Generation of multiparticle three-dimensional entanglement state via adiabatic passage*

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A scheme is proposed for generating a multiparticle three-dimensional entangled state by appropriately adiabatic evolutions, where atoms are respectively trapped in separated cavities so that individual addressing is needless. In the ideal case, losses due to the spontaneous transition of an atom and the excitation of photons are efficiently suppressed since atoms are all in ground states and the fields remain in a vacuum state. Compared with the previous proposals, the present scheme reduces its required operation time via simultaneously controlling four classical fields. This advantage would become even more obvious as the number of atoms increases. The experimental feasibility is also discussed. The successful preparation of a high-dimensional multiparticle entangled state among distant atoms provides better prospects for quantum communication and distributed quantum computation.

Keywords: multiparticle three-dimensional entanglement state, adiabatic evolutions

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1. Introduction

Quantum entanglement is one of the most striking features of quantum physics. As is well known, the tasks of quantum information can be performed normally by using two-dimensional quantum states. However, it has been recently recognized that significantly fundamental and practical advantages can be gained by employing higher-dimensional quantum states instead. For example, violations of local realism are stronger for two maximally entangled qudits ($3 \leq d \leq 9$) than those for two qubits and increase with d;[1,2] quantum key distributions based on multilevel system show increased resistance to noise;[3,4] a qudit-based quantum computation may require less resources for its implementation than those based on a two-level system;[5] N-particle N-level singlet states can solve "N-strangers", "secret sharing", and "liar detection" problems which have no solutions using classical tools.[6] These facts have triggered a lot of studies on the generation of high-dimensional entangled states in recent years.[7–12] For instance, Zou *et al*.[8] proposed a scheme for creating the entanglement of two three-level atoms, which is insensitive to the cavity decay but requires individual addressing on two identical atoms in a tiny cavity. Subsequently, Ye *et al*.[10] proposed a scheme for realizing a three-dimensional bipartite entangled state through an adiabatic passage along, where two identical atoms are separately trapped in two optical cavities. Most of the previous schemes only prepare a two-particle three-dimensional entanglement state while the generation of a multiparticle d-dimensional entangled state becomes difficult with the increase of the number of the qudits involved. It is worthwhile to mention that Zheng[7] proposed generating the entangled states of more multilevel atoms with an additional strong classical driven field. Here we propose an alternative scheme for generating a three-dimensional entangled state for two atoms respectively trapped in separated cavities, where losses due to the spontaneous transition of atoms and the excitation of photons are efficiently suppressed by employing adiabatic passage. The required operation time is shorter than the previous protocols by simultaneously controlling four classical fields. The scheme can be extended to prepare a high-dimensional multiparticle entangled state among distant atoms, which is important in the sense of distributed quantum computation and quantum communication.

The rest of the present paper is arranged as follows. In Section 2, we describe the fundamental model for creating a multiparticle three-dimensional entangled state. In Section 3, we present a scheme for generating a two-atom three-dimensional entangled state in detail. In Section 4, we extend the scheme to the multiparticle case. Finally, we analyze the experimental feasibility for the scheme and draw some conclusions in Section 5.

2. Model

The basic elements of the protocol are illustrated schematically in Fig. 1. N atoms are respectively trapped in N corresponding optical cavities which are connected by short optical fibers and coupled by a fiber coupler (FC) and have the

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same transverse mode. Under the short fiber limit $(lv)/(2\pi c)$, only the resonant mode of the fiber will interact with the cavity mode,[13–16] where l is the length of the fiber and v is the decay rate of the cavity field into a continuum of fiber modes. $T_2, T_3, \ldots, T_N$ denote the optical devices, which can exactly control the switching on or off of the interaction between cavities. The corresponding level structures of atoms are shown in Fig. 2. Atom 1 has two excited states $|e_k\rangle$ $(k = L, R)$ and five ground states $|1\rangle$, $|R\rangle$, $|g\rangle$, $|L\rangle$, and $|0\rangle$ while other $N-1$ atoms are five-level system with three ground states $|R\rangle$, $|g\rangle$, $|L\rangle$, and two excited states $|e_k\rangle$ $(k = L, R)$. For atom 1, the transitions $|1\rangle \to |e_L\rangle$ and $|0\rangle \to |e_R\rangle$ are driven by the classical fields with Rabi frequencies Ω_1 and Ω_2, respectively. The transition $|e_k\rangle \to |k\rangle$ $(k = L, R)$ is resonantly driven by the cavity mode a_k with k-circular polarization. For atom n $(n = 2, \ldots, N)$,

