Quantum information transfer with superconducting flux qubits coupled to a resonator

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(Received 20 September 2010; published 24 November 2010)

We propose a way for implementing quantum information transfer with two superconducting flux qubits by coupling them to a resonator. This proposal does not require adjustment of the level spacings or uniformity in the device parameters. Moreover, neither adiabatic passage nor a second-order detuning is needed by this proposal, thus the operation can be performed much faster when compared with the previous proposals.

Introduction. Cavity QED with superconducting qubits have been considered as one of the most promising candidates for quantum information processing. Superconducting qubits have the features such as design flexibility, large-scale integration, and compatibility to conventional electronics [1–3]. A cavity or resonator acts as a "quantum bus" which can mediate long-distance, fast interaction between distant superconducting qubits [4].

In recent years, there is much interest in quantum information transfer (QIT). Experimentally, QIT has been demonstrated with superconducting phase qubits and transmon qubits in cavity QED [5,6]. However, to the best of our knowledge, no experimental demonstration of QIT with superconducting flux qubits in cavity QED has been reported.

Several theoretical methods have been proposed for implementing QIT with flux qubits (e.g., SQUID qubits) or charge-flux qubits based on cavity QED technique [7–12]. However, these methods have some disadvantages. For instance: (i) The method presented in Ref. [8] requires adjustment of the level spacings of the devices during the operation; (ii) the methods proposed in Ref. [7,9–11] require slowly changing the Rabi frequencies to satisfy the adiabatic passage; and (iii) the approach introduced in Ref. [12] requires a second-order detuning to achieve an off-resonant Raman coupling between two relevant levels. Note that the adjustment of the level spacings during the operation is undesirable and also may cause extra decoherence. In addition, when the adiabatic passage or a second-order detuning is applied, the operation slows down (the operation time required for the information transfer is on the order of 1 μs to a few microseconds [7,12]).

In this Brief Report, we present a way for implementing QIT with two flux qubits coupled to a superconducting resonator. This proposal has the following advantages: (a) the qubits are not required to have identical level spacings, therefore superconducting devices, which often have considerable parameter nonuniformity, can be used; (b) the method does not require adjustment of the level spacings of each qubit during the operation, thus decoherence caused by tuning the level spacings is avoided; and (c) neither adiabatic passage nor a second-order detuning is needed, thus the speed of the operation is increased (as shown below, the operation time for the information transfer is on the order of 10 ns).

Basic theory. The flux qubits throughout this Brief Report have a Λ-type three-level configuration (Fig. 1). The transition between the two lowest levels is forbidden due to the optical selection rules [13] or weak via increasing the potential barrier between the two lowest levels [14–16]. For flux qubits, the two

logic states of a qubit are represented by the two lowest levels $|0\rangle$ and $|1\rangle$.

(A) Qubit-resonator-pulse resonant Raman coupling. Consider a flux qubit coupled to a single-mode resonator and driven by a classical microwave pulse (Fig. 1). Suppose that the resonator mode is coupled to the $|0\rangle \leftrightarrow |2\rangle$ transition but decoupled (highly detuned) from the transition between any other two levels. In addition, assume that the classical microwave pulse is coupled to the $|1\rangle \leftrightarrow |2\rangle$ transition but decoupled from the transition between any other two levels. The Hamiltonian of the system can thus be written as

$$H = \sum_l E_l \sigma_{ll} + \omega_c a^\dagger a + \hbar g(a^\dagger \sigma_{02}^- + \text{H.c.})$$
$$+ \hbar \Omega(e^{i\omega_{\mu w}t}\sigma_{12}^- + \text{H.c.}), \qquad (1)$$

where $a^\dagger$ and a are the photon creation and annihilation operators of the resonator mode with frequency ω_c; g is the coupling constant between the resonator mode and the $|0\rangle \leftrightarrow |2\rangle$ transition of the qubit; Ω is the Rabi frequency of the pulse and $\omega_{\mu w}$ is the frequency of the pulse; $\sigma_{02}^- = |0\rangle\langle 2|$, $\sigma_{12}^- = |1\rangle\langle 2|$, and $\sigma_{ll} = |l\rangle\langle l|$ ($l = 0,1,2$).

