Generation of entanglement via adiabatic passage

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We propose several robust schemes to prepare entangled states among spatially separated Λ-type atoms via stimulated Raman adiabatic passage and fractional stimulated Raman adiabatic passage techniques. The atomic spontaneous radiation, the cavity decay, and the fiber loss are efficiently suppressed by engineering adiabatic passage and controlling appropriately atom-field couplings. The schemes can be extended to generate the n-cavity mode W state.

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I. INTRODUCTION

Entanglement between separate subsystems is the crucial ingredient in many quantum-information processes, such as quantum teleportation [1], quantum dense coding [2], and quantum cryptography [3]. In recent years, fair attention has been paid to exploit suitable coherent dynamics to prepare quantum entanglement between separate subsystems. Several schemes have been proposed to implement quantum communication or engineer entanglement between atoms trapped in distant optical cavities, through direct linking of the cavities [4–8] or through detection of leaking photons [9–11]. These schemes are either probabilistic or rely on accurately controlled interacting time.

The technique of stimulated Raman adiabatic passage (STIRAP), which was first used to coherently control dynamical processes in atoms and molecules [12–14], has become an extensively used tool for realizing quantum-information processing (QIP) [15–18]. It has some advantages in QIP because decoherence due to spontaneous emission from excited states can be compressed and it is robust against some experimental parameter errors. Hennrich *et al.* [19] have prepared one intracavity photon by means of STIRAP based on the proposal of Ref. [20]. In comparison with STIRAP, the fractional stimulated Raman adiabatic passage (f-STIRAP) [21,22] guarantees the creation of any preselected coherent superposition of two ground states in the Λ-type system. Unlike STIRAP where the Stokes pulse vanishes first, in f-STIRAP the two pulses vanish simultaneously while maintaining a constant finite ratio of amplitudes. Song *et al.* [23] have experimentally demonstrated the control of the atomic coherence and the population transfer among Rb hyperfine atomic levels by the f-STIRAP.

In this paper, we will present schemes for generating the entangled state for spatially separated atoms via STIRAP and f-STIRAP techniques [21,22]. Λ-type atoms drop individually through spatially separated cavities that are connected by optical fibers. By choosing appropriate parameters we can create the entangled atomic state. Similar to Refs. [5,6], the usage of STIRAP or f-STIRAP technique in our schemes keeps fiber mode and the atomic excited states unpopulated during the whole interaction process so that the proposals are robust to atomic spontaneous emission noise and fiber loss. In addition, the schemes can be generalized to prepare the n-cavity mode W state.

II. FUNDAMENTAL MODEL

Two Λ-type atoms are trapped in two distant single-mode optical cavities, which are connected by an optical fiber (see Fig. 1). The states $|0\rangle$ and $|1\rangle$ are two ground levels of the atom, and $|e\rangle$ is an excited level. The ith atomic transition $|0\rangle_i \to |e\rangle_i$ $(i=1,2)$ is resonantly coupled to the ith cavity mode a_i. The ith classical field drives the transition from level $|1\rangle_i$ to level $|e\rangle_i$ resonantly with coupling coefficient $\Omega_i(t)$. In the rotating wave approximation, the interaction Hamiltonian of the atom-cavity system can be written as (setting $\hbar=1$)

$$H_{ac} = \sum_{i=1}^{2} [g_i(t) a_i |e\rangle_i\langle 0| + \Omega_i(t)|e\rangle_i\langle 1| + \text{H.c.}], \tag{1}$$

where a_i is the annihilation operator for photons in the mode of cavity i, $g_i(t)$ is the coupling coefficient between the cavity mode i and the atom i. The coupling between the cavity fields and the fiber modes can be written as the interaction Hamiltonian [5,6]

$$H_{cf} = \sum_{j=1}^{\infty} \nu_j \{ b_j [a_1^\dagger + (-1)^j e^{i\varphi} a_2^\dagger] + \text{H.c.}\} + \sum_{j=1}^{\infty} \Delta_j b_j^\dagger b_j, \tag{2}$$

where b_j is the annihilation operator for photons in the fiber mode j, Δ_j is the frequency difference between the jth fiber-mode and the cavity-mode, ν_j is the coupling strength between fiber mode j and the cavity mode, and the phase is induced by the propagation of the field through the length of

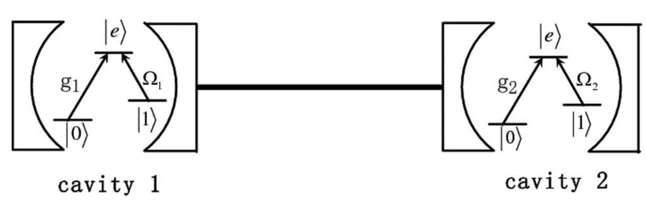

FIG. 1. Two Λ-type atoms are trapped in two spatially separated cavities 1 and 2, respectively. The two cavities are linked through an optical fiber.