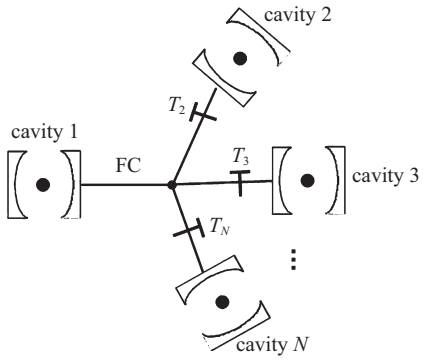


Fig. 1. Schematic setup for preparing an N-atom three-dimensional entanglement state, where N atoms are trapped in N separated cavities connected by optical fibers and FC is a fiber coupler. $T_2, T_3, \ldots, T_N$ are the optical devices.

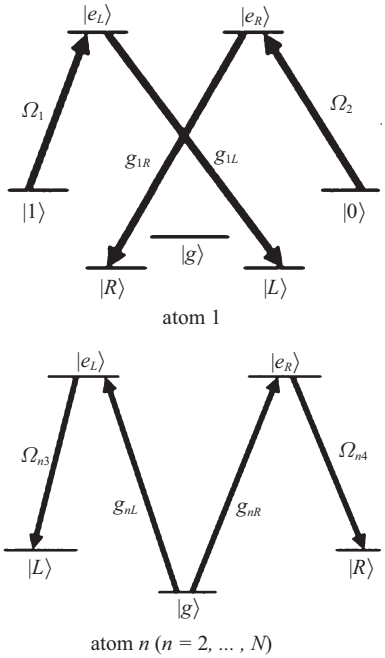


Fig. 2. Level structure of the involved atoms. For atom 1 the transitions $|1\rangle \to |e_L\rangle$ and $|0\rangle \to |e_R\rangle$ are driven by the classical fields while $|e_k\rangle \to |k\rangle$ is resonantly driven by the cavity mode. For atom n the transition $|g\rangle \to |e_k\rangle$ is resonantly driven by the cavity mode and the transition $|e_k\rangle \to |k\rangle$ is driven by the classical field with Rabi frequency Ω_{n3} or Ω_{n4}.

the transition $|g\rangle \to |e_k\rangle$ $(k = L, R)$ is resonantly driven by the n-th cavity mode a_{nk} with k-circular polarization, the transition $|e_k\rangle \to |k\rangle$ $(k = L, R)$ is driven by the classical field with Rabi frequency Ω_{n3} or Ω_{n4}.

When we only turn on the interaction between the 1st cavity and the n-th cavity by the optical device T_n $(n = 2, 3, \ldots, N)$, the interaction Hamiltonian has the following form $(\hbar = 1)$:

$$\begin{aligned} H_{1n} = {} & \Omega_1 |e_L\rangle_1 \langle 1| + g_{1L} a_{1L} |e_L\rangle_1 \langle L| + \Omega_2 |e_R\rangle_1 \langle 0| \\ & + g_{1R} a_{1R} |e_R\rangle_1 \langle R| + \Omega_{n3} |e_L\rangle_n \langle L| + g_{nL} a_{nL} |e_L\rangle_n \langle g| \\ & + \Omega_{n4} |e_R\rangle_n \langle R| + g_{nR} a_{nR} |e_R\rangle_n \langle g| \\ & + \eta b_L (a_{1L}^{\dagger} + a_{nL}^{\dagger}) + \eta b_R (a_{1R}^{+} + a_{nR}^{+}) + \text{H.C.}, \end{aligned} \tag{1}$$