Suppose that the resonator mode is off-resonant with the $|0\rangle \leftrightarrow |2\rangle$ transition, i.e., $\Delta_c = \omega_{02} - \omega_c \gg g$, and the pulse is off-resonant with the $|1\rangle \leftrightarrow |2\rangle$ transition, i.e., $\Delta_{\mu w} = \omega_{12} - \omega_{\mu w} \gg \Omega$ (Fig. 1), where ω_{02} (ω_{12}) is the $|0\rangle \leftrightarrow |2\rangle$ ($|1\rangle \leftrightarrow |2\rangle$) transition frequency. Under this condition, the level $|2\rangle$ can be adiabatically eliminated [17]. Thus, for $\Delta_c = \Delta_{\mu w}$, the effective Hamiltonian in the interaction picture is [12,18]

$$H_{\text{eff}} = -\hbar \left[\frac{\Omega^2}{\Delta_{\mu w}}\sigma_{11} + \frac{g^2}{\Delta_c}a^\dagger a \sigma_{00} + \frac{\Omega g}{\Delta_c}(a^\dagger \sigma_{01}^- + \text{H.c.}) \right],$$
$$(2)$$

where $\sigma_{01}^- = |0\rangle\langle 1|$. The last two terms in Eq. (2) describe the resonant Raman coupling between the two lowest levels $|0\rangle$ and $|1\rangle$.

For the case of $\Omega = g$, the initial states $|0\rangle|1\rangle_c$ and $|1\rangle|0\rangle_c$ of the system, under the Hamiltonian (2), evolve as follows

$$|0\rangle|1\rangle_c \rightarrow e^{ig^2t/\Delta_c}[\cos(g^2t/\Delta_c)|0\rangle|1\rangle_c$$
$$- i\sin(g^2t/\Delta_c)|1\rangle|0\rangle_c],$$
$$(3)$$
$$|1\rangle|0\rangle_c \rightarrow e^{ig^2t/\Delta_c}[-i\sin(g^2t/\Delta_c)|0\rangle|1\rangle_c$$
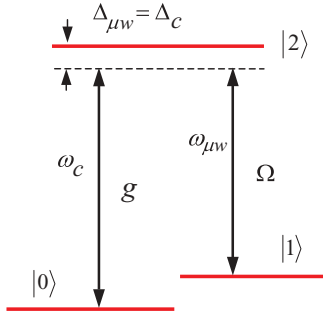$$+ \cos(g^2t/\Delta_c)|1\rangle|0\rangle_c],$$

FIG. 1. (Color online) Qubit-resonator-pulse resonant Raman coupling. The tunneling between the two lowest levels is forbidden or weak such that quantum information for each qubit, encoded in the two lowest levels, can be stored for a long time.

where $|0\rangle_c$ and $|1\rangle_c$ are the vacuum state and the single-photon state of the resonator mode, respectively. The state $|0\rangle|0\rangle_c$ remains unchanged under the Hamiltonian (2).

The coupling strength g may vary with different qubits due to nonuniform device parameters and/or nonexact placement of qubits in the resonator. Therefore, in the information transfer operation below, we will replace g with g_a and g_b for qubits a and b, respectively. Accordingly, we will replace Δ_c with Δ_c^a and Δ_c^b, $\Delta_{\mu w}$ with $\Delta_{\mu w}^a$ and $\Delta_{\mu w}^b$, and Ω with Ω_a and Ω_b for qubits a and b, respectively.

