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Quantum state transfer via the selective pairing of off-resonant Raman transitions

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Abstract. A simple scheme for transferring an unknown atomic state based on the pairing of off-resonant Raman transitions is proposed. The scheme is insensitive to the atomic spontaneous emission, cavity decay, and fiber decay. Meanwhile, in the scheme, operations between any pair of atomic qubits and selective parallel two-qubit operations on different qubit pairs can be implemented. The atoms, the cavity modes and the fiber are not excited during the operations. A quantum communication network for transferring quantum information can be established. Therefore the scheme would be a useful step toward future scalable quantum computing networks.

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Key words: transfer, off-resonant Raman transitions, separate cavities

1 Introduction

Quantum state transfer (QST), which is an important part of quantum information processing such as quantum teleportation [1,2], quantum dense coding [3], quantum cryptography [4], and quantum computer[5] etc. has attracted much attention. It is a process of transferring a quantum state from one node to another node with the help of a career (a quantum channel).In recent years,a great many of QST protocols have been presented in various quantum systems [6-13]. For example, Yang *et al.* [6, 7] presented two different schemes for transferring of quantum state with superconducting quantum interference device qubits in cavity QED. Christandl *et al.* [8] presented a QST scheme through quantum network using a linear XY chain of N interacting qubits. Quantum state transfer between two atoms in a cavity has been demonstrated via resonant interaction[9]. Cirac

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et al. proposed a QST scheme [10] between two atoms trapped inside two spatially separated cavities via an optical fiber in cavity quantum electrodynamics(cavity QED). Biswas *et al.* [11] presented a QST proposal based on two-mode cavity interacting dispersively with three-level atoms in the configuration. Ye *et al.* [12,13] proposed some schemes for transferring of two-mode entangled state and unknown atomic entangled state via cavity QED. Among the different quantum systems, cavity QED system is always considered as the most effective system due to its ability of constructing quantum networking [14] and low decoherent rate[15].Recently, the system of separate cavities connected by optical fibers have been attracted more and more attention in quantum information processing such as entanglement preparation, QST *et al.*[16–22]. Zheng [16] proposed an efficient scheme for quantum communication between two atoms trapped in distant cavities which are connected by an optical fibre. Pellizzari *et al.* [17] proposed a scheme of transferring quantum information between two distant $\wedge$-type atoms via an adiabatic passage in a cavity-fiber-cavity system. Yin *et al.* [18] proposed a QST scheme between two remote coupled systems of cavity-atom. However, to the best of our knowledge, the most of previous QST schemes are two-dimension schemes of transferring quantum information between two qubits, and there are few schemes to consider how to realize entangled state QST between two atom pairs trapped in separate cavities linked by optical fibers.

In this paper we present a simple QST scheme between two atom pairs trapped in separate cavities linked by optical fibers based on the pairing of off-resonant Raman transitions. In the scheme two ground states of each atom are coupled via the respective cavity mode and a classical field in the Raman manner. Under the large detuning condition, the atoms do not undergo real Raman transitions and the Hamiltonian for the atomic system is decoupled from the cavity modes and fiber mode. The quantum state is mediated by the vacuum fields.

In the conventional two-dimensional (2D) QST schemes, the transferred quantum information is coded in such state $\alpha|0\rangle+\beta|1\rangle$. But in our QST scheme, the transferred quantum information is coded in such state $\alpha|0\rangle 1\rangle_{12}+\beta|1\rangle|0\rangle_{12}$. Therefore, the transferred quantum information in our QST schemes is more secure than that in the 2D QST schemes. In addition, there are more information carriers in the present QST scheme, and hence more abundant information can be transferred based on the present QST scheme. Therefore, the present QST scheme motivates the current work due to its inherent advantage compared to 2D QST. In addition, our scheme has the following advantages:

(i) The scheme is insensitive to the atomic spontaneous emission, cavity decay, and fiber decay.

