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A scheme for implementing quantum clock synchronization algorithm in cavity QED*

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In this paper, we propose a scheme for implementing the quantum clock synchronization (QCS) algorithm in cavity quantum electrodynamic (QED) formalism. Our method is based on three-level ladder-type atoms interacting with classical and quantized cavity fields. Atom-qubit realizations of three-qubit and four-qubit QCS algorithms are explicitly presented.

Keywords: quantum clock synchronization algorithm, three-level atoms, cavity QED
PACC: 4250, 0365

1. Introduction

Clock synchronization has been the focus of intense study due to the potential for both commercial and scientific rewards. Accurate timekeeping is key to navigation, telecommunication, long baseline interferometry and tests of the general theory of relativity. Currently used synchronization protocols fall into two categories: Eddington adiabatic transfer[1] and Einstein clock synchronization.[2] In the Eddington adiabatic transfer scheme, the two clocks A and B are first synchronized locally, and then they are transported adiabatically to their final separate locations.[1,3] The Einstein clock synchronization is much easier to implement in which Alice sends a signal pulse to Bob, which he then returns to Alice. By recording the signal's times of departure and arrival, Alice and Bob can synchronize their clocks. Notice that the above protocols can be implemented using only classical resources. It is believed that synchronization protocols using the peculiar properties of prior entanglement, called quantum clock synchronization (QCS), may provide increased robustness and accuracy. Several such QCS protocols have recently been proposed.[4−7] The protocol proposed in Ref.[5] utilizes the resource of shared prior entanglement between the two synchronizing parties. In this protocol, no actual clocks exist initially but rather only 'entangled clocks' in a global state which does not evolve in time. The synchronized clocks are then extracted via measurements and classical communications performed by Alice and Bob. In this way the scheme establishes synchrony without having to transport timing information between Alice and Bob. In contrast, in classical synchronization schemes, actual timing information must be transmitted from Alice to Bob over some channel, whose imperfections generally limit the accuracy of the synchronization. The two-party protocol was generalized to a multiparty QCS protocol in Ref.[6]. The basic problem of clock synchronization is easily formulated: determine the time difference Δ between two spatially separated clocks by using the minimum communication resources. Chuang[4] proposed a QCS algorithm in which n digits of the time difference Δ can be obtained by communicating only $O(n)$ quantum messages. In Ref.[7], Preskill investigated whether entanglement distillation or quantum error-correcting codes can improve the robustness of these protocols.

Recently, the QCS algorithm has been implemented in a three-qubit nuclear magnetic resonance quantum system.[8] As is well known, cavity quantum electron-dynamics (QED) is another qualified system for realizing quantum information process.[9−11] A two-qubit phase gate has been experimentally realized in the resonant interaction of a two-level atom with a cavity mode[12] and a scheme for the realization

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of quantum phase gates between two atoms in cavity QED has been presented in Ref.[13]. Moreover, the way of the realization of the quantum controlled-not (CNOT) gate has been proposed in Ref.[14]. Schemes have been proposed for realizing a quantum discrete Fourier transform[15] and a Grover search algorithm in cavity QED.[16] In this paper, we propose a scheme for implementing the QCS algorithm in cavity QED. So far as we know up to now, this is the first scheme for the implementation of this algorithm in cavity QED.

2. QCS algorithm and simplified circuit

Before going into the realization, we briefly review the QCS algorithm[4] which involves three steps. In the QCS algorithm of a $(m+1)$-qubit system, Alice possesses $m+1$ qubits initialized to $|\phi_0\rangle = |0\rangle|0\rangle$. The first m qubits are the working qubits and the extra qubit is an ancilla qubit.