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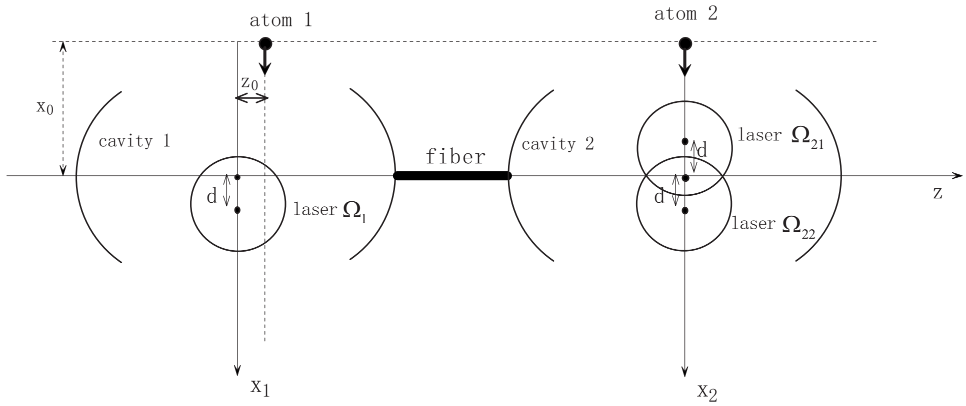

FIG. 2. The geometry of the cavity modes and laser fields in the xy plane with different waists, and the trajectories of the atoms.

fiber l, $\varphi=2\pi\omega l/c$. In the short fiber limit $(2l\bar{v})/(2\pi C)\leq 1$, where $\bar{v}$ is the decay rate of the cavity fields into a continuum of fiber modes, only resonant mode b of the fiber interacts with the cavity mode. For this case, the Hamiltonian H_{cf} can be approximately written as [5,24]

$$H_{cf}=\nu[b(a_1^\dagger+a_2^\dagger)+\text{H.c.}],\tag{3}$$

where the phase $(-1)^j e^{i\varphi}$ in (2) has been absorbed into the annihilation and creation operators of the mode of the second cavity field.

In the interaction picture, the total Hamiltonian now becomes

$$H_I=\sum_{i=1}^{2}[g_i(t)a_i|e\rangle_i\langle 0|+\Omega_i(t)|e\rangle_i\langle 1|]+\nu b(a_1^\dagger+a_2^\dagger)+\text{H.c.}\tag{4}$$

III. GENERATION OF TWO-ATOM ENTANGLEMENT STATE

Define the excitation number operator

$$N_e=\sum_{i=1}^{2}(|e\rangle_i\langle e|+|1\rangle_i\langle 1|+a_i^\dagger a_i)+b^\dagger b,\tag{5}$$

N_e commutes with H_I so that the excitation number is conserved during the evolution. The subspace with $N_e=1$ is spanned by the state vectors [25]

$$|\phi_1\rangle=|10\rangle_a|00\rangle_c|0\rangle_f,$$

$$|\phi_2\rangle=|e0\rangle_a|00\rangle_c|0\rangle_f,$$

$$|\phi_3\rangle=|00\rangle_a|10\rangle_c|0\rangle_f,$$

$$|\phi_4\rangle=|00\rangle_a|00\rangle_c|1\rangle_f,$$

$$|\phi_5\rangle=|00\rangle_a|01\rangle_c|0\rangle_f,$$

$$|\phi_6\rangle=|0e\rangle_a|00\rangle_c|0\rangle_f,$$

$$|\phi_7\rangle=|01\rangle_a|00\rangle_c|0\rangle_f,\tag{6}$$

where $|m_1m_2\rangle_a(m_{1,2}=0,1,e)$ is the state of atoms trapped in cavities 1 and 2, respectively, $|n_1n_2\rangle_c$ denotes the field state with n_1 photons in the mode of cavity 1, n_2 in the mode of cavity 2, and $|n_f\rangle_f$ represents n_f photons in the fiber mode. The Hamiltonian H_I has the following dark state:

$$|D(t)\rangle=K_{12}[g_1(t)\Omega_2(t)|\phi_1\rangle-\Omega_1(t)\Omega_2(t)|\phi_3\rangle+\Omega_1(t)\Omega_2(t)|\phi_5\rangle-g_2(t)\Omega_1(t)|\phi_7\rangle],\tag{7}$$

which is the eigenstate of the Hamiltonian corresponding to zero eigenvalue. Here and in the following g_i, Ω_i are real, and $K_{12}^{-2}=g_1^2\Omega_2^2+2\Omega_1^2\Omega_2^2+g_2^2\Omega_1^2$. Under the condition

$$g_1(t),g_2(t)\gg\Omega_1(t),\Omega_2(t),\tag{8}$$

we have

$$|D(t)\rangle\sim g_1(t)\Omega_2(t)|\phi_1\rangle-g_2(t)\Omega_1(t)|\phi_7\rangle,\tag{9}$$

Suppose the initial state of the system is $|\phi_1\rangle$, if we design pulse shapes such that

$$\lim_{t\to-\infty}\frac{g_2(t)\Omega_1(t)}{g_1(t)\Omega_2(t)}=0,\tag{10}$$

$$\lim_{t\to+\infty}\frac{g_2(t)\Omega_1(t)}{g_1(t)\Omega_2(t)}=\tan\theta,\tag{11}$$

we can adiabatically transfer the initial state $|\phi_1\rangle$ to a superposition of $|\phi_1\rangle$ and $|\phi_7\rangle$, i.e., $\cos\theta|\phi_1\rangle-\sin\theta|\phi_7\rangle=(\cos\theta|10\rangle_a-\sin\theta|01\rangle_a)|00\rangle_c|0\rangle_f$, which is a product state of the two-atom entangled state, the cavity mode state, and the fiber mode state.

Next we discuss that such a pulse sequence can be designed by an appropriate choice of the parameters. As shown in Fig. 2, the first atom, initially in the state $|1\rangle_1$, drops with a speed v (on the $y=0$ plane at the $z=z_0$ line) through cavity 1 initially in vacuum state and then meets the laser beam $\Omega_1(t)$, which is parallel to the y axis and orthogonal to the cavity axis and atomic trajectory. The distance between the center of the cavity and the laser axis is d. The second atom initially in the state $|0\rangle_2$, moves with the same velocity v (on the $y=0$ plane at $z=0$ in the same direction with respect to the first atom) through cavity 2 initially in vacuum state and then meets the laser beam $\Omega_{21}(t)$ and $\Omega_{22}(t)$. The time-dependent and delayed Rabi frequencies of the cavity and the laser fields are as follows [22]:

$$g_1(t) = g_0 \exp\left(-\frac{(vt)^2}{W_c^2}\right)\cos\left(\frac{2\pi z_0}{\lambda}\right),$$

$$\Omega_1(t) = \Omega_0 \sin\theta \exp\left(-\frac{z_0^2}{W_l^2}\right)\exp\left(-\frac{(vt-d)^2}{W_l^2}\right), \quad (12)$$

$$g_2(t) = g_0 \exp\left(-\frac{v^2(t-\tau)^2}{W_c^2}\right),$$

$$\Omega_2(t) = \Omega_{21}(t) + \Omega_{22}(t), \quad (13)$$

$$\Omega_{21}(t) = \Omega_0 \exp\left(-\frac{[v(t-\tau)+d]^2}{W_l^2}\right),$$

$$\Omega_{22}(t) = \Omega_0 \cos\theta \exp\left(-\frac{[v(t-\tau)-d]^2}{W_l^2}\right), \quad (14)$$

where g_0, Ω_0, and $\Omega_0 \sin\theta$ $[\Omega_0 \cos\theta]$ are the maximal values of $g_{1,2}(t)$, $\Omega_{21}(t)$, and $\Omega_1(t)$ $[\Omega_{22}(t)]$, respectively; W_l and W_c are the laser beam waist and the cavity waist [26], respectively; τ is the time delay of the atom 2 with respect to the atom 1, the instant when the atom 1 encounters at the center of the cavity 1 defined as $t=0$.