(ii) In the scheme, the Raman transitions of each qubit only can be coupled to those of selected qubits to produce the desired qubit-qubit interaction.

(iii) In our scheme, the operations between any pair of atomic qubits can be implemented without exciting both the atoms and the field modes, thus our scheme would be a useful step toward future scalable quantum computing networks.

The rest of the paper is organized as follows. In Section 2, we describe the basic model of atoms trapped in separated cavities connected by optical fibers. In Section 3, we propose a scheme to implement quantum state transferring via the selective pairing of Raman transitions. Finally, a conclusion is given in Section 4.

2 Brief review of the model of atoms trapped in separated cavities connected by optical fibers

We consider n identical three-level atoms whose states are denoted by one excited state $|i\rangle$ and two ground states $|e\rangle$ and $|g\rangle$ trapped in separated cavities connected by optical fibers. The transition $|e\rangle_l \rightarrow |i\rangle_l$ of atom l is driven by a classical laser field with Rabi frequency Ω_l, while the transition $|g\rangle_l \rightarrow |i\rangle_l$ is coupled to the cavity mode with the coupling constant g. Here we assume that the classical field driving the lth atom and the cavity mode are detuned from the respective transitions by Δ_1 and Δ_2, respectively. And in the short-fiber limit, essentially only one fiber mode interacts with the cavity modes [18,20,23]. In interaction picture, the effective Hamiltonian can be written as [24]

$$H_{eff}=\sum_l\left\{\varepsilon_l|e_l\rangle\langle e_l|+\sum_m\chi_{lm}S_l^+S_m^-e^{i(\Delta_{1,m}-\Delta_{1,l})t}+H.c.\right\}, \tag{1}$$

where $\sum\limits_l=\sum\limits_{l=1}^{n}$, $\sum\limits_m=\sum\limits_{m=1}^{n}$ and $\sum\limits_k=\sum\limits_{k=1}^{2n}$, $l\neq m$, $\varepsilon_l=\sum\limits_k\mu_{k,l}-\eta_l$, $\chi_{l,m}=\sum\limits_k\chi_{k,l,m}$, is the coupling strength and $\Delta_{1,m}-\Delta_{1,l}$ is the detuning, $\chi_{l,m}$ and $(\Delta_{1,m}-\Delta_{1,l})$ can be controlled via the external fields.

The effective coupling Hamiltonian(1) describes multiple off-resonant Raman transitions for each atom induced by the classical field and the bosonic modes c_k. It can be used to realize quantum information processing between qubits trapped in separated cavities. Consider selective any coupling atom pairs between qubit I and qubit II, under the conditions

$$\Omega_{|}=\Omega_{\|}=\Omega,\ \Omega_j=0(j\neq |,\|),\ \Delta_{l,|}=\Delta_{l,\|},$$

we can have $\lambda_{k,l}=0\,(l\neq |,\|)$, $\chi_{l,m}=0\,(l\neq |,\|$ or $m\neq |,\|)$, $\varepsilon_{|}=\varepsilon_{\|}=\varepsilon$.

Then the coupling Hamiltonian (1) reduces to [24]

$$H_{eff}=\varepsilon\sum_{j=|,\|}\Big|e_j\rangle\langle e_j\Big|+\chi\left(S_{|}^+S_{\|}^-+S_{|}^-S_{\|}^+\right). \tag{2}$$

This is the Hamiltonian describing the selective coupling between qubit | and qubit ‖. For the following different initial states, governed by the Hamiltonian (2), they evolve as follows,

$$|e\rangle_{|}|g\rangle_{\|}\rightarrow e^{-i\varepsilon t}(\cos\chi t|e\rangle_{|}|g\rangle_{\|}-i\sin\chi t|g\rangle_{|}|e\rangle_{\|}), \tag{3}$$

$$|g\rangle_{|}|e\rangle_{\|}\rightarrow e^{-i\varepsilon t}(\cos\chi t|g\rangle_{|}|e\rangle_{\|}-i\sin\chi t|e\rangle_{|}|g\rangle_{\|}), \tag{4}$$

$$|g\rangle_{|}|g\rangle_{\|}\rightarrow |g\rangle_{|}|g\rangle_{\|}, \tag{5}$$

$$|e\rangle_{|}|e\rangle_{\|}\rightarrow e^{-2i\varepsilon t}|e\rangle_{|}|e\rangle_{\|}. \tag{6}$$