(B) Qubit-pulse resonant interaction. Consider a three-level flux qubit driven by a classical microwave pulse. Suppose that the pulse is resonant with the transition $|i\rangle \leftrightarrow |j\rangle$ of the qubit.
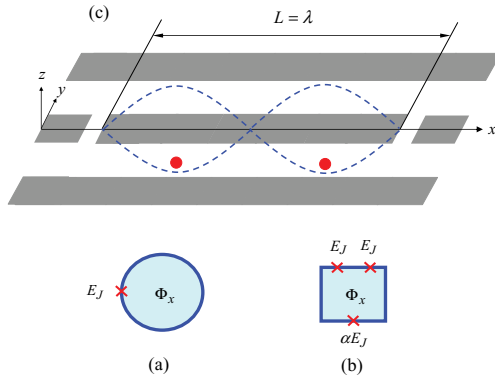

FIG. 2. (Color online) (a) An rf SQUID consisting of one Josephson junction enclosed by a superconducting loop. (b) A superconducting device with three Josephson junctions enclosed by a loop. The level spacings of a flux qubit shown in Fig. 1 can be adjusted by changing external magnetic flux Φ_x applied to the loop. Here, E_J is the Josephson junction energy and $0 < \alpha < 1$. (c) Sketch of the setup for two superconducting flux qubits (red circles) and a (gray) standing-wave quasi-one-dimensional coplanar waveguide resonator. The two dashed blue curved lines represent the standing wave magnetic field, which is in the z direction. Each qubit could be an rf SQUID shown in (a) or a superconducting device with three Josephson junctions shown in (b). The qubits are placed at antinodes of the resonator mode to achieve maximal qubit-resonator coupling constants. The superconducting loop of each qubit is located in the plane of the resonator between the two lateral ground planes (i.e., the x-y plane). λ is the wavelength of the resonator mode and L is the length of the resonator.

Here, $|i\rangle$ is the lower energy level. The interaction Hamiltonian in the interaction picture is given by

$$H_I = \hbar(\widetilde{\Omega}e^{i\phi}|i\rangle\langle j| + \text{H.c.}), \qquad (4)$$

where $\widetilde{\Omega}$ and ϕ are the Rabi frequency and the initial phase of the pulse, respectively. Based on this Hamiltonian, it is easy to show that a pulse of duration t results in

$$\begin{aligned} |i\rangle &\to \cos\widetilde{\Omega}t|i\rangle - ie^{-i\phi}\sin\widetilde{\Omega}t|j\rangle, \\ |j\rangle &\to \cos\widetilde{\Omega}t|j\rangle - ie^{i\phi}\sin\widetilde{\Omega}t|i\rangle. \end{aligned} \qquad (5)$$

The transition frequency ω_{ij} between the two levels $|i\rangle$ and $|j\rangle$ may be different for qubits a and b due to their nonidentical level spacings. Thus, in the following, we will replace ω_{ij} by ω_{ij}^a and ω_{ij}^b for qubits a and b, respectively.
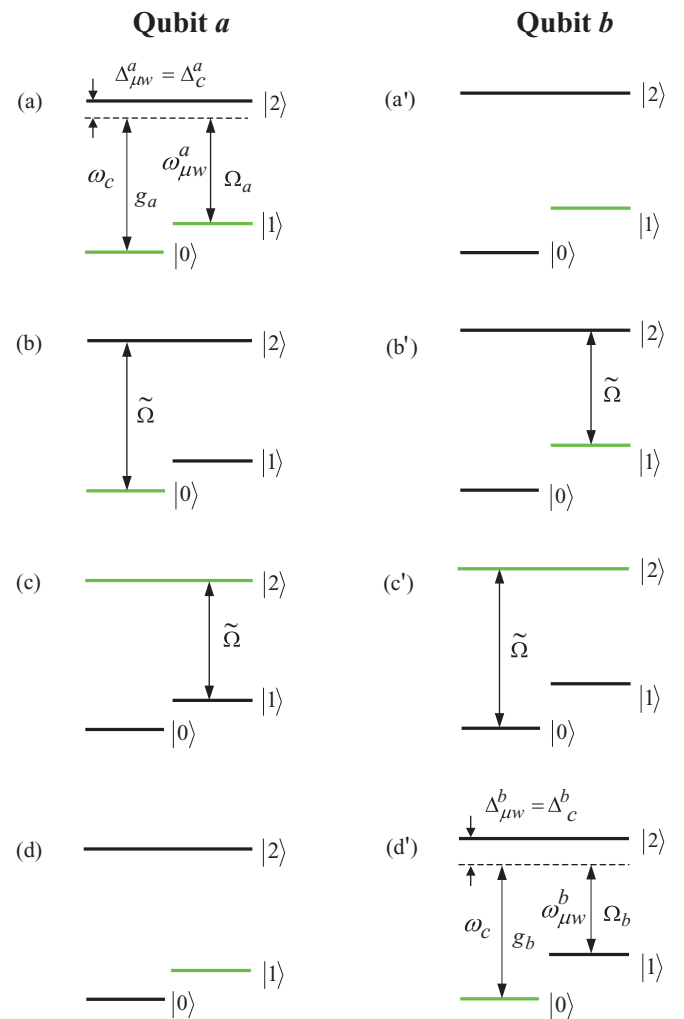