Figure 3(a) shows the time dependence of the Rabi frequencies for cavity modes and laser fields for atoms, and Fig. 3(b) shows the time evolution of the populations, where we have chosen $\theta=\pi/4$, $d=3\Gamma^{-1}$, $z_0=0$, $\tau=0$, the pulse parameters as $W_l=5\Gamma^{-1}$, $W_c=10\Gamma^{-1}$, $v=1$ m/s, $\lambda=852.36$ nm, $\Omega_0=5\Gamma$, $g_0=25\Gamma$, and $\Gamma/2\pi=5$ MHz is the spontaneous emission rate for the state $|e\rangle$ [27,28]. This case corresponds to the generation of the atom entangled state $1/\sqrt{2}(|10\rangle_a - |01\rangle_a)$ by adiabatic passage.

Figure 4(a) shows the corresponding Rabi frequencies of the cavity modes and laser fields for atoms. Figure 4(b) shows the time evolution of populations, where we have chosen $\theta=\pi/2$, and other pulse parameters are the same as in Fig. 3. It is obvious that all population is completely transferred from the state $|\phi_1\rangle$ to the state $-|\phi_7\rangle$ without populating the other states during the dynamics. If the state of the whole system is initially in the state $(\alpha|00\rangle_a + \beta|10\rangle_a)|00\rangle_c|0\rangle_f$, after the above process we can achieve the following evolution:

$$(\alpha|00\rangle_a + \beta|10\rangle_a)|00\rangle_c|0\rangle_f \rightarrow (\alpha|00\rangle_a - \beta|01\rangle_a)|00\rangle_c|0\rangle_f, \quad (15)$$

where α and β are complex numbers ($|\alpha|^2+|\beta|^2=1$), the state $|00\rangle_a|00\rangle_c|0\rangle_f$ does not change during the evolution since $H_I|00\rangle_a|00\rangle_c|0\rangle_f=0$. Thus, we have transferred quantum state from atom 1 to atom 2.

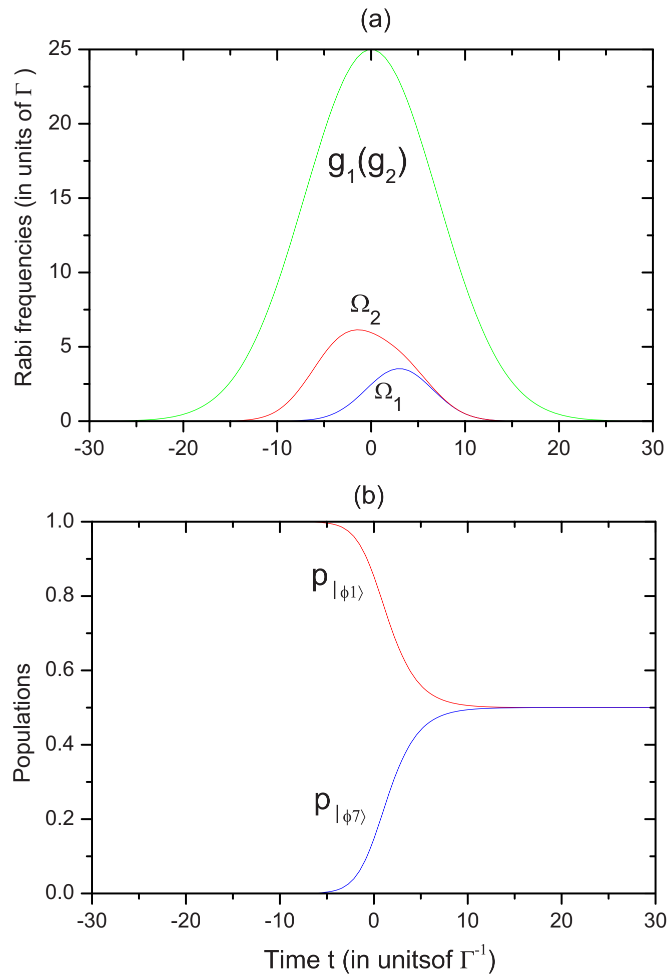

FIG. 3. (Color online) (a) The time dependence of the Rabi frequencies for cavity modes and laser fields for atoms. (b) Time evolution of the populations. We have chosen $\theta=\pi/4$, $d=3\Gamma^{-1}$, $z_0=0$, $\tau=0$, the pulse parameters $W_l=5\Gamma^{-1}$, $W_c=10\Gamma^{-1}$, $v=1$ m/s, $\lambda=852.36$ nm, $\Omega_0=5\Gamma$, $g_0=25\Gamma$, and $\Gamma/2\pi=5$ MHz as the spontaneous emission rate for the state $|e\rangle$.