In the first step, Alice performs the Hadamard operation on each of the first m qubits to transform the initial state of the m working qubits to the equal-weight superposition state

$$|\phi_1\rangle = \frac{1}{\sqrt{2^m}} \sum_{k=0}^{2^m-1} |k\rangle|0\rangle. \tag{1}$$

In the second step, Alice performs the T operation which is implemented through making CNOT operations between the working and ancilla qubits and carries out the ticking qubit handshaking protocol.[4] The T operation introduces the time difference between two clocks into quantum state of the working qubits; it is a key step of the QCS algorithm. After completing the T operation, the state of the $(m+1)$-qubit system becomes

$$|\phi_2\rangle = \frac{1}{\sqrt{2^m}} \sum_{k=0}^{2^m-1} \mathrm{e}^{2\pi \mathrm{i} k\omega\Delta}|k\rangle|0\rangle. \tag{2}$$

In the third step, Alice applies an inverse quantum Fourier transform F^{-1} on the quantum state of m working qubits

$$F^{-1}|k\rangle = \frac{1}{\sqrt{2^m}} \sum_{j=0}^{2^m-1} \mathrm{e}^{-2\pi \mathrm{i} kj/2^m}|j\rangle. \tag{3}$$

From Eqs.(2) and (3), we can see that after the inverse quantum Fourier transform, the quantum state of the m working qubits is given by

$$|\phi_3\rangle = \frac{1}{2^m} \sum_{k=0}^{2^m-1} \sum_{j=0}^{2^m-1} \mathrm{e}^{2\pi \mathrm{i} k(\omega\Delta - j/2^m)}|j\rangle, \tag{4}$$

which peaks at $j = 2^m\omega\Delta$. If $2^m\omega\Delta$ is an integer, the equality holds. One can obtain the value of j (i.e., the time difference Δ) by making quantum measurements upon the quantum states of the m working qubits.

The quantum network to implement the three-qubit QCS algorithm[8] is shown in Fig.1. The three input lines denote the three qubits; H denotes the Hadamard transformation; I_1 is the controlled phase shift operation applied to the subsystem constructed by qubits 1 and 2 with the following matrix form:

$$I_1 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -i \end{pmatrix}. \tag{5}$$

The two rotation operations about the z-axis R_{Z_l} in the quantum network are given by

$$R_{Z_l} = \mathrm{e}^{\mathrm{i}(2^l\pi\varphi/2)\sigma_z} = \begin{pmatrix} \exp(-\mathrm{i}2^l\pi\varphi/2) & 0 \\ 0 & \exp(\mathrm{i}2^l\pi\varphi/2) \end{pmatrix}, \tag{6}$$

where $\varphi = \omega\Delta$ and $l = 1, 2$. The time evolution direction in Fig.1 goes from left to right. $|x_1\rangle|y_2\rangle$ is the output state, which can be obtained through measuring qubits 1 and 2.

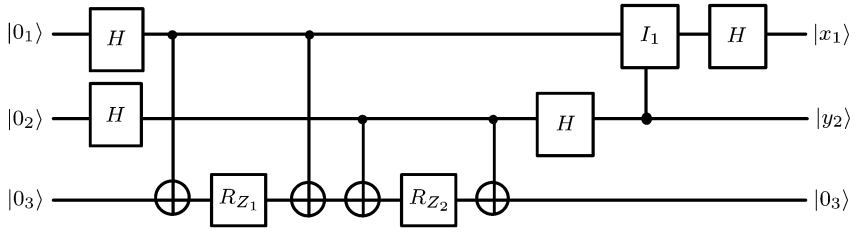


Fig.1. The quantum network for implementing the three-qubit QCS algorithm.

3. Cavity QED realization of QCS algorithm

In this section, we shall present the realization of quantum network of three-qubit QCS algorithm in cavity QED. In order to do this, first of all, we need to carry out the controlled phase shift operation I_1, the CNOT gate and the single-qubit gates in cavity QED formalism. The single-qubit gates can be realized simply by letting the atoms interact with the classical fields.

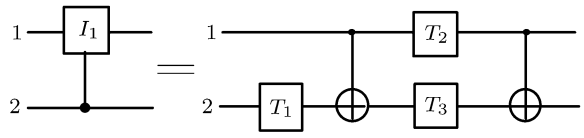


Fig.2. The quantum network for implementing the controlled phase shift operation I_1.

