Int J Theor Phys (2009) 48: 2793–2799
DOI 10.1007/s10773-009-0069-z

Robust Conditional z Gate Operation in the Decoherence-Free Subspace of Superconducting Quantum-Interference Devices

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Received: 15 February 2009 / Accepted: 18 June 2009 / Published online: 7 July 2009

Abstract A scheme for implementing a conditional z gate in the decoherence-free subspace of superconducting quantum-interference devices (SQUIDs) is presented based on the dispersive interaction. Each logic qubit is encoded in the ground states of two rf SQUIDs, which own lower energy and can be relatively stable in operation. By switching on/off the classical pulses and selecting the gating time appropriately, a high fidelity is obtained. Moreover, this scheme can be generalized to the multi-qubit case without changing the gating time.

Keywords Conditional z gate · Decoherence-free subspaces · SQUID

Quantum computer is a kind of information processor which uses the principles of superposition and entanglement of quantum mechanics to solve certain mathematical problems faster than classical computer, such as factorizing a number and searching for data in an array [1, 2]. So far, a lot of substantial efforts have been dedicated to the field of quantum computation and a number of significant progresses have been made, for instance, ion-trap system [3], cavity quantum electrodynamics (QED) [4, 5], nuclear magnetic resonance (NMR) system [6] and linear optics [7].

While the quantum computer is more powerful than the classical counterpart, the coherence between qubits would be destroyed since the system cannot be placed in a totally closed condition in practice. To avoid the decoherence effect, different methods are applied to implement quantum computation. A straight way is to find an effective path to suppress

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the spontaneous emission of excited state or decay of the qubus [8, 9]. Quantum errorcorrecting code (QECC) can also be used to overcome decoherence [10]. Recently, many works encode the logic qubit in the decoherence-free subspace with respect to certain error, which utilize the symmetric properties of the interaction between the system and environment to avoid the effect of decoherence caused by the environment [11–15].

In many physical carriers of qubits, the solid-state qubits are better for quantum computation because they are scalable and can be easily fabricated to implement a large-scale quantum computing. As one kind of the solid-state systems, the superconducting qubits placed in a superconducting cavity own the relatively long decoherence time and can be considered as a good candidate. Hitherto many works for actualizing quantum computation have been advanced [16–22] with SQUID qubits.

In this paper, we construct a theoretical model for implementing a conditional z gate in cavity QED system with rf SQUID qubits. The advantages of our scheme are fourfold: (i) The position of rf SQUID qubits in a cavity is fixed, which reduces the experimental complexity for control since it is needed to well control the center of mass motion of a neutral atom for cavity-atom systems, which is still a technical challenge. (ii) The low flux states of the SQUID are utilized. So there is no energy relaxation for the SQUIDs in the cavity through the gate operation. (iii) No information transfer between SQUIDs and the cavity, thus the effect of decoherence induced by cavity decay is suppressed. (iv) Qubit is encoded in the decoherence-free subspace which is robust against the phase errors.

We consider N rf SQUIDs with Λ-type configuration simultaneously interaction with a single-mode vacuum cavity field. The transition between the levels $|0\rangle_i \leftrightarrow |2\rangle_i$ is coupled to the cavity mode with the coupling strength g_i and the detuning $\Delta_i + \delta_i$. The classical field drives the transition between the level $|1\rangle_i$ and the level $|2\rangle_i$ with Rabi frequency Ω_i and the detuning Δ_i, the level $|a\rangle$ is an auxiliary state which is decoupled to the system [23], as shown in Fig. 1. The Hamiltonian of the system in the interaction picture can be written as

$$H_I = \sum_{i=1}^{N} g_i (a|2\rangle_{ii}\langle 0|e^{i(\Delta_i+\delta_i)t} + |0\rangle_{ii}\langle 2|a^\dagger e^{-i(\Delta_i+\delta_i)t}) + \sum_{j=1}^{N} \Omega_i (|2\rangle_{ii}\langle 1|e^{i\Delta_i t} + |1\rangle_{ii}\langle 2|e^{-i\Delta_i t}), \quad (1)$$

where $a^\dagger$ and a are, respectively, the creation and annihilation operators for the cavity mode,

$$g_i = \frac{1}{L_i}\sqrt{\frac{\omega_c}{2\mu_0\hbar}}{}_i\langle 0|\Phi_i|2\rangle_i \int_{S_i} \mathbf{B}_c^i(\mathbf{r}) \cdot d\mathbf{S}, \quad (2)$$

