Physics Letters A 382 (2018) 2626–2631

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Quantum switch for coupling highly detuned superconducting qubits

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ARTICLE INFO

Article history:
Received 4 May 2018
Received in revised form 25 July 2018
Accepted 27 July 2018
Available online 1 August 2018
Communicated by M.G.A. Paris

Keywords:
Superconducting qubit
Quantum state transfer
Quantum entanglement

ABSTRACT

We propose to implement a quantum switch scheme for coupling highly detuned superconducting qubits connected by a gap-tunable bridge qubit. By modulating the frequency of the bridge qubit, it can be used as a coupler to switch on/off and adjust the coupling strength between the initially non-interaction qubits. It is shown that the proposals of quantum information transfer and quantum entangled gate between two highly detuned qubits can be implemented with high fidelity. Moreover, we extend the case of coupling the switch to multiple qubits for the generation of W states. The advantages of our scheme are that it eliminates the need for tuning the gaps of the qubits and the cross-talk interaction is greatly suppressed. The influence of decoherence and parameter variation is also investigated by numerical simulation, which suggests that the present scheme is feasible in current experiment.

1. Introduction

Many remarkable breakthroughs have been made on the field of quantum information processing in the past few years. The superconducting circuit has been considered as one of the most promising candidates for the present-day realization of quantum information protocols [1–6]. There are many merits such as flexibility, tunability, and scaling on-chip with nanofabrication techniques. Meanwhile, elements in superconducting circuits can be strongly coupled to each other [7], which makes it a good candidate for control, storage, and readout of quantum information [8–13]. In this solid-state circuits, Josephson-junction acting as a nonlinear circuit element is one of the key components. The energy-level separation of the artificial atom becomes nonuniform due to the nonlinearity of Josephson junctions [14]. The lowest two levels are highly detuned from the other excited states. Thus, these lowest two levels can be encoded as a qubit for implementing quantum computing and simulation [15–18]. Compared with naturally occurring atoms, superconducting qubits can be easily manipulated by currents, voltages and external microwave fields [19–21].

For supercondcting qubits, significant progress have been made towards building a quantum net work, i.e., scaling up to larger numbers of qubits [22–25]. However, as the numbers of qubits increases, the fidelity of quantum gates will be dominated by the unwanted qubit interactions, increased decoherence, and frequency-crowding. For large-scale quantum computation and simulation, it is crucial to realize the controllable coupling between different qubits [26–35]. Usually, one option is to couple/decouple two superconducting quantum elements with always-on coupling by adjusting their frequencies in/out of resonance [36–40]. But this method is susceptible to dephasing noise because it requires quickly change the magnetic flux to tune the energy levels of qubits, which is a severe problem to induce decoherence. Additionally, it becomes difficult to selectively tune individual element fast enough to avoid unwanted interactions when scaling to large number of qubits. Another competing approach is to use nonlinear couplers such as radio frequency superconducting quantum interference device, which can provide resonant coupling strengths from zero to the strong coupling regime [41–45]. On the other hand, the superconducting qubit has intrinsic characteristic of nonlinearity, i.e., one can apply the external driving field to induce the resonant qubit-resonator interaction via sideband excitations [46–51], which is similar to the trapped ion system. Therefore, it can be readily treated as a quantum switch to couple multiple quantum elements for quantum information processing.

In this work, we propose an efficient scheme for coupling highly detuned superconducting qubits via a quantum switch, which is implemented by a gap-tunable bridge qubit. The detunings between them are chosen to be sufficiently large, so that their initial interbit coupling is almost negligible. By modulating the frequency of the bridge qubit, it can be used as a quantum switch to switch on/off and adjust the coupling strength between

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https://doi.org/10.1016/j.physleta.2018.07.042