FIG. 3. (Color online) Illustration of qubits interacting with the resonator mode and/or the microwave pulses for each step of operations during the information transfer operation. Figures from top to bottom correspond to the operations of steps (i)∼(iv), respectively. The figures on the left side correspond to qubit a while the figures on the right side correspond to qubit b. In addition, in each figure, the green lines represent the level population of qubits before each step of operation. Note that the nonidentical level spacings for the two qubits are caused by the nonuniform device parameters of the two qubits.

Quantum information transfer. Let us now consider two flux qubits a and b coupled to a resonator [Fig. 2(c)]. Each qubit has a Λ-type three-level configuration as depicted in Fig. 1. Suppose that qubit a is the original carrier of quantum information, which is in an arbitrary state $\alpha|0\rangle + \beta|1\rangle$. The QIT from qubit a to qubit b initially in the state $|1\rangle$ is described by

$$(\alpha|0\rangle_a + \beta|1\rangle_a)|1\rangle_b \rightarrow |1\rangle_a(\alpha|0\rangle_b + \beta|1\rangle_b). \tag{6}$$

To realize the transformation (6), suppose that the resonator mode is off-resonant with the $|0\rangle \leftrightarrow |2\rangle$ transition of each qubit (with a detuning $\Delta_c^a = \omega_{02}^a - \omega_c$ for qubit a while $\Delta_c^b = \omega_{02}^b - \omega_c$ for qubit b) but highly detuned (decoupled) from the transition between any other two levels of each qubit. Note that this condition can be readily achieved by prior adjustment of the level spacings of the qubits before the operation (e.g., via varying the external flux applied to the superconducting loop [14–16,19,20]). The resonator mode is initially in the vacuum state $|0\rangle_c$.

We find that the transformation (6) can be implemented through the following operations:

Step (i): Apply a microwave pulse (with a frequency $\omega_{\mu w}^a$) to qubit a [Fig. 3(a)]. The pulse is off-resonant with the $|1\rangle \leftrightarrow |2\rangle$ transition of qubit a, with a detuning $\Delta_{\mu w}^a = \omega_{12}^a - \omega_{\mu w}^a$. To establish the resonant Raman coupling between the two levels $|0\rangle$ and $|1\rangle$, set $\Delta_{\mu w}^a = \Delta_c^a$. The Rabi frequency Ω_a of the pulse is set by $\Omega_a = g_a$, which can be achieved by adjusting the pulse intensity. It can be seen from Eq. (3) that after a pulse duration $t_1 = \pi\Delta_c^a/(2g_a^2)$, the state $|1\rangle_a|0\rangle_c$ for qubit a and the resonator mode is transformed to the state $|0\rangle_a|1\rangle_c$. On the other hand, the state $|0\rangle_a|0\rangle_c$ remains unchanged during the pulse.