Let us first consider the cavity QED realization of the controlled phase shift operation I_1. We note that the operation I_1 can be decomposed into a product of two CNOTs and three T_i $(i = 1, 2, 3)$ operations

$$I_1 = (\mathrm{CNOT})_{12}(T_2)_1(T_3)_2(\mathrm{CNOT})_{12}(T_1)_2, \qquad (7)$$

where the three T_i operations are given by the following unitary transformations:

$$T_1 = \begin{pmatrix} 0 & 1 \\ \exp(-\mathrm{i}\pi/4) & 0 \end{pmatrix},$$

$$T_2 = \begin{pmatrix} 1 & 0 \\ 0 & \exp(-\mathrm{i}\pi/4) \end{pmatrix},$$

$$T_3 = \begin{pmatrix} 0 & \exp(\mathrm{i}\pi/4) \\ 1 & 0 \end{pmatrix}, \qquad (8)$$

which can be further expressed in terms of rotation operations of single qubit about the z- and y- axes as follows:

$$T_1 = \mathrm{e}^{\mathrm{i}3\pi/8} R_y(\pi) R_{Z_3}\left(\frac{5\pi}{4}\right),$$

$$T_2 = \mathrm{e}^{-\mathrm{i}\pi/8} R_{Z_4}\left(-\frac{\pi}{4}\right),$$

$$T_3 = \mathrm{e}^{\mathrm{i}5\pi/8} R_y(\pi) R_{Z_3}\left(\frac{5\pi}{4}\right). \qquad (9)$$

Here the three rotation operations are defined as

$$R_y(\pi) = \mathrm{e}^{-\mathrm{i}(\pi/2)\sigma_y},$$

$$R_{Z_3}\left(\frac{5\pi}{4}\right) = \mathrm{e}^{-\mathrm{i}(5\pi/8)\sigma_z},$$

$$R_{Z_4}\left(-\frac{\pi}{4}\right) = \mathrm{e}^{\mathrm{i}(\pi/8)\sigma_z}. \qquad (10)$$

We present the quantum network to realize the controlled phase shift operation I_1 in Fig.2.

Making use of the decomposition of the controlled phase shift operation I_1, we can express the quantum network for realizing the QCS algorithm given in Fig.1 in terms of only single qubit operations and CNOT gate as in Fig.3.

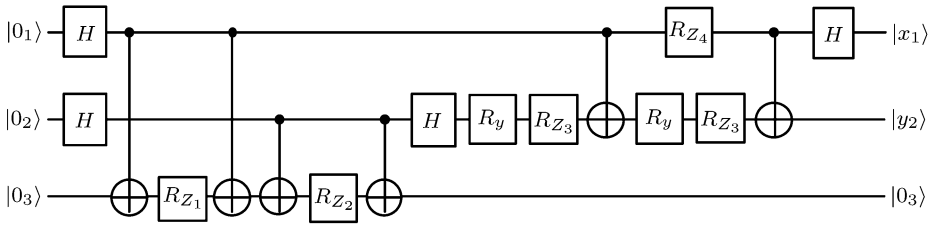


Fig.3. The quantum network for implementing the three-qubit QCS algorithm with only single qubit operations and CNOT gate.

In what follows, we want to show that all operations which appear in the quantum network of the QCS algorithm given in Fig.3 can be realized in a cavity QED formalism. In order to do this, we use three three-level atoms with ladder-type configuration. States of these atoms are denoted by $|g\rangle_j$, $|e\rangle_j$ and $|i\rangle_j$ with $j = 1, 2, 3$.