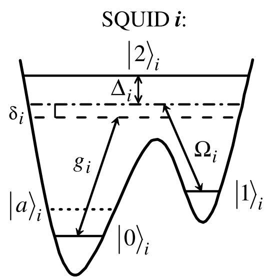


Fig. 1 The level configuration of a rf SQUID. The levels $|0\rangle_i$ and $|2\rangle_i$ are coupled to the cavity mode with the coupling constants g_i and the level $|1\rangle_i$ and $|2\rangle_i$ are coupled to the classical microwave pulse with the coupling strength Ω_i. The two qubits are encoded in the ground states $|0\rangle_{1(2)}$, $|1\rangle_{1(2)}$ and $|0\rangle_{3(4)}$, $|a\rangle_{3(4)}$, respectively

$$\Omega_i = \frac{1}{L_i \hbar}{}_i\langle 1|\Phi_i|2\rangle_i \int_{S_i} \mathbf{B}^i_{\mu w}(\mathbf{r},t)\cdot d\mathbf{S}; \tag{3}$$

with L_i being the inductance of the ith SQUID loop, μ_0 being the vacuum permeability, Φ_i being the externally applied biased flux; $\mathbf{B}^i_c(\mathbf{r})$ being the magnetic component of the cavity mode in the superconducting loop of the ith rf SQUID, $\mathbf{B}^i_{\mu w}(\mathbf{r})$ being the magnetic component of the classical microwave in the superconducting loop of the ith rf SQUID and S being the surface bounded by the SQUID ring. For the sake of convenience, we assume g_i and Ω_i to be real. In the large detuning condition $\Delta_i + \delta_i \gg g_i$ and $\Delta_i \gg \Omega_i$, we can eliminate the excited state adiabatically and obtain the effective Hamiltonian as

$$H_{eff} = \sum_{i=1}^{N} \frac{g_i^2}{(\Delta_i + \delta_i)} |0\rangle_{ii}\langle 0|a^\dagger a + \lambda_i (a|1\rangle_{ii}\langle 0|e^{i\delta_i t} + |0\rangle_{ii}\langle 1|a^\dagger e^{-i\delta_i t}), \tag{4}$$

with $\lambda_i = \frac{g_i\Omega_i}{2}(\frac{1}{\Delta_i} + \frac{1}{\Delta_i+\delta_i})$. The stark-shift term induced by the classical field is unwritten since it can be compensated via using another laser which couples the corresponding level $|1\rangle_i$ nonresonantly with an additional level [24, 25]. To make a further approximation, we assume $\delta_i = \delta \gg \lambda_i$. If the cavity is in the vacuum state, we acquire the final effective Hamiltonian which only includes the interaction between SQUIDs:

$$H_{eff} = \sum_{i=1}^{N} \frac{\lambda_i^2}{\delta} |1\rangle_{ii}\langle 1| + \sum_{i,j=1, i\neq j}^{N} \frac{\lambda_i\lambda_j}{\delta}\sigma_i\sigma_j^\dagger. \tag{5}$$

Equation (5) is an effective Hamiltonian with high controllability since the interaction between two arbitrary SQUIDs depends on the classical pulses acting on them. We encode the first qubit in the state $|0\rangle_{L_1} \equiv |0\rangle_1|1\rangle_2$, $|1\rangle_{L_1} \equiv |1\rangle_1|0\rangle_2$, and the second qubit in the state $|0\rangle_{L_2} \equiv |0\rangle_3|a\rangle_4$, $|1\rangle_{L_2} \equiv |a\rangle_3|0\rangle_4$. Therefore, if the system interacts with the environment in the following phase error

$$H_{pe} = \begin{pmatrix} \epsilon_0(t) & 0 \\ 0 & \epsilon_{1(a)}(t) \end{pmatrix}, \tag{6}$$

which acts on the subspace $\{|0\rangle, |1(a)\rangle\}$, the logical qubits $|0\rangle_L$ and $|1\rangle_L$ both accumulate a global phase factor:

$$\begin{aligned} |0\rangle_{k_1}|1(a)\rangle_{k_2} &\to \exp\left[-i\int_0^t [\epsilon_0(\tau) + \epsilon_{1(a)}(\tau)]d\tau\right]|0\rangle_{k_1}|1(a)\rangle_{k_2} \\ |1(a)\rangle_{k_1}|0\rangle_{k_2} &\to \exp\left[-i\int_0^t [\epsilon_0(\tau) + \epsilon_{1(a)}(\tau)]d\tau\right]|1(a)\rangle_{k_1}|0\rangle_{k_2}, \end{aligned} \tag{7}$$

which shows that the subspace is robust against the collective dephasing. Now we illustrate our idea of implementing the conditional z gate operation. We first switch off all the classical pulses except Ω_1 and Ω_3, then the Hamiltonian in (5) reads

$$H_{eff} = \sum_{i=1,3} \frac{\lambda_i^2}{\delta}|1\rangle_{ii}\langle 1| + \sum_{i,j=1,3}^{i\neq j} \frac{\lambda_i\lambda_j}{\delta}\sigma_i\sigma_j^\dagger. \tag{8}$$