To have a qubit coupled with the resonator mode, the qubit must be in either of the levels $|0\rangle$ or the level $|2\rangle$. Note that qubit b was initially prepared in the state $|1\rangle$ and kept in the same state $|1\rangle$ during this step. Therefore, qubit b is decoupled from the resonator mode during this step.

Step (ii): Apply a microwave pulse (with a frequency $\omega_{\mu w}^a = \omega_{02}^a$ and a phase $\phi = -\pi/2$) to qubit a [Fig. 3(b)] and a microwave pulse (with a frequency $\omega_{\mu w}^b = \omega_{12}^b$ and a phase $\phi = -\pi/2$) to qubit b [Fig. 3(b′)]. The Rabi frequency for each pulse is $\widetilde{\Omega}$. Thus, it can be seen from Eq. (5) that after the pulse duration $t_2 = \pi/(2\widetilde{\Omega})$, the state $|0\rangle$ of qubit a is transformed to the state $|2\rangle$ while the state $|1\rangle$ of qubit b is transformed to the state $|2\rangle$.

Step (iii): Apply a microwave pulse (with a frequency $\omega_{\mu w}^a = \omega_{12}^a$ and a phase $\phi = \pi/2$) to qubit a [Fig. 3(c)] and a microwave pulse (with a frequency $\omega_{\mu w}^b = \omega_{02}^b$ and a phase $\phi = \pi/2$) to qubit b [Fig. 3(c′)]. The Rabi frequency for each pulse is $\widetilde{\Omega}$. It can be found from Eq. (5) that after the pulse duration $t_3 = \pi/(2\widetilde{\Omega})$, the state $|2\rangle$ of qubit a is transformed to the state $|1\rangle$ while the state $|2\rangle$ of qubit b is transformed to the state $|0\rangle$.

Step (iv): Apply a microwave pulse (with a frequency $\omega_{\mu w}^b$) to qubit b [Fig. 3(d′)]. The pulse is off-resonant with the $|1\rangle \leftrightarrow |2\rangle$ transition of qubit b, with a detuning $\Delta_{\mu w}^b = \omega_{12}^b - \omega_{\mu w}^b = \Delta_c^b$ [Fig. 3(d′)]. The Rabi frequency Ω_b of the pulse is set by $\Omega_b = g_b$. It can be seen from Eq. (3) that after a pulse duration $t_4 = \pi\Delta_c^b/(2g_b^2)$, the state $|0\rangle_b|1\rangle_c$ for qubit b and the resonator mode is transformed to the state $|1\rangle_b|0\rangle_c$. On the other hand, the state $|0\rangle_b|0\rangle_c$ remains unchanged during the pulse.

The states of the whole system after each step of the above operations are summarized in the following table:

$$|01\rangle|0\rangle_c \xrightarrow{\text{Step(i)}} |01\rangle|0\rangle_c \xrightarrow{\text{Step(ii)}} |22\rangle|0\rangle_c \xrightarrow{\text{Step(iii)}} |10\rangle|0\rangle_c \xrightarrow{\text{Step(iv)}} |10\rangle|0\rangle_c$$
$$|11\rangle|0\rangle_c \qquad\quad |01\rangle|1\rangle_c \qquad\quad |22\rangle|1\rangle_c \qquad\quad |10\rangle|1\rangle_c \qquad\quad |11\rangle|0\rangle_c, \tag{7}$$

where $|ij\rangle$ is abbreviation of the state $|i\rangle_a|j\rangle_b$ of qubits (a,b) with $i, j \in \{0,1,2\}$. It can be found from Eq. (7) that after the above process, the transformation (6) was achieved with two qubits while the resonator mode returns to its original vacuum state.

From the description above, it can be seen that the method presented here does not require (a) adjustment of the level spacings of each qubit during the operation, (b) slow variation of the Rabi frequency, (c) a finite second-order detuning $\delta_a = \Delta_c^a - \Delta_{\mu w}^a$ or $\delta_b = \Delta_c^b - \Delta_{\mu w}^b$, or (d) the identical level spacings for the two qubits.