3.1. The realization of the Hadamard transformation

From the quantum network in Fig.3 we can see that the Hadamard transformation is needed to realize the QCS algorithm for the first two qubits encoded in atoms 1 and 2. We first let atoms 1 and 2 cross two classical fields both tuned to the transi-

tion $|g\rangle_j \longrightarrow |e\rangle_j$. The interaction Hamiltonian in the interaction picture is

$$H_{\rm I} = g \sum_{j=1,2} ({\rm e}^{-{\rm i}\delta t} S_j^- + {\rm e}^{{\rm i}\delta t} S_j^\dagger), \tag{11}$$

where $S_j^\dagger = |e\rangle_{jj}\langle g|$ and $S_j^- = |g\rangle_{jj}\langle e|$ with $|e\rangle_j$ and $|g\rangle_j$ (j=1, 2) being the excited and the ground states of the jth atom respectively. Choose the amplitudes and phases of the classical fields in order that the atoms undergo the transitions

$$|g\rangle_j \longrightarrow \frac{1}{\sqrt{2}}(|e\rangle_j + |g\rangle_j) \longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_j + |e\rangle_j),$$

$$|e\rangle_j \longrightarrow \frac{1}{\sqrt{2}}(|e\rangle_j - |g\rangle_j) \longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_j - |e\rangle_j). \tag{12}$$

If we make $|g\rangle$ and $|e\rangle$ correspond to states of qubits $|0\rangle$ and $|1\rangle$, respectively, then Eq.(12) implies the Hadamard transformation.

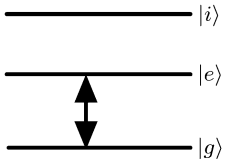


Fig.4. The level diagram of the ladder-type three-level atom used in the realization.

3.2. The realization of the $R_y(\pi)$ operation

The quantum network in Fig.3 shows that the second qubit encoded in atom 2 needs the $R_y(\pi)$ operation. By using the same way for applying classical field as above and choosing appropriate parameters, atom 2 undergoes the following transition:

$$|g\rangle_2 \longrightarrow |e\rangle_2, \quad |e\rangle_2 \longrightarrow -|g\rangle_2, \tag{13}$$

which is the single qubit rotation gate $R_y(\pi)$.

3.3. The realization of the $R_{Z_k}(\theta_k)$ operations

In order to realize the three-qubit QCS algorithm, each of the three qubits needs rotating operations about the z-axis denoted by $R_{Z_k}(\theta_k)$ which can be expressed as

$$R_{Z_k}(\theta_k) = \begin{pmatrix} \exp(-{\rm i}\theta_k/2) & 0 \\ 0 & \exp({\rm i}\theta_k/2) \end{pmatrix}, \tag{14}$$

where $\theta_k = 2\pi\varphi,\ 4\pi\varphi,\ 5\pi/4$, and $-\pi/4$ corresponds to $k = 1, 2, 3$, and 4, respectively. In order to realize these $R_{Z_k}(\theta_k)$ operations, we need the following three steps:

Step 1 Let the jth atom interact with the first classical field as above. Choosing the amplitude and phase of the classical field appropriately so that the atom undergos the following transitions,

$$|g\rangle_j \longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_j + |e\rangle_j),$$

$$|e\rangle_j \longrightarrow \frac{1}{\sqrt{2}}(|e\rangle_j - |g\rangle_j). \tag{15}$$

Step 2 Then let the jth atom cross the second classical field to realize the following transitions:

$$|g\rangle_j \longrightarrow \cos(\theta_k/2)|g\rangle_j - {\rm i}\sin(\theta_k/2)|e\rangle_j,$$

$$|e\rangle_j \longrightarrow \cos(\theta_k/2)|e\rangle_j - {\rm i}\sin(\theta_k/2)|g\rangle_j. \tag{16}$$

Step 3 Finally let the jth atom cross the third classical field to undergo the following transitions:

$$|g\rangle_j \longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_j - |e\rangle_j),$$

$$|e\rangle_j \longrightarrow \frac{1}{\sqrt{2}}(|e\rangle_j + |g\rangle_j). \tag{17}$$

After completing the above three steps, we arrive at the following transformations:

$$|g\rangle_j \longrightarrow {\rm e}^{-{\rm i}\theta_k/2}|g\rangle_j, \qquad |e\rangle_j \longrightarrow {\rm e}^{{\rm i}\theta_k/2}|e\rangle_j. \tag{18}$$

This means that if we make atomic states $|g\rangle$ and $|e\rangle$ correspond to the states of qubits $|0\rangle$ and $|1\rangle$, respectively, the transformations in Eq.(18) represent the one-qubit rotation operations about z-axis $R_{Z_k}(\theta_k)$.