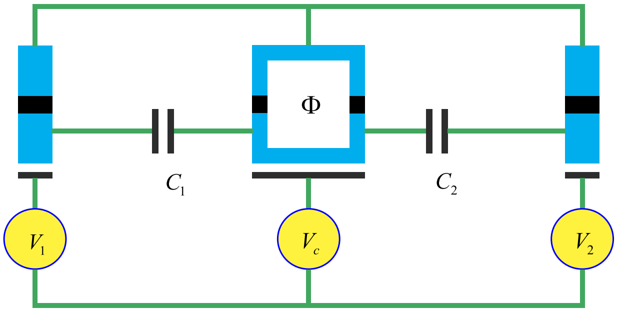

Fig. 1. (Color online). Schematic of three charge qubits are coupled via capacitances C_1 and C_2. The first and the second qubit are controlled by gate voltage V_i $(i = 1, 2)$. The central bridge qubit is manipulated through gate voltage V_c and external magnetic flux Φ.

the initially non-interaction qubits, i.e., both the Jaynes–Cummings and anti-Jaynes–Cummings couplings can be engineered effectively. Firstly, we consider the setup by interacting the quantum switch with two separated qubits, and it is shown that the protocols for quantum information transfer and quantum entangled gate between the two highly detuned qubits can be implemented with high fidelity. Additionally, we also extend the case of coupling the quantum switch to multiple qubits, and the generation of multi-qubit W state can be realized. Compared with the method by suddenly tuning pairs of qubits into and out of specific resonance condition [36–40], our scheme does not need adjust the energy gap of the qubits and the qubit-qubit coupling and decoupling can be easily implemented by controlling the external driving fields. Besides, the qubits in our system is highly detuned from each other, so the crosstalk interaction is greatly suppressed. Compared with the approach by using the nonlinear coupler of superconducting quantum interference device, which can be acted as a tunable inductor to realize the controllable coupling between different qubits [41–45]. The superconducting qubit as a coupler can be robustly initialized, manipulated, and measured with unprecedented level, which is more applicable for building a quantum network and implementing large-scale quantum computation. On the other hand, the disadvantage of our scheme is that the coupler qubit has to be suffered from a two-color external drivings to engineer the desirable couplings. Hence, it has to precisely control the frequencies and amplitudes of the driving fields to avoid the unwanted interactions and the parameters variation. Finally, the effects of decoherence and parameter variation are also analyzed by numerical simulation, which suggests that this proposal is feasible in current experiment. The present work may have useful applications for quantum information processing with superconducting quantum circuits.

2. Model

As shown in Fig. 1, the system under consideration consists of three highly detuned superconducting charge qubits, in which two surrounding qubits are capacitively coupled to the central gap-tunable bridge qubit via capacitances C_1 and C_2. Note that the central qubit can be manipulated by applying the external magnetic flux threading the superconducting quantum interference device (SQUID) loop, which is used as a quantum switch to control the coupling between the surrounding qubits. Here, the qubits in our setup can also be replaced by other kinds of Josephson qubits such as transmons [52,53], flux qubits [54,55], or shunted fluxonium qubits [56]. The interaction of two non-nearest-neighbor qubits (between the first and the second qubit) is very weak thus it can be neglected safely [57]. The total Hamiltonian of the coupling system is given by (let $\hbar = 1$ hereafter)

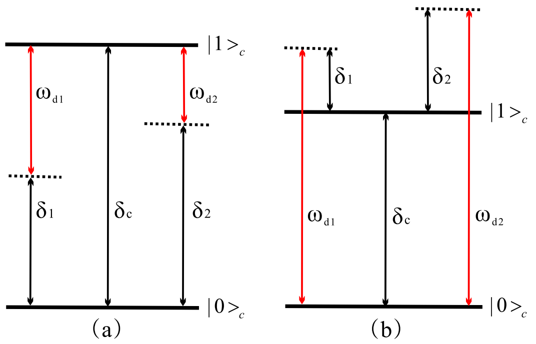

Fig. 2. (Color online). (a) Setup of red sideband excitations ($\omega_{d1} = \delta_c - \delta_1$ and $\omega_{d2} = \delta_c - \delta_2$) for the realization of the quantum state transfer. (b) Schematic of blue sideband excitations ($\omega_{d1} = \delta_c + \delta_1$ and $\omega_{d2} = \delta_c - \delta_2$) for preparing the entangled state.