where η is the coupling strength between cavity mode and the fiber mode, $b_{R(L)}$ is the annihilation operator for the fiber mode with $R(L)$-circular polarization, $a_{nR(L)}$ the annihilation operation for corresponding cavity field with $R(L)$-circular polarization, and $g_{nR(L)}$ is the coupling strength between the corresponding cavity mode and the trapped atom. Without loss of generality, all Rabi frequencies and coupling rates are assumed to be real. We use the notation $|t\rangle_n \left|m_{L(R)}\right\rangle_{nC} \left|x_{L(R)}\right\rangle_f$ to describe the state of the atom–cavity–fiber system, where $|t\rangle_n$ $(t = e_k, R, g, L, 0, 1; n = 1, \ldots, N)$ is the state of the n-th atom trapped in the n-th cavity, $\left|m_{L(R)}\right\rangle_{nC}$ $(m = 0, 1)$ denotes that there is m photon with left-circular (right-circular) polarization for the n-th cavity mode, and $\left|x_{L(R)}\right\rangle_f$ $(x = 0, 1)$ represents x photon with left-circular (right-circular) polarization for the corresponding fiber mode.

3. Generation of a two-atom three-dimensional entanglement state

Now we consider the case that the interaction between cavity 1 and cavity 2 is turned on. Our purpose is to show that the following two-atom three-dimensional entangled state:

$$|\Psi\rangle = \frac{1}{\sqrt{3}} [-|R\rangle_1 |R\rangle_2 + |g\rangle_1 |g\rangle_2 - |L\rangle_1 |L\rangle_2] \tag{2}$$

can be prepared using an adiabatic passage.

On condition that both the cavity modes and the fiber mode are all in vacuum state, we will first show that $|0\rangle_1 |g\rangle_2$ can adiabatically evolve into $-|R\rangle_1 |R\rangle_2$, and then $|1\rangle_1 |g\rangle_2$ can adiabatically evolve into $-|L\rangle_1 |L\rangle_2$. We also note that $|g\rangle_1 |g\rangle_2$ will not change since there is no photon for all the field modes. So when the atoms are initially in the state

$$\frac{1}{\sqrt{3}} (|0\rangle_1 |g\rangle_2 + |1\rangle_1 |g\rangle_2 + |g\rangle_1 |g\rangle_2), \tag{3}$$

we can obtain the desired three-dimensional entanglement state (2) after a series of adiabatic processes.

Consider that atom 1 is prepared in the superposition state $(|0\rangle_1 + |1\rangle_1 + |g\rangle_1)/\sqrt{3}$ with the method of Ref. [17] while

atom 2 is prepared in the state $|g\rangle_2$, and all the field modes are initially in vacuum state $|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f$, i.e., the state of the whole compound system is initially in the state

$$\frac{1}{\sqrt{3}}(|0\rangle_1|g\rangle_2+|1\rangle_1|g\rangle_2+|g\rangle_1|g\rangle_2)|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f. \quad (4)$$

Define the excitation number operators as

$$\begin{aligned} N_L &= |e_L\rangle_1\langle e_L|+|1\rangle_1\langle 1|+|e_L\rangle_n\langle e_L|+|L\rangle_n\langle L| \\ &\quad + a_{1L}^{\dagger}a_{1L}+a_{nL}^{\dagger}a_{nL}+b_L^{\dagger}b_L \end{aligned} \quad (5)$$

and

$$\begin{aligned} N_R &= |e_R\rangle_1\langle e_R|+|0\rangle_1\langle 0|+|e_R\rangle_n\langle e_R|+|R\rangle_n\langle R| \\ &\quad + a_{1R}^{\dagger}a_{1R}+a_{nR}^{\dagger}a_{nR}+b_R^{\dagger}b_R, \end{aligned} \quad (6)$$

then N_k $(k=L,R)$ will commute with H of Eq. (1) so that the excitation number is conserved during the evolution. For the initial state $|0\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f$, the eigenvalue of N_R is $n_R=1$. The subspace with $n_R=1$ is spanned by the state vectors

$$|\phi_1\rangle = |0\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (7a)$$
$$|\phi_2\rangle = |e_R\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (7b)$$
$$|\phi_3\rangle = |R\rangle_1|g\rangle_2|1_R\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (7c)$$
$$|\phi_4\rangle = |R\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|1_R\rangle_f, \quad (7d)$$
$$|\phi_5\rangle = |R\rangle_1|g\rangle_2|0\rangle_{1C}|1_R\rangle_{2C}|0\rangle_f, \quad (7e)$$
$$|\phi_6\rangle = |R\rangle_1|e_R\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (7f)$$
$$|\phi_7\rangle = |R\rangle_1|R\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f. \quad (7g)$$