3.4. The realization of the CNOT gate

In the quantum network of the three-qubit QCS algorithm, there are six CNOT gate operations for three related qubits encoded in three atoms. Making use of the method proposed in Ref.[14], one can realize the CNOT gate operation between two atomic qubits. For instance, assume that atoms 1 and 3 act as the control bit and the controlled bit, respectively, then the CNOT gate between atom 1 and atom 3 can be realized through the following three steps:

Step 1 Let atom 3 cross two classical fields tuned to the transitions $|g\rangle \longrightarrow |e\rangle$ and $|e\rangle \longrightarrow |i\rangle$, respectively. Choosing the amplitudes and phases of the

classical fields appropriately so that atom 3 undergoes the following transitions.

$$|g\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_3 - |e\rangle_3) \longrightarrow \frac{1}{\sqrt{2}}(|g\rangle_3 - |i\rangle_3),$$
$$|e\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}(|e\rangle_3 + |g\rangle_3) \longrightarrow \frac{1}{\sqrt{2}}(|i\rangle_3 + |g\rangle_3). \tag{19}$$

This leads to the following transformations for atoms 1 and 3

$$|g\rangle_1|g\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|g\rangle_1(|g\rangle_3 - |i\rangle_3),$$
$$|g\rangle_1|e\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|g\rangle_1(|i\rangle_3 + |g\rangle_3),$$
$$|e\rangle_1|g\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|e\rangle_1(|g\rangle_3 - |i\rangle_3),$$
$$|e\rangle_1|e\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|e\rangle_1(|i\rangle_3 + |g\rangle_3). \tag{20}$$

Step 2 Then let atoms 1 and 3 simultaneously enter a single-mode cavity of a quantized cavity field. If initially the cavity is in the vacuum state, under the condition of large detuning the effective Hamiltonian reduces to

$$H = \lambda \left[\sum_{j=1,3} |e\rangle_{jj}\langle e| + (S_1^\dagger S_3^- + S_1^- S_3^\dagger) \right], \tag{21}$$

indicating that if we take the output states after the first step as the input states of the second step, then a time evolution of $\lambda t = \pi$ leads to the following state transformations:

$$|g\rangle_1|g\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|g\rangle_1(|g\rangle_3 - |i\rangle_3),$$
$$|g\rangle_1|e\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|g\rangle_1(|i\rangle_3 + |g\rangle_3),$$
$$|e\rangle_1|g\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|e\rangle_1(|g\rangle_3 + |i\rangle_3),$$
$$|e\rangle_1|e\rangle_3 \longrightarrow \frac{1}{\sqrt{2}}|e\rangle_1(-|i\rangle_3 + |g\rangle_3). \tag{22}$$

Step 3 Finally let atom 3 cross two classical fields tuned to the transitions $|e\rangle \longrightarrow |i\rangle$ and $|g\rangle \longrightarrow |e\rangle$, respectively. By properly choosing the amplitudes and phases of the classical fields, one can complete the CNOT gate operation between the two atomic qubits,

$$|g\rangle_1|g\rangle_3 \longrightarrow |g\rangle_1|g\rangle_3,$$
$$|g\rangle_1|e\rangle_3 \longrightarrow |g\rangle_1|e\rangle_3,$$
$$|e\rangle_1|g\rangle_3 \longrightarrow |e\rangle_1|e\rangle_3,$$
$$|e\rangle_1|e\rangle_3 \longrightarrow |e\rangle_1|g\rangle_3. \tag{23}$$