IV. GENERATION OF *n*-ATOM *W* STATE

If $n+1$ Λ-type atoms are trapped in $n+1$ distant single-mode optical cavities, which are connected by n optical fibers. The Hamiltonian of the whole system in the interaction picture is

$$H_I = \left(\sum_{i=1}^{n} \nu_i b_i (a_i^\dagger + a_{i+1}^\dagger) + \sum_{i=1}^{n+1} [g_i(t) a_i |e\rangle_i\langle 0| + \Omega_i(t)|e\rangle_i\langle 1|] + \text{H.c.}\right). \quad (16)$$

We can find a dark state of H_I, i.e.,

$$|\Psi_d\rangle = K_{n+1}\left(\frac{g_1(t)}{\Omega_1(t)}|\Psi_1\rangle + |\Psi_2\rangle + |\Psi_3\rangle\right), \quad (17)$$

where

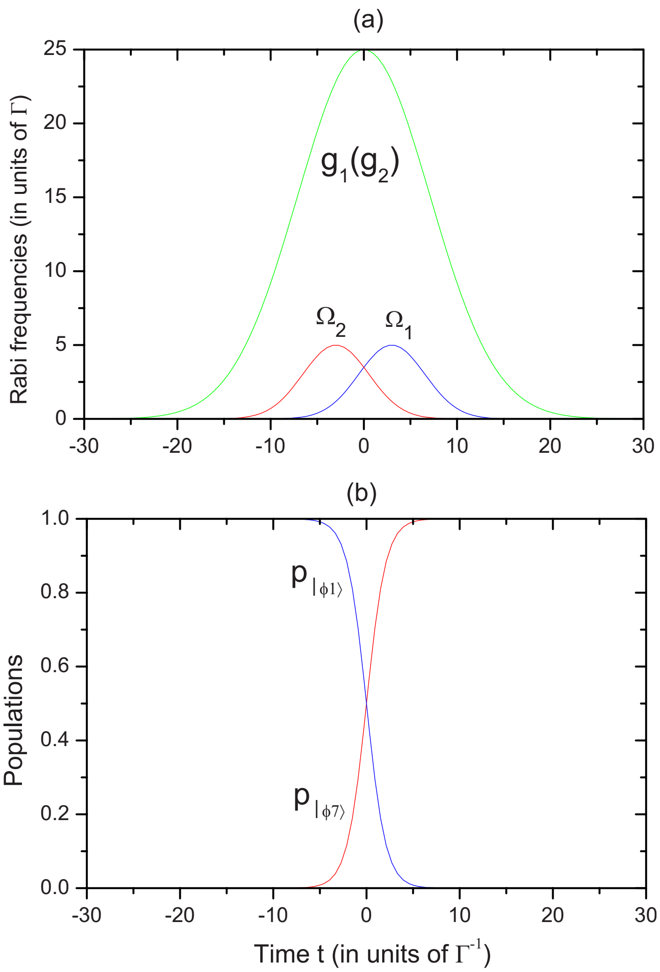

FIG. 4. (Color online) (a) Rabi frequencies of the cavity modes and laser fields for two atoms. (b) Time evolution of the populations. We have chosen $\theta = \pi/2$, and other pulse parameters are the same as in Fig. 3.

$$K_{n+1}^{-2} = \sum_{i=1}^{n+1} \left(\frac{g_i(t)}{\Omega_i(t)} \right)^2 + (n+1), \tag{18}$$

$$|\Psi_1\rangle = |1_1\rangle_a \prod_{k=2}^{n+1} |0_k\rangle_a \prod_{i=1}^{n+1} |0_i\rangle_c \prod_{j=1}^{n} |0_j\rangle_f, \tag{19}$$

$$|\Psi_2\rangle = \left(\sum_{i=1}^{n+1} (-1)^i |0_1\rangle_c \cdots |0_{i-1}\rangle_c |1_i\rangle_c |0_{i+1}\rangle_c \cdots |0_{n+1}\rangle_c \right) \times \prod_{k=1}^{n+1} |0_k\rangle_a \prod_{j=1}^{n} |0_j\rangle_f, \tag{20}$$

$$|\Psi_3\rangle = \left(\sum_{i=2}^{n+1} (-1)^{i+1} \frac{g_i(t)}{\Omega_i(t)} |0_1\rangle_a \cdots |0_{i-1}\rangle_a |1_i\rangle_a |0_{i+1}\rangle_a \cdots |0_{n+1}\rangle_a \right) \times \prod_{k=1}^{n+1} |0_k\rangle_c \prod_{j=1}^{n} |0_j\rangle_f. \tag{21}$$