3 Scheme for quantum state transfer via the selective pairing of Raman transitions

Now let us introduce our scheme for quantum state transfer.

First consider the selective coupling atom pairs (a,b) which are initially in the state $|e\rangle_a|g\rangle_b$, with the Hamiltonian governed by Eq. (2), after an interaction time t, the state of the atom pairs (a,b) evolve as follow

$$|\psi(t)\rangle_{a,b}=e^{-i\varepsilon t}[\cos(\chi t)|e\rangle|g\rangle-i\sin(\chi t)|g\rangle|e\rangle]_{a,b} \tag{7}$$

Without loss of generality, denote that $\alpha=\cos(\chi t)$, $\beta=-i\sin(\chi t)$, and the common phase factor $e^{-i\varepsilon t}$ is discarded, then we can obtain two-atom entangled state.

$$|\psi\rangle_{a,b}=(\alpha|eg\rangle+\beta|ge\rangle)_{a,b} \tag{8}$$

Next we transfer the entangled state to the other atom pairs e.g. atom pairs (p,q) which are initially in the state $|g\rangle_p|g\rangle_q$. This process can be written as

$$\begin{aligned}|\psi\rangle_{abpq}&=(\alpha|eg\rangle+\beta|ge\rangle)_{a,b}|g\rangle_p|g\rangle_q\\&\rightarrow|\psi\rangle_{abpq}=(\alpha|eg\rangle+\beta|ge\rangle)_{p,q}|g\rangle_a|g\rangle_b\end{aligned} \tag{9}$$

Select atom pairs (a,p), suitably adjust the frequencies of these classical fields, so that $\Omega_a=\Omega_p=\Omega$, $\Omega_j=0(j\neq a,p)$, $\Delta_{l,a}=\Delta_{l,p}$, thus qubit a is coupled to qubit p, with the Hamiltonian governed by Eq. (2), after an interaction time t_1, the state of the four atoms is

$$\begin{aligned}|\psi(t)\rangle_{abpq}=&\alpha e^{-i\varepsilon_a t_1}\left[\cos(\chi_{ap}t_1)|e\rangle_a|g\rangle_p-i\sin(\chi_{ap}t_1)|g\rangle_a|e\rangle_p\right]|g\rangle_b|g\rangle_q\\&+\beta|g\rangle_b|e\rangle_q|g\rangle_a|g\rangle_p\end{aligned} \tag{10}$$

If we choose $\chi_{ap}t_1=\dfrac{\pi}{2}$,

$$|\psi(t_1)\rangle_{abpq}=-i\alpha e^{-i\varepsilon_a t_1}|g\rangle_a|e\rangle_p|g\rangle_b|g\rangle_q+\beta|g\rangle_b|e\rangle_q|g\rangle_a|g\rangle_p$$

Then select atom pairs (b,q), suitably adjust the frequencies of these classical fields, so that $\Omega_b=\Omega_q=\Omega$, $\Omega_j=0(j\neq b,q)$, $\Delta_{l,b}=\Delta_{l,q}$, thus qubit b is coupled to qubit q, with the

Hamiltonian governed by Eq. (2), after an interaction time t_2, the state of the four atoms is

$$|\psi(t_1+t_2)\rangle_{abpq} = -i\alpha e^{-i\varepsilon_a t_1}|g\rangle_a|e\rangle_p|g\rangle_b|g\rangle_q + \beta e^{-i\varepsilon_b t_2}\Big[\cos(\chi_{bq}t_2)|e\rangle_b|g\rangle_q - i\sin(\chi_{bq}t_2)|g\rangle_b|e\rangle_q\Big]|g\rangle_a|g\rangle_p \tag{11}$$