So far we have realized all of the quantum logic operations which are needed in the quantum network of the three-qubit QCS algorithm in the cavity QED formalism. If we write $\varphi = 0, \varphi_1\varphi_2 = \varphi_1/2 + \varphi_2/2^2$, after implementing the quantum network of the QCS algorithm in Fig.3, we can see that the output state will be $|x_1\rangle = |\varphi_1\rangle$, $|y_2\rangle = |\varphi_2\rangle$. So by measuring quantum states of the atoms 1 and 2, we can determine the value of φ_1 and φ_2, i.e., the ground state would correspond to the output 0 and the excited state would correspond to the output 1.

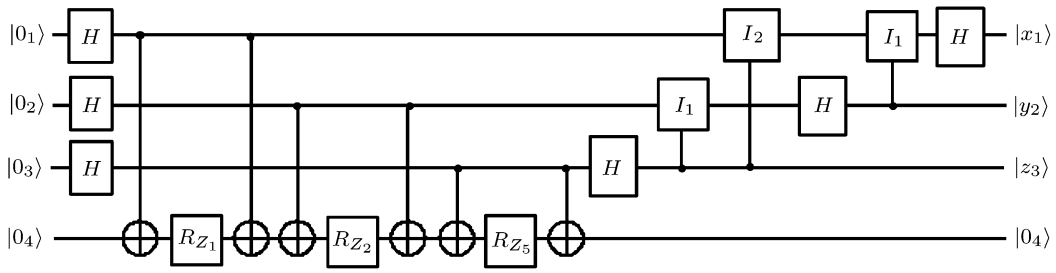


Fig.5. The quantum network for implementing the four-qubit QCS algorithm.

The above cavity QED approach to realize the quantum network of the three-qubit QCS algorithm can be extended to many-qubit QCS algorithm. As an example, we consider the situation of the four-qubit QCS algorithm in which four atom qubits are needed. In Fig.5 we give the quantum network for implementing the four-qubit QCS algorithm. In the network time goes from left to right. The input and output states are $|0_1\rangle|0_2\rangle|0_3\rangle|0_4\rangle$ and $|x_1\rangle|y_2\rangle|z_3\rangle|0_4\rangle$, respectively. The four lines denote the four qubits. H denotes the Hadamard transformation. The rotation operations I_1 and R_{Z_l} $(l = 1, 2)$ are given by Eqs.(5)

and (6), respectively. The two-qubit controlled phase shift operation I_2 and the rotation operation R_{Z_5} are given by the following unitary transformations:

$$I_2 = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \mathrm{e}^{-\mathrm{i}\frac{\pi}{4}} \end{pmatrix},$$

$$R_{Z_5} = \begin{pmatrix} \mathrm{e}^{-\mathrm{i}4\pi\varphi} & 0 \\ 0 & \mathrm{e}^{\mathrm{i}4\pi\varphi} \end{pmatrix}. \tag{24}$$

The two-qubit controlled phase shift operation I_2 can be decomposed into a product of two CNOT and three T_i $(i = 4, 5, 6)$ operations as shown in Fig.6.

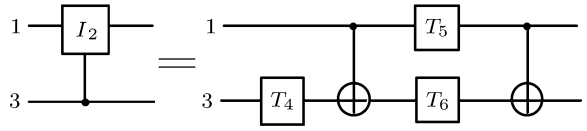


Fig.6. The quantum network for implementing the two-qubit controlled phase shift operation I_2.

$$I_2 = (\mathrm{CNOT})_{13}(T_5)_1(T_6)_3(\mathrm{CNOT})_{13}(T_4)_3, \tag{25}$$

where the three T_i $(i = 4, 5, 6)$ operations are given by the following unitary transformations:

$$T_4 = \begin{pmatrix} 0 & 1 \\ \exp(-\mathrm{i}\pi/8) & 0 \end{pmatrix},$$

$$T_5 = \begin{pmatrix} 1 & 0 \\ 0 & \exp(-\mathrm{i}\pi/8) \end{pmatrix},$$

$$T_6 = \begin{pmatrix} 0 & \exp(\mathrm{i}\pi/8) \\ 1 & 0 \end{pmatrix}. \tag{26}$$