For four initial states of the system, we obtain the corresponding form of evolution as

$$
\begin{aligned}
|0\rangle_1|1\rangle_2|0\rangle_3|a\rangle_4 \quad &\Leftrightarrow \quad |0\rangle_1|1\rangle_2|0\rangle_3|a\rangle_4 \\
|0\rangle_1|1\rangle_2|a\rangle_3|0\rangle_4 \quad &\Leftrightarrow \quad |0\rangle_1|1\rangle_2|a\rangle_3|0\rangle_4 \\
|1\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4 \quad &\Leftrightarrow \quad \frac{e^{-i\frac{(\lambda_1^2+\lambda_3^2)t}{\delta}}\lambda_1^2+\lambda_3^2}{\lambda_1^2+\lambda_3^2}|1\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4 \\
&\qquad + \frac{[e^{-i\frac{(\lambda_1^2+\lambda_3^2)t}{\delta}}-1]\lambda_1\lambda_3}{\lambda_1^2+\lambda_3^2}|0\rangle_1|0\rangle_2|1\rangle_3|a\rangle_4 \\
|1\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4 \quad &\Leftrightarrow \quad e^{-i\frac{\lambda_1^2 t}{\delta}}|1\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4.
\end{aligned}
\tag{9}
$$

If we set $\lambda_1 = \lambda_3 = \lambda$ $(g_1 = g_3, \Omega_1 = \Omega_3, \Delta_1 = \Delta_3)$, $\lambda^2 t/\delta = \pi$, a perfect conditional z gate can be actualized in the decoherence-free subspace of SQUIDs

$$
\begin{aligned}
|0\rangle_{L_1}|0\rangle_{L_2} &\Leftrightarrow |0\rangle_{L_1}|0\rangle_{L_2} \\
|0\rangle_{L_1}|1\rangle_{L_2} &\Leftrightarrow |0\rangle_{L_1}|1\rangle_{L_2} \\
|1\rangle_{L_1}|0\rangle_{L_2} &\Leftrightarrow |1\rangle_{L_1}|0\rangle_{L_2} \\
|1\rangle_{L_1}|1\rangle_{L_2} &\Leftrightarrow -|1\rangle_{L_1}|1\rangle_{L_2}.
\end{aligned}
\tag{10}
$$

With (10), we can realize measurement-based quantum computation, i.e., we can generate the cluster state with many qubits. Suppose two qubits are initially in the state $|\varphi\rangle = \frac{1}{2}(|0\rangle_{L_1} + |1\rangle_{L_1})(|0\rangle_{L_2} + |1\rangle_{L_2})$, through (10), we obtain a two-qubit cluster state as

$$
|\varphi_c\rangle = \frac{1}{2}(|0\rangle_{L_1} + |1\rangle_{L_1}\sigma_z^2)(|0\rangle_{L_2} + |1\rangle_{L_2}), \tag{11}
$$

where $\sigma_z^2 = |0\rangle_{L_2}\langle 0| - |1\rangle_{L_2}\langle 1|$. Then we introduce a third qubit $\frac{1}{\sqrt{2}}(|0\rangle_{L_3} + |1\rangle_{L_3})$ which is encoded as $|0\rangle_{L_3} \equiv |0\rangle_5|1\rangle_6$, $|1\rangle_{L_3} \equiv |1\rangle_5|0\rangle_6$, we switch off other classical pulses leaving the ones coupling the third and the fifth SQUIDs. Similar to the process of (10), we obtain

$$
|\varphi_c^{'}\rangle = \frac{1}{2\sqrt{2}}(|0\rangle_{L_1} + |1\rangle_{L_1}\sigma_z^2)(|0\rangle_{L_2} + |1\rangle_{L_2}\sigma_z^3)(|0\rangle_{L_3} + |1\rangle_{L_3}), \tag{12}
$$

where $\sigma_z^2 = |0\rangle_{L_2}\langle 0| - |1\rangle_{L_2}\langle 1|$. Hence a decoherence-free cluster state with N qubits can be achieved step by step as

$$
|\varphi_n\rangle = 2^{-N/2}\prod_{i=1,\, j=i+1}^{N}(|0\rangle_{L_i} + |1\rangle_{L_i}\sigma_z^j) \tag{13}
$$

where $\sigma_z^N = I$ and $\sigma_z^j = |0\rangle_{L_j}\langle 0| - |1\rangle_{L_j}\langle 1|$, $|0\rangle_{L_j} = |0\rangle|1(a)\rangle$, $|1\rangle_{L_j} = |1(a)\rangle|0\rangle$ for j $(j < N)$ being odd (even) number.