Discussion. The occupation probability $p_{2,a}$ of the level $|2\rangle$ for qubit a during step (i) and the occupation probability $p_{2,b}$ of the level $|2\rangle$ for qubit b during step (iv) are given by [20]

$$p_{2,a} \simeq \frac{2}{4 + (\Delta_{\mu w}^a/\Omega_a)^2} + \frac{2}{4 + (\Delta_c^a/g_a)^2},$$
$$p_{2,b} \simeq \frac{2}{4 + (\Delta_{\mu w}^b/\Omega_b)^2} + \frac{2}{4 + (\Delta_c^b/g_b)^2}, \tag{8}$$

where both $p_{2,a}$ and $p_{2,b}$ need to be negligibly small in order to reduce the operation error. For the choice of $\Delta_{\mu w}^a = \Delta_c^a = 10g_a, \Delta_{\mu w}^b = \Delta_c^b = 10g_b$, $\Omega_a = g_a$, and $\Omega_b = g_b$, we have $p_{2,a}$, $p_{2,b} \sim 0.04$, which can be further reduced by increasing the ratio of Δ_c^a/g_a, Δ_c^a/g_b, Ω_a/Δ_a, and Ω_b/Δ_b.

The level $|2\rangle$ of each qubit is only occupied in steps (ii) and (iii). Because resonant pulses are applied in these steps, the pulse durations t_2 for step (ii) and t_3 for step (iii) can be reduced by increasing the pulse Rabi frequencies, such that $t_2 \ll T_2$ and $t_3 \ll T_2$ (where T_2 is the spontaneous time of the level $|2\rangle$ of the qubits). In this way, spontaneous emission from the level $|2\rangle$ can be suppressed.

During steps (ii) and (iii), the off-resonant interaction between the resonator mode and the $|0\rangle \leftrightarrow |2\rangle$ transition of qubit a induces a phase shift to the state $|0\rangle$ or $|2\rangle$ of qubit a when the resonator mode is in the single-photon state $|1\rangle_c$. For step (ii), it is $\exp(it_2g_a^2/\Delta_c^a)$ for the state $|0\rangle$ while $\exp(-it_2g_a^2/\Delta_c^a)$ for the state $|2\rangle$. For step (iii), it is $\exp(it_3g_a^2/\Delta_c^a)$ for the state $|0\rangle$ while $\exp(-it_3g_a^2/\Delta_c^a)$ for the state $|2\rangle$. These phase shifts, which are not considered in Eq. (7), will affect the information transfer performance. However, note that $t_2, t_3 \propto 1/\widetilde{\Omega}$. Thus,

these unwanted phase shifts can be made negligibly small, by increasing the pulse Rabi frequencies such that $\widetilde{\Omega} \gg g_a^2/\Delta_c^a$. In addition, it is noted that phase shifts on the states $|0\rangle$ and $|2\rangle$ of qubit b during steps (ii) and (iii), which are caused by the off-resonant interaction between the resonator mode and the $|0\rangle \leftrightarrow |2\rangle$ transition of qubit b, can be neglected when $\widetilde{\Omega} \gg g_b^2/\Delta_c^b$. To see more clearly, we will give an analysis on the effect of the unwanted qubit-resonator off-resonant interaction on the fidelity of the QIT.

In the ideal case, it can be seen from Eq. (7) that after the operations described above, the state of the two qubits and the resonator mode is $|\psi_{id}(\tau)\rangle = |1\rangle_a(\alpha|0\rangle_b + \beta|1\rangle_b) \otimes |0\rangle_c$. Here, τ is the total operation time. On the other hand, when the off-resonant interaction between the resonator mode and the $|0\rangle \leftrightarrow |2\rangle$ transition of each qubit is included during steps (ii) and (iii), one can easily work out the expression for the final state $|\psi(\tau)\rangle$ of the whole system after performing the operations above. To simplify our presentation, we will not give a complete expression for $|\psi(\tau)\rangle$ due to its complexity. A simple calculation shows that the fidelity for the QIT is

