 (2007).
[17] The second-order level shift of the SC qubit, η_{qc}^2/Δ, is assumed to be incorporated in Δ_{qc}.
[18] T. F. Gallagher, *Rydberg Atoms* (Cambridge University Press, Cambridge, England, 1994).
[19] J.-M. Raimond, M. Brune, and S. Haroche, Rev. Mod. Phys. **73**, 565 (2001).
[20] The second-order shift η_{ac}^2/Δ of the atomic Rydberg state $|r\rangle$ is incorporated in Δ_{ri}.