By choosing

$$\lim_{t\to-\infty} \frac{\Omega_1(t)}{\Omega_i(t)} = 0,$$

$$\lim_{t\to+\infty} \frac{\Omega_i(t)}{\Omega_1(t)} = 0 \quad (i = 2,3, \ldots ,n+1),$$

$$g_1(t) \sim g_i(t) \gg \Omega_1(t), \Omega_i(t) \quad (i = 2,3, \ldots ,n+1),$$

$$g_2(t) = g_3(t) = \cdots = g_{n+1}(t) = g(t),$$

$$\Omega_2(t) = \Omega_3(t) = \cdots = \Omega_{n+1}(t) = \Omega(t), \tag{22}$$

the system in the initial state $|\Psi_1\rangle$ will end up in the state

$$|\Psi_4\rangle = \frac{1}{\sqrt{n}} \sum_{i=2}^{n+1} (-1)^{i+1} |0_1\rangle_a \cdots |0_{i-1}\rangle_a |1_i\rangle_a |0_{i+1}\rangle_a \cdots |0_{n+1}\rangle_a \times \prod_{k=1}^{n+1} |0_k\rangle_c \prod_{j=1}^{n} |0_j\rangle_f. \tag{23}$$

Obviously we have prepared the atoms $2,3,\ldots,n+1$ in the W state. We choose the pulse $g_1(t)$, $\Omega_1(t)$, $g(t)$, and $\Omega(t)$ as in Sec. III, i.e.,

$$g_1(t) = g_0 \exp\left(-\frac{(vt)^2}{W_c^2} \right) \cos\left(\frac{2\pi z_0}{\lambda} \right),$$

$$\Omega_1(t) = \Omega_0 \exp\left(-\frac{z_0^2}{W_l^2} \right) \exp\left(-\frac{(vt-d)^2}{W_l^2} \right),$$

$$g(t) = g_0 \exp\left(-\frac{v^2(t-\tau)^2}{W_c^2} \right),$$

$$\Omega(t) = \Omega_0 \exp\left(-\frac{[v(t-\tau)+d]^2}{W_l^2} \right), \tag{24}$$

as shown in Fig. 5(a), where the pulse parameters are the same as in Fig. 3. Figure 5(b) shows the time population evolution of $n=4$.

V. GENERATION OF n-CAVITY MODE W STATE

Suppose n distant single-mode optical cavities are connected by $n-1$ optical fibers, and only one Λ-type atom is trapped in the first cavity 1, while there is no atom in other $n-1$ cavities. The Hamiltonian of the whole system in the interaction picture is

$$H_I = \left(\sum_{i=1}^{n-1} \nu_i b_i (a_i^\dagger + a_{i+1}^\dagger) + g_1(t) a_1 |e\rangle_1 \langle 0| + \Omega_1(t) |e\rangle_1 \langle 1| + \text{H.c.} \right). \tag{25}$$