$$H=\frac{1}{2}\sum_{j=1}^{2}(E_C^j\sigma_z^j+E_J^j\sigma_x^j+g_j\sigma_z^j\sigma_z^c) +\frac{1}{2}\left[E_C^c\sigma_z^c+E_J^c\cos(\Phi)\cdot\sigma_x^c\right], \tag{1}$$

where $\sigma_z^j = |1_j\rangle\langle 1_j| - |0_j\rangle\langle 0_j|$ and $\sigma_x^j = |0_j\rangle\langle 1_j| + |1_j\rangle\langle 0_j|$ are the pseudospin operators and the superscript c denotes the central qubit hereafter. E_C^j $(j = 1, 2, c)$ is the effective charging energy of the jth qubit, whose effective Josephson energy is E_J^j $(j = 1, 2, c)$; $g_1(g_2)$ is the coupling strength between the nearest-neighbor qubits; $\Phi = \Phi_0 + \sum_{l=1}^{2}\Phi_l\cos(\omega_{dl}t)$ is the static and time-dependent magnetic flux penetrating the SQUID loop of the bridge qubit, which is crucial for realizing controllable coupling. Working at the optimal point with $E_C^j(j = 1, 2, c) = 0$, the above Hamiltonian reduces to the form

$$H=\frac{1}{2}\left[\sum_{j=1}^{2}(E_J^j\sigma_x^j+g_j\sigma_z^j\sigma_z^c)+E_J^c\cos(\Phi)\cdot\sigma_x^c\right]. \tag{2}$$

In the case of $\Phi_0 \gg \Phi_l$ $(l = 1, 2)$, we only keep the first order in the expanded form of $\cos(\Phi)$. After making a rotation, i.e., $\sigma_x \to \sigma_z, \sigma_z \to \sigma_x$, we will obtain

$$H=\sum_{j=1}^{2}\left[\frac{1}{2}\delta_j\sigma_z^j+g_j(\sigma_+^j+\sigma_-^j)\left(\sigma_+^c+\sigma_-^c\right)\right] +\frac{1}{2}\delta_c\sigma_z^c-\sum_{l=1}^{2}\xi_l\omega_{dl}\cos\left(\omega_{dl}t\right)\cdot\sigma_z^c, \tag{3}$$

in which $\sigma_+^j = |1_j\rangle\langle 0_j|$, $\sigma_-^j = |0_j\rangle\langle 1_j|$ are spin-flip operators for the superconducting qubit satisfying the relation $\sigma_+^j + \sigma_-^j = \sigma_x^j$ $(j = 1, 2, c)$, $\delta_c = E_J^c\cos(\Phi_0)$, $\xi_l\omega_{dl} = \frac{1}{2}E_J^c\Phi_l\sin(\Phi_0)$ and $\delta_j = E_J^j$ $(j = 1, 2)$.

3. Quantum switch for controllable coupling

In this section, we will show the detail that how to realize the controllable coupling between the highly detuned qubits via the quantum switch. Then, we will discuss to implement the protocols of quantum information transfer and entangled gate. First of all, we perform a unitary transformation $U_1(t) = \exp(-iH_0t)$ with $H_0 = \frac{1}{2}(\delta_1\sigma_z^1 + \delta_c\sigma_z^c + \delta_2\sigma_z^2)$ to the Hamiltonian (3), and the Hamiltonian in the interaction picture will read

$$H_I=\sigma_+^c e^{i\delta_c t}\sum_{j=1}^{2}g_j(\sigma_+^j e^{i\delta_j t}+\sigma_-^j e^{-i\delta_j t})+H.c. -\sum_{l=1}^{2}\xi_l\omega_{dl}\cos\left(\omega_{dl}t\right)\cdot\sigma_z^c. \tag{4}$$

Note that the system is operated in the highly detuned regime, so the interqubit interaction is negligible. If we turn on the external driving to the bridge qubit described by the last term of