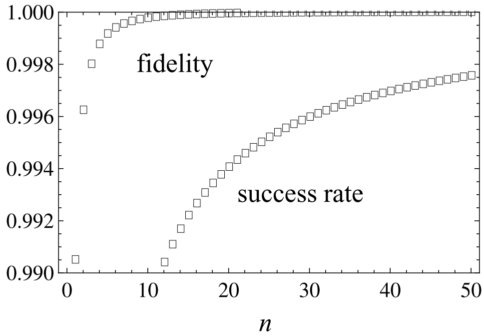
While multiqubit gates can be decomposed into conditional z gates and one-qubit gates [26], the procedure of decomposing multiqubit gate into the elementary gates becomes more complicated when a multi-qubit gate is wanted. The scheme of ours can be directly generalized to implement multi-qubit conditional z gate with only some minor modifications. As an example, we mainly discuss about the realization of three-qubit conditional z gate, the logic qubits are encoded in the subspace $\{|0\rangle_1|1\rangle_2, |1\rangle_1|0\rangle_2, |0\rangle_3|a\rangle_4, |a\rangle_3|0\rangle_4, |0\rangle_5|a\rangle_6, |a\rangle_5|0\rangle_6\}$. If we only switch on Ω_1, Ω_3 and Ω_5, the evolutions of the qubit-states are

$$\begin{aligned}
|0\rangle_1|1\rangle_2|0\rangle_3|a\rangle_4|0\rangle_5|a\rangle_6 &\Leftrightarrow |0\rangle_1|1\rangle_2|0\rangle_3|a\rangle_4|0\rangle_5|a\rangle_6 \\
|0\rangle_1|1\rangle_2|0\rangle_3|a\rangle_4|a\rangle_5|0\rangle_6 &\Leftrightarrow |0\rangle_1|1\rangle_2|0\rangle_3|a\rangle_4|a\rangle_5|0\rangle_6 \\
|0\rangle_1|1\rangle_2|a\rangle_3|0\rangle_4|0\rangle_5|a\rangle_6 &\Leftrightarrow |0\rangle_1|1\rangle_2|a\rangle_3|0\rangle_4|0\rangle_5|a\rangle_6 \\
|0\rangle_1|1\rangle_2|a\rangle_3|0\rangle_4|a\rangle_5|0\rangle_6 &\Leftrightarrow |0\rangle_1|1\rangle_2|a\rangle_3|0\rangle_4|a\rangle_5|0\rangle_6 \\
|1\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4|0\rangle_5|a\rangle_6 &\Leftrightarrow a|1\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4|0\rangle_5|a\rangle_6 \\
&\quad + b|0\rangle_1|0\rangle_2|1\rangle_3|a\rangle_4|0\rangle_5|a\rangle_6 \\
&\quad + c|0\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4|1\rangle_5|a\rangle_6 \\
|1\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4|a\rangle_5|0\rangle_6 &\Leftrightarrow a_1|1\rangle_1|0\rangle_2|0\rangle_3|a\rangle_4|a\rangle_5|0\rangle_6 \\
&\quad + b_1|0\rangle_1|0\rangle_2|1\rangle_3|a\rangle_4|a\rangle_5|0\rangle_6 \\
|1\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4|0\rangle_5|a\rangle_6 &\Leftrightarrow a_2|1\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4|0\rangle_5|a\rangle_6 \\
&\quad + b_2|0\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4|1\rangle_5|a\rangle_6 \\
|1\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4|a\rangle_5|0\rangle_6 &\Leftrightarrow a_3|1\rangle_1|0\rangle_2|a\rangle_3|0\rangle_4|a\rangle_5|0\rangle_6,
\end{aligned} \tag{14}$$