The Hamiltonian H of Eq. (1) has a dark state (i.e., zero-energy eigenstate of Hamiltonian H)

$$\begin{aligned} |\psi_{D1}\rangle &= K_{24}[g_{1R}(t)\Omega_{24}(t)|\phi_1\rangle-\Omega_2(t)\Omega_{24}(t)|\phi_3\rangle \\ &\quad + \Omega_2(t)\Omega_{24}(t)|\phi_5\rangle-g_{2R}(t)\Omega_2(t)|\phi_7\rangle], \end{aligned} \quad (8)$$

where $K_{24}^{-2}=g_{1R}^2\Omega_{24}^2+2\Omega_2^2\Omega_{24}^2+g_{2R}^2\Omega_2^2$. Under the condition of

$$g_{1R}(t),g_{2R}(t)\gg\Omega_2(t),\Omega_{24}(t), \quad (9)$$

the dark state (8) reduces to

$$|\psi_{D1}\rangle\propto g_{1R}(t)\Omega_{24}(t)|\phi_1\rangle-g_{2R}(t)\Omega_2(t)|\phi_7\rangle. \quad (10)$$

If pulse shapes are designed such that

$$\lim_{t\to-\infty}\frac{g_{2R}(t)\Omega_2(t)}{g_{1R}(t)\Omega_{24}(t)}=0, \quad (11)$$
$$\lim_{t\to\infty}\frac{g_{2R}(t)\Omega_2(t)}{g_{1R}(t)\Omega_{24}(t)}=\infty, \quad (12)$$

the initial state $|\phi_1\rangle$ of the system is adiabatically transferred into $(-|\phi_7\rangle)$.

For the initial state $|1\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f$, the eigenvalue of N_L is $n_L=1$. The subspace with $n_L=1$ is spanned by the state vectors

$$|\varphi_1\rangle = |1\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (13a)$$
$$|\varphi_2\rangle = |e_L\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (13b)$$
$$|\varphi_3\rangle = |L\rangle_1|g\rangle_2|1_L\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (13c)$$
$$|\varphi_4\rangle = |L\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|1_L\rangle_f, \quad (13d)$$
$$|\varphi_5\rangle = |L\rangle_1|g\rangle_2|0\rangle_{1C}|1_L\rangle_{2C}|0\rangle_f, \quad (13e)$$
$$|\varphi_6\rangle = |L\rangle_1|e_L\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f, \quad (13f)$$
$$|\varphi_7\rangle = |L\rangle_1|L\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f. \quad (13g)$$

The Hamiltonian H of Eq. (1) has the other dark state

$$\begin{aligned} |\psi_{D2}\rangle &= K_{13}[g_{1L}(t)\Omega_{23}(t)|\varphi_1\rangle-\Omega_1(t)\Omega_{23}(t)|\varphi_3\rangle \\ &\quad + \Omega_1(t)\Omega_{23}(t)|\varphi_5\rangle-g_{2L}(t)\Omega_1(t)|\varphi_7\rangle], \end{aligned} \quad (14)$$

where $K_{13}^{-2}=g_{1L}^2\Omega_{23}^2+2\Omega_1^2\Omega_{23}^2+g_{2L}^2\Omega_1^2$. Similar to the dark state $|\psi_{D1}\rangle$, under the condition of

$$g_{1L}(t),g_{2L}(t)\gg\Omega_1(t),\Omega_{23}(t), \quad (15)$$

the dark state (14) reduces to

$$|\psi_{D2}\rangle\propto g_{1L}(t)\Omega_{23}(t)|\varphi_1\rangle-g_{2L}(t)\Omega_1(t)|\varphi_7\rangle. \quad (16)$$