We can find a dark state of the system, i.e.,

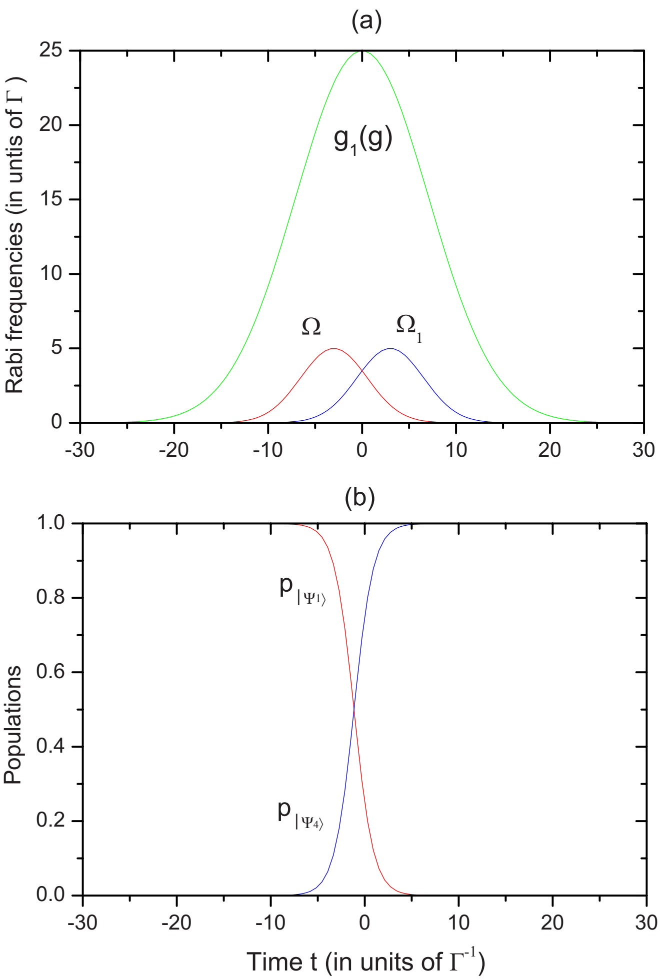

FIG. 5. (Color online) (a) Rabi frequencies of the cavity modes and laser fields for atoms. The pulse parameters are the same as in Fig. 3. (b) The time population evolution of $n=4$.

$$|\Phi_d\rangle = K_n\left[\frac{g_1(t)}{\Omega_1(t)}|\Phi_1\rangle + \left(\sum_{i=1}^{n}(-1)^i|0_1\rangle_c\cdots \times|0_{i-1}\rangle_c|1_i\rangle_c|0_{i+1}\rangle_c\cdots|0_n\rangle_c\right)|0\rangle_a\prod_{j=1}^{n-1}|0_j\rangle_f\right], \quad (26)$$

where the normalization constant is given by $K_n^{-2}=\left(\frac{g_1}{\Omega_1}\right)^2+n$, and

$$|\Phi_1\rangle = |1\rangle_a\prod_{i=1}^{n}|0_i\rangle_c\prod_{j=1}^{n-1}|0_j\rangle_f. \quad (27)$$

If we have

$$\lim_{t\to-\infty}\frac{\Omega_1(t)}{g_1(t)}=0,$$

$$\lim_{t\to+\infty}\frac{g_1(t)}{\Omega_1(t)}=0, \quad (28)$$

the system in the initial state $|\Phi_1\rangle$ will end up in the state

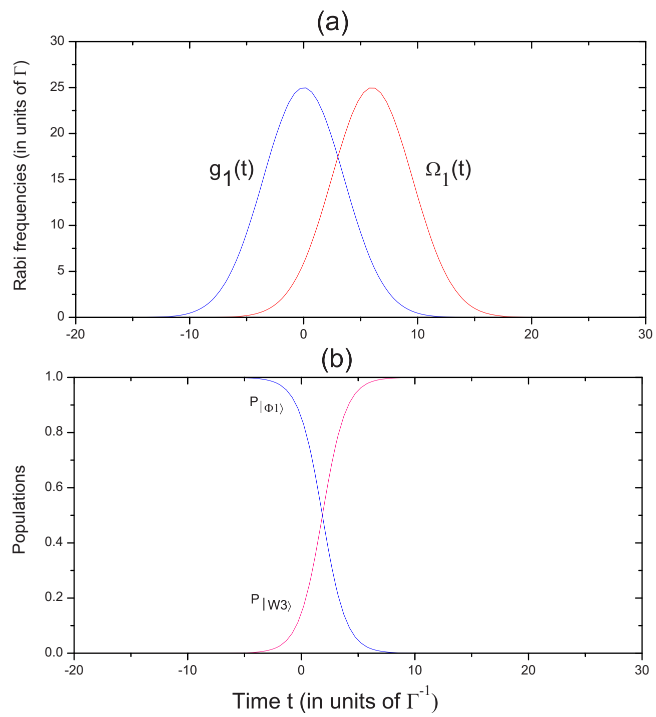

FIG. 6. (Color online) (a) The corresponding Rabi frequencies of the cavity modes and laser fields for atom 1. (b) The time population evolution of $n=3$, where we have chosen $\Omega_0=25\Gamma$, $W_l=10\Gamma^{-1}$, and $d=6\Gamma^{-1}$. Other parameters are the same as in Fig. 3.