$$F = |\langle\psi_{id}(\tau)|\psi(\tau)\rangle|^2 = (|\alpha|^2 + pq|\beta|^2), \quad (9)$$

where $p = (\widetilde{\Omega}/\eta_a)\sin[\pi\eta_a/(2\widetilde{\Omega})]$, $q = (\widetilde{\Omega}/\eta_b)\sin[\pi\eta_b/(2\widetilde{\Omega})]$. The parameters η_a and η_b are given by $\eta_a = \sqrt{\widetilde{\Omega}^2 + s_a^2/4}$ and $\eta_b = \sqrt{\widetilde{\Omega}^2 + s_b^2/4}$, with $s_a = 2g_a^2/\Delta_c^a$ and $s_b = 2g_b^2/\Delta_c^b$.

Defining $\alpha = \cos\frac{\vartheta}{2}$ and $\beta = e^{i\varphi}\sin\frac{\vartheta}{2}$, where $\vartheta \in [0,\pi]$ and $\varphi \in [0,2\pi]$. Thus, the average fidelity over all possible initial states of the message qubit a is given by

$$\overline{F} = \int_0^{2\pi} d\varphi \int_0^\pi F\sin\vartheta\, d\vartheta/4\pi$$
$$= \frac{1}{3}(1 + p^2q^2 + p^4q^4). \quad (10)$$

It can be verified that when the unwanted qubit-resonator off-resonant interaction in steps (ii) and (iii) is not considered (i.e., the case for $g_a^2/\Delta_c^a, g_b^2/\Delta_c^b = 0$ or $s_a, s_b = 0$), we have $p = q = 1$, leading to $F = 1$ and $\overline{F} = 1$. We have plotted the
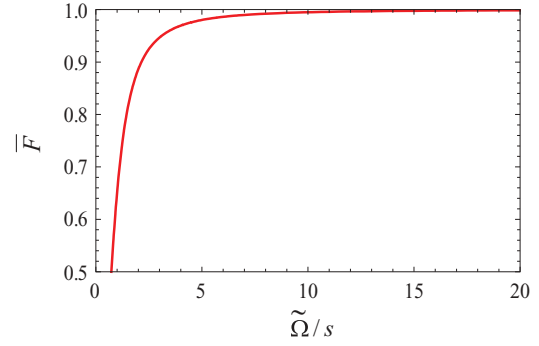

FIG. 4. (Color online) Average fidelity $\overline{F}$ as a function of the Rabi frequency $\widetilde{\Omega}$ (in unit of s).

average fidelity $\overline{F}$ as a function of $\widetilde{\Omega}/s$ for the choice of $s_a = s_b = s$ (Fig. 4). One can see from Fig. 4 that the average fidelity $\overline{F}$ increases as the pulse Rabi frequency $\widetilde{\Omega}$ becomes larger, and the $\overline{F}$ is ~ 1 when $\widetilde{\Omega} = 10s$. This result demonstrates that the effect of the qubit-resonator off-resonant interaction in steps (ii) and (iii) on the fidelity of the operation is negligible when the pulse Rabi frequencies are sufficiently large.

Finally, let us give a rough estimate on the operation time. The total operation time for the information transfer is

$$\tau = \pi\Delta_c^a/(2g_a^2) + \pi\Delta_c^b/(2g_b^2) + \pi/\widetilde{\Omega}. \quad (11)$$

Without loss of generality, consider $g_a \sim g_b \sim 3.0 \times 10^9$ s^{-1}, which is available at present [21]. By choosing $\Delta_c^a = 10g_a, \Delta_c^b = 10g_b$, and $\widetilde{\Omega} \sim 10g_a$, we have $\tau \sim 11$ ns.

Conclusion. We have proposed a way for realizing the quantum information transfer with superconducting flux qubits coupled to a resonator. As shown above, this proposal avoids most of the problems existing in the previous proposals. The method presented here is quite general, which can be applied to the other physical systems such as atoms and quantum dots with the Λ-type three-level structure within cavity QED.

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