If pulse shapes are designed such that

$$\lim_{t\to-\infty}\frac{g_{2L}(t)\Omega_1(t)}{g_{1L}(t)\Omega_{23}(t)}=0, \quad (17)$$
$$\lim_{t\to\infty}\frac{g_{2L}(t)\Omega_1(t)}{g_{1L}(t)\Omega_{23}(t)}=\infty, \quad (18)$$

the initial state $|\varphi_1\rangle$ of the system is adiabatically transferred into $(-|\varphi_7\rangle)$.

For the initial state $|g\rangle_1|g\rangle_2|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f$, it is always unchanged during the evolution. Therefore, the initial state (4) of the compound system will evolve into the state

$$\begin{aligned} |\Psi\rangle &= \frac{1}{\sqrt{3}}[-|R\rangle_1|R\rangle_2+|g\rangle_1|g\rangle_2 \\ &\quad - |L\rangle_1|L\rangle_2]|0\rangle_{1C}|0\rangle_{2C}|0\rangle_f \end{aligned} \quad (19)$$

after the above processes, which is a product state of two-atom three-dimensional entanglement state, the cavities state, and the fiber mode state. It is worth noting that conditions (11) and (17) (or (12) and (18)) can be simultaneously met by simultaneously controlling four classical fields $\Omega_1(t)$, $\Omega_{23}(t)$, $\Omega_2(t)$, and $\Omega_{24}(t)$.

4. Generation of a multiparticle three-dimensional entanglement state

The above scheme can be extended to generate a N-atom three-dimensional entanglement state, i.e.,

$$|\Theta\rangle_N = \frac{1}{\sqrt{3}}[(-1)^{N-1}|R\rangle_1|R\rangle_2\cdots|R\rangle_N + |g\rangle_1|g\rangle_2\cdots|g\rangle_N + (-1)^{N-1}|L\rangle_1|L\rangle_2\cdots|L\rangle_N]. \quad (20)$$

Assume that the compound system including a N-atom and N-cavity is initially in the state

$$|\Theta\rangle_1 = \frac{1}{\sqrt{3}}(|0\rangle_1+|1\rangle_1+|g\rangle_1)|g\rangle_2|g\rangle_3\cdots \times |g\rangle_N|0\rangle_{1C}|0\rangle_{2C}|0\rangle_{3C}\cdots|0\rangle_{NC}|0\rangle_f. \quad (21)$$

(i) Primarily, the first two atoms are prepared in state (2) by the above method.

(ii) Switch off the classical fields in cavity 1. Then, the transformations $|L\rangle_1 \to |1\rangle_1$ and $|R\rangle_1 \to |0\rangle_1$ are performed on atom 1, which leads the compound system to the state

$$|\Theta\rangle_2 = \frac{1}{\sqrt{3}}[-|0\rangle_1|R\rangle_2+|g\rangle_1|g\rangle_2-|1\rangle_1|L\rangle_2]|g\rangle_3\cdots \times |g\rangle_N|0\rangle_{1C}|0\rangle_{2C}|0\rangle_{3C}\cdots|0\rangle_{NC}|0\rangle_f. \quad (22)$$

(iii) Subsequently, only T_n $(n=3,\ldots,N)$ is in the transmitted state, thus the interaction between the 1st cavity and the n-th cavity is turned on. Under the condition of

$$g_{1R}(t), g_{nR}(t) \gg \Omega_2(t), \Omega_{n4}(t), \quad (23)$$

$$g_{1L}(t), g_{nL}(t) \gg \Omega_1(t), \Omega_{n3}(t), \quad (24)$$

if pulse shapes are designed such that

$$\lim_{t\to-\infty}\frac{g_{nR}(t)\Omega_2(t)}{g_{1R}(t)\Omega_{n4}(t)} = 0, \quad (25)$$

$$\lim_{t\to-\infty}\frac{g_{nL}(t)\Omega_1(t)}{g_{1L}(t)\Omega_{n3}(t)} = 0, \quad (26)$$