where

$$\begin{aligned}
a &= \frac{e^{-i\frac{(\lambda_1^2+\lambda_3^2+\lambda_5^2)t}{\delta}}\lambda_1^2 + \lambda_3^2 + \lambda_5^2}{\lambda_1^2 + \lambda_3^2 + \lambda_5^2} \\
b &= \frac{[e^{-i\frac{(\lambda_1^2+\lambda_3^2+\lambda_5^2)t}{\delta}} - 1]\lambda_1\lambda_3}{\lambda_1^2 + \lambda_3^2 + \lambda_5^2} \\
c &= \frac{[e^{-i\frac{(\lambda_1^2+\lambda_3^2+\lambda_5^2)t}{\delta}} - 1]\lambda_1\lambda_5}{\lambda_1^2 + \lambda_3^2 + \lambda_5^2} \\
a_1 &= \frac{e^{-i\frac{(\lambda_1^2+\lambda_3^2)t}{\delta}}\lambda_1^2 + \lambda_3^2}{\lambda_1^2 + \lambda_3^2} \\
b_1 &= \frac{[e^{-i\frac{(\lambda_1^2+\lambda_3^2)t}{\delta}} - 1]\lambda_1\lambda_3}{\lambda_1^2 + \lambda_3^2} \\
a_2 &= \frac{e^{-i\frac{(\lambda_1^2+\lambda_5^2)t}{\delta}}\lambda_1^2 + \lambda_5^2}{\lambda_1^2 + \lambda_5^2} \\
b_2 &= \frac{[e^{-i\frac{(\lambda_1^2+\lambda_5^2)t}{\delta}} - 1]\lambda_1\lambda_5}{\lambda_1^2 + \lambda_5^2} \\
a_3 &= e^{-i\frac{\lambda_1^2 t}{\delta}},
\end{aligned} \tag{15}$$

Fig. 2 The fidelity and success rate of the three-qubit conditional z gate versus n



we set $\lambda_3^2 = \lambda_5^2 = (2n+1)\lambda_1^2$ (n being an arbitrary integer), which can be carried out by tuning the amplitude of the classical field. After selecting the interaction time $\lambda_1^2 t/\delta = \pi$, we obtain an approximate three-qubit conditional z gate whose fidelity and success rate depend on the value of n closely. In Fig. 2 we plot the fidelity and success rate of the three-qubit conditional z gate versus n, from which we can see that the larger the value of n is, the higher the fidelity and the success rate are. Even for $n = 1$, the fidelity is still above 99.00% and the success rate is 93.87%.

Now we give a brief discuss about the experimental feasibility of our scheme. The states $|0\rangle$, $|1\rangle$, $|a\rangle$ and $|2\rangle$ correspond to the three lowest and an excited flux states of the SQUID, respectively. To carry out our scheme, there are some conditions to be satisfied: (i) No dipole-dipole interaction. The distance between the two SQUIDs should be made larger than the linear dimension of each SQUID, thus the direct coupling between the two SQUIDs is negligible. (ii) The same coupling strength between SQUID and cavity. The coupling between the SQUID and the cavity is determined by (2), and the magnetic component of the cavity mode can be expanded in the form [27]

$$\mathbf{B}_c(z) = \mu_0\sqrt{2/V}\cos(kz), \tag{16}$$

where we have adopted a standing-wave form of the single-mode cavity. V is the volume of the cavity, k is wave vector of the cavity mode and z is the cavity axis, respectively. Because the linear dimension of SQUID is much less than the wavelength of the cavity mode, the factor $\cos(kz)$ is independent of the integral area with a good approximate and we can obtain the couplings between SQUID and the cavity as [28]

$$g = \frac{S}{L}\Phi_{\alpha\beta}\sqrt{\frac{\hbar\omega_c}{\varepsilon_0 V c^2}}\cos(kz), \quad (\alpha, \beta = 0, 2) \tag{17}$$

with ε_0 being the permittivity of the vacuum, and the coupling strengths are only depended on the positions of the SQUIDs in the cavity. Hence the condition $g_1 = g_3$ for the case of two-qubit conditional z gate is satisfied if each qubit resides in a standing-wave node [23]. (iii) When the number of the qubits are more than two, different effective coupling constants are needed. This condition can be satisfied via adjusting the Rabi frequency of classical pulse in (4) rather than resorting to the nonidentical couplings between qubits and qubus [29].

In summary, we have proposed a scheme for implementing the conditional z gate with SQUIDs dispersive interaction with a superconducting cavity. This gate is robust against decoherence for no excited level of the SQUID and population of the cavity involved through the gate operation. The dephasing error can also be suppressed via encoding the logic qubit in the decoherence-free subspace. The results show that the fidelity and the success rate in our scheme are relatively high, and the gate is easy to be generalized.

Acknowledgement This work was supported by the National Natural Science Foundation of China under Grant No. 60667001.

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