These can be further expressed in terms of rotating operations of single qubit about the z- and y- axes as follows:

$$T_4 = \mathrm{e}^{\mathrm{i}(7\pi/16)} R_y(\pi) R_{Z_6}\left(\frac{9\pi}{8}\right),$$

$$T_5 = \mathrm{e}^{-\mathrm{i}(\pi/16)} R_{Z_7}\left(-\frac{\pi}{8}\right),$$

$$T_6 = \mathrm{e}^{\mathrm{i}(9\pi/16)} R_y(\pi) R_{Z_6}\left(\frac{9\pi}{8}\right), \tag{27}$$

where

$$R_{Z_6}\left(\frac{9\pi}{8}\right) = \mathrm{e}^{-\mathrm{i}(9\pi/16)\sigma_z},$$

$$R_{Z_7}\left(-\frac{\pi}{8}\right) = \mathrm{e}^{\mathrm{i}(\pi/16)\sigma_z}. \tag{28}$$

Making use of the decompositions of the controlled phase shift operations I_1 and I_2, we can express the quantum network for realizing the four-qubit QCS algorithm given in Fig.5 in terms of only single qubit operations and CNOT gate as in Fig.7.

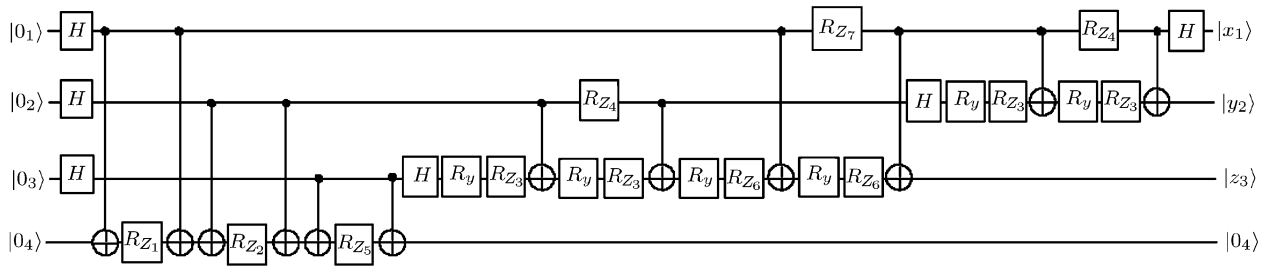


Fig.7. The quantum network for implementing the four-qubit QCS algorithm with only single qubit operations and CNOT gate.

From the network given in Fig.7 we can see that there are twelve CNOT gate operations for four related qubits encoded in four atoms. Six Hadamard transformations are needed for the three working qubits encoded in atoms 1, 2 and 3. Each of the four qubits needs rotating operations about the z-axis, which have been expressed in Eqs.(14), (24) and (28). The second and the third qubits encoded in the atoms 2 and 3 need the $R_y(\pi)$ operation expressed in Eq.(10). So using the same method as in the realization of the three-qubit QCS algorithm, we can also realize the quantum network of the four-qubit QCS algorithm in cavity QED.

4. Conclusion

In summary, we have proposed a scheme to realize QCS algorithm in cavity QED formalism. In

our method, qubits are encoded in terms of energy levels of atoms in ladder-type configurations. Operations of atomic qubits are completed through controlling interactions between atoms and classical or/and quantized cavity fields. Single-qubit Hadamard operations, single-qubit rotating operations, two-qubit CNOT gates and two-qubit controlled phase shift operations are needed for implementing QCS algorithm. We have explicitly presented atom-qubit realizations of three-qubit, and four-qubit QCS algorithms. It can also be expected to use this method to realize more general quantum networks of many-qubit QCS algorithm.

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