$$\lim_{t\to\infty}\frac{g_{nR}(t)\Omega_2(t)}{g_{1R}(t)\Omega_{n4}(t)} = \infty, \quad (27)$$

$$\lim_{t\to\infty}\frac{g_{nL}(t)\Omega_1(t)}{g_{1L}(t)\Omega_{n3}(t)} = \infty, \quad (28)$$

the state (22) will be adiabatically transferred into

$$|\Theta\rangle_3 = \frac{1}{\sqrt{3}}[(-1)^{n-1}|R\rangle_1\ldots|R\rangle_n + (-1)^{n-1}|L\rangle_1\ldots|L\rangle_n+|g\rangle_1\ldots|g\rangle_n] \times |g\rangle_{n+1}\cdots|g\rangle_N|0\rangle_{1C}|0\rangle_{2C}|0\rangle_{3C}\cdots|0\rangle_{NC}|0\rangle_f. \quad (29)$$

(iv) Repeat $N-2$ times steps (ii) and (iii), where n $(n=3,\ldots,N)$ only takes a different number in order each time. Thus, the state of the compound system evolves finally into

$$|\Theta\rangle_4 = \frac{1}{\sqrt{3}}[(-1)^{N-1}|R\rangle_1\ldots|R\rangle_N + (-1)^{N-1}|L\rangle_1\ldots|L\rangle_N+|g\rangle_1\ldots|g\rangle_N] \times |0\rangle_{1C}|0\rangle_{2C}|0\rangle_{3C}\ldots|0\rangle_{NC}|0\rangle_f, \quad (30)$$

which is a product state of an N-atom three-dimensional entanglement state, the cavities state, and the fiber mode state.

Similar to the above cases, the conditions (25) and (26) (or (27) and (28)) can be simultaneously met by simultaneously controlling four classical fields $\Omega_1(t)$, $\Omega_{n3}(t)$, $\Omega_2(t)$, and $\Omega_{n4}(t)$.

5. Discussion and conclusion

We now make a simple analysis on the experimental feasibility for the scheme. The required atomic level configuration can be chosen from the hyperfine states of ^{133}Cs. For atom 1, the states $|R\rangle$ ($|L\rangle$) and $|0\rangle$ ($|1\rangle$) correspond to $|F=3,m=2\rangle$ ($|F=3,m=-2\rangle$) and $|F=2,m=1\rangle$ ($|F=2,m=-1\rangle$) of $5S_{1/2}$ ground levels, while $|e_R\rangle$ ($|e_L\rangle$) corresponds to $|F=3,m=1\rangle$ ($|F=3,m=-1\rangle$) of $5P_{3/2}$ excited level. Other hyperfine levels in the ground-state manifold can be used as $|g\rangle$. For the atom n ($n=2,\ldots,N$), the states $|R\rangle$, $|L\rangle$, and $|g\rangle$ correspond to $|F=2,m=-1\rangle$, $|F=2,m=1\rangle$, and $|F=3,m=0\rangle$ of $5S_{1/2}$ ground levels, while the upper levels $|e_R\rangle$ and $|e_L\rangle$ correspond to $|F=3,m=-1\rangle$ and $|F=3,m=1\rangle$ of $5P_{3/2}$, respectively.

In order to meet the adiabatic condition, the adiabatic operation time t should be larger than the inverse of the energy gap between the dark state and bright state (i.e., the nonzero-energy eigenstate of Hamiltonian H).[18] Take the generation of the two-atom entanglement state for example. Assume that the energy gap between a dark state and its most closest bright state is denoted by ΔE. If $g_{nL}=g_{nR}=1$ GHz,[19] $\Omega_{1\max}=\Omega_{2\max}=\Omega_{n3\max}=\Omega_{n4\max}=g/4$,[20–22] and $\eta=10g$,[16] then the energy gap ΔE is about $0.25g$. Taking $t=10/\Delta E$ and neglecting single qubit operation time, the total time of generating two-atom three-dimensional entangled state is $T=t=40$ ns, but it is 100 ns in the previous scheme.[10] For generating an N-atom three-dimensional entangled state, the required operation time is about $(N-1)\times 40$ ns, which is much shorter than the single atom information storage time $t_s \sim 180$ μs if $N<1000$.[23] In addition, the strong coupling of the fiber-cavity system has been observed in Ref. [24]. All of these open up possibilities for the experimental implementation of the scheme.