If we choose $\chi_{bq}t_2 = \dfrac{\pi}{2}$,

$$|\psi(t)\rangle_{abpq} = \left(-i\alpha e^{-i\varepsilon_a t_1}|e\rangle_p|g\rangle_q - i\beta e^{-i\varepsilon_b t_2}|g\rangle_p|e\rangle_q\right)\big(|g\rangle|g\rangle\big)_{a,b} \tag{12}$$

Implement the single-qubit operations $|e\rangle_p \to -ie^{-i\varepsilon_a t_1}|e\rangle_p$ and $|e\rangle_q \to -ie^{-i\varepsilon_b t_2}|e\rangle_q$, respectively. We can obtain

$$|\psi(t)\rangle_{abpq} = \left(\alpha|e\rangle_p|g\rangle_q + \beta|g\rangle_p|e\rangle_q\right)\big(|g\rangle|g\rangle\big)_{a,b} \tag{13}$$

From Eq. (13), we note that the entanglement of the atom pairs (a,b) has been transferred to the atom pairs (p,q). Thus the state of the atom pairs (p,q) can be written as

$$|\psi\rangle = (\alpha|eg\rangle + \beta|ge\rangle)_{p,q} \tag{14}$$

This means that entanglement transfer between atom pairs (a,b) and atom pairs (p,q) has happened. If we repeat the above procedures, then the two-atom entangled state can be further transferred to any atom pairs. Thus we can establish a quantum communication network for transferring information between atom pairs, and each entangled atom pair can be regarded as a node of the quantum network. In this case we can realize a long-distance communication.

Let us give a brief discussion on the experimental feasibility of the proposed scheme. Set $n=3, \Omega_1=\Omega_3=v=g, \Omega_2=0, \Delta_{1,1}=\Delta_{1,3}=16\text{g}$ and $\Delta_2=18.5g$ [24]. Then we have $\lambda \approx g/10$ and $\chi \approx 0.67\times 10^{-2}g$. The probability that the atoms undergo a transition to the excited state due to the off-resonant interaction with the classical fields is $P_1 \approx \Omega^2/\Delta_{1,1}^2 = 3.9\times 10^{-3}$ [24]. Meanwhile, the probability that the field modes are excited due to off-resonant Raman couplings is $P_2 \approx \sum_k \lambda_{k,1}^2/\delta_{k,1}^2 \approx 3.1\times 10^{-3}$ [24]. Thus the effective Hamiltonian H_{eff} is valid. A near-perfect fiber-cavity coupling with an efficiency larger than 99.9% can be realized using fiber-taper coupling to high-Q silica microspheres [25]. The fiber loss at a 852nm wavelength is about 2.2 dB/km [26], which corresponds to the fiber decay rate 1.52×10^5 Hz, lower than the available cavity decay rate.

4 Conclusions

In summary, we have proposed a simple scheme for transferring an unknown atomic state via atoms trapped in separate cavities linked by optical fibers. In the scheme two ground states of each atom are coupled via the respective cavity mode and a classical field in the Raman manner. Under the large detuning condition, the atoms do not undergo real Raman transitions and the Hamiltonian for the atomic system is decoupled from the cavity modes and fiber mode. During the interaction, the quantum number of the bosonic modes is conserved, therefore, under the condition they are initially in the vacuum state, they will remain in the vacuum state. Thus the scheme is insensitive to the atomic spontaneous emission, cavity decay, and fiber decay. Meanwhile, in our scheme, operations between any pair of atomic qubits and selective parallel two-qubit operations on different qubit pairs can be implemented without exciting both the atoms and the field modes. Therefore, the scheme would be a useful step toward future scalable quantum computing networks.

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