In summary, we proposed an alternative scheme for creating a multiparticle three-dimensional entangled state via adiabatic evolution in the cavity and fiber system. Our scheme has the advantages that the atomic spontaneous emission and the decay of optical fields can be greatly reduced since atoms are all in ground states and the fields remain in a vacuum state in the ideal case. A two-atom three-dimensional entangled state is prepared by simultaneously controlling four classical fields,

which can reduce the operation time. This benefit would become even more obvious as the number of atoms increases. Individual addressing is needless, which lowers experimental difficulties. In addition, the created maximally multiparticle three-dimensional entangled state spreads among separated cavities, which is important in the sense of distributed quantum computation and multi-party quantum communication.

References

[1] Kaszlikowski D, Gnacinski P, Zukowski M, Miklaszewski W and Zeilinger A 2000 *Phys. Rev. Lett.* **85** 4418
[2] Kaszlikowski D, Gosal D, Ling E J, Kwek L C, Zukwski M and Oh C H 2002 *Phys. Rev. A* **66** 032103
[3] Bourennane M, Karlsson A and Bjork G 2001 *Phys. Rev. A* **64** 012306
[4] Bruss D and Macchiavello C 2002 *Phys. Rev. Lett.* **88** 127901
[5] Lanyon B P, Barbieri M, Almeida M P, Jennewein T, Ralph T C, Resch K J, Pryde G J, O'Brien J L, Gilchrist A and White A G 2009 *Nature Phys.* **5** 134
[6] Cabello A 2002 *Phys. Rev. Lett.* **89** 100402
[7] Zheng S B 2003 *Phys. Rev. A* **68** 035801
[8] Zou X B, Pahlke K and Mathis W 2003 *Phys. Rev. A* **67** 044301
[9] Lü X Y, Liu J B, Ding C L and Li J H 2008 *Phys. Rev. A* **78** 032305
[10] Ye S Y, Zhong Z R and Zheng S B 2008 *Phys. Rev. A* **77** 014303
[11] Chen Z H and Lin X M 2011 *Chin. Phys. Lett.* **28** 010304
[12] Yang Z B, Wu H Z and Zheng S B 2010 *Chin. Phys. B* **19** 094205
[13] Chen L B, Ye M Y, Lin G W and Lin X M 2007 *Phys. Rev. A* **76** 062304
[14] Zheng S B 2009 *Eur. Phys. J. D* **54** 719
[15] Zhong Z R 2010 *Opt. Commun.* **283** 1972
[16] Serafini A, Mancini S and Bose S 2006 *Phys. Rev. Lett.* **96** 010503
[17] Law C and Eberly J 1998 *Opt. Express* **2** 368
[18] Duan L M, Cirac J I and Zoller P 2001 *Science* **292** 1695
[19] Trupke M, Hinds E A, Eriksson S, Curtis E A, Moktadir Z, Kukharenka E and Kraft M 2005 *Appl. Phys. Lett.* **87** 211106
[20] Vitanov N V, Fleischhauer M, Shore B W and Bergmann K 2001 *Adv. At. Mol. Opt. Phys.* **46** 55
[21] McKeever J, Boca A, Boozer A D, Buck J R and Kimble H J 2003 *Nature* **425** 268
[22] Miller R, Northup T E, Birnbaum K M, Boca A, Boozer A D and Kimble H J 2005 *J. Phys. B: At. Mol. Opt. Phys.* **38** S551
[23] Specht H P, Nöleke C, Reiserer A, Uphoff M, Figueroa E, Ritter S and Rempe G 2011 *Nature* **473** 190
[24] Cai M, Painter O and Vahala K J 2000 *Phys. Rev. Lett.* **85** 74