$$|W_n\rangle = \frac{1}{\sqrt{n}}\left(\sum_{i=1}^{n}(-1)^i|0_1\rangle_c\cdots|0_{i-1}\rangle_c|1_i\rangle_c|0_{i+1}\rangle_c\cdots|0_n\rangle_c\right) \times|0\rangle_a\prod_{j=1}^{n-1}|0_j\rangle_f. \quad (29)$$

Thus we have prepared the n-cavity mode in the W state. We choose the pulse $g_1(t)$, $\Omega_1(t)$ as in Sec. III, i.e.,

$$g_1(t) = g_0\exp\left(-\frac{(vt)^2}{W_c^2}\right)\cos\left(\frac{2\pi z_0}{\lambda}\right),$$

$$\Omega_1(t) = \Omega_0\exp\left(-\frac{z_0^2}{W_l^2}\right)\exp\left(-\frac{(vt-d)^2}{W_l^2}\right), \quad (30)$$

as shown in Fig. 6(a), where we have chosen $\Omega_0=25\Gamma$, $W_l=10\Gamma^{-1}$, and $d=6\Gamma^{-1}$, other parameters are the same as in Fig. 3. Figure 6(b) shows the time population evolution of $n=3$.

VI. DISCUSSION AND CONCLUSION

Next we analyze the influence on the prepared state due to the imperfection of experiment. Take the generation of the two-atom entanglement state as an example. First, it is difficult to send two atoms through the cavities simultaneously. If τ is not exactly zero, we plot the fidelity of the two-atom entanglement state vs τ in Fig. 7. Second, another difficulty is that the two atoms should share the same speed. If the

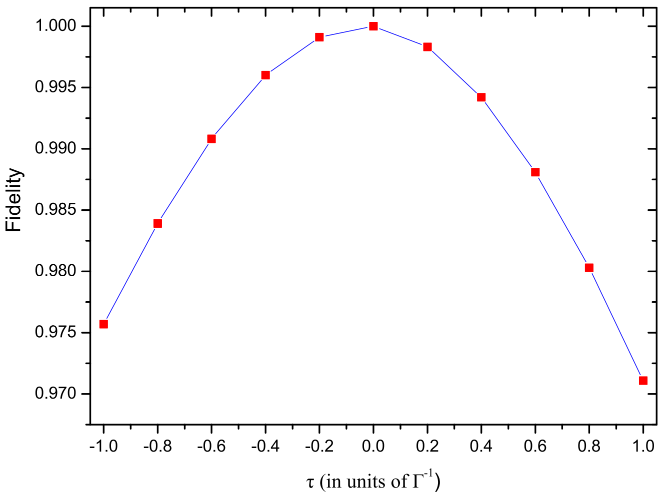

FIG. 7. (Color online) The fidelity for the generation of two-atom entangled state vs the delay time τ, where the pulse parameters are the same as in Fig. 3.

speed of atom 2 is 10% smaller than atom 1, i.e., $v_2=0.9v_1=0.9$ m/s, our calculation shows the fidelity of the two-atom entanglement state $F\approx 0.97$. Third, if the distance z_0 is not zero, the final state is

$$|\varphi(z_0)\rangle \sim \exp\left(\frac{z_0^2}{W_l^2}\right)\cos\left(\frac{2\pi z_0}{\lambda}\right)|\phi_1\rangle - |\phi_7\rangle, \qquad (31)$$

so the variation of the population is very sensitive to z_0. Since the pulses $\Omega_{21}(t)$ and $\Omega_{22}(t)$ should have sufficient overlap areas to make sure of the validity of the f-STIRAP, we have $0<d<5\Gamma^{-1}$. In this range the final state is almost not influenced by d. Finally, in the process for generation of atomic entanglement states, the cavity modes are not populated, so these schemes are free of the effects of the cavity decay. However, the cavity damping is an important issue for the generation of the n-cavity mode W state. The interaction time between the atoms and the fields is $T_{\rm int}\approx W_c/v\approx W_l/v\approx 0.3$ μs, but the cavity lifetime is $T_{\rm cav}\approx 0.3$ μs [27]. So in current optical cavity QED experiment the requirement $T_{\rm int}\ll T_{\rm cav}$ is still a challenge. Remarkably, the requirement of long cavity lifetime may be obtained in whispering-gallery-mode-based microcavities, in which a quality factor of 10^{10} was demonstrated [29]. This type of microcavity has also been proposed to implement quantum information [30]. Following the improvement of the experiment technology, the preparation of the n-cavity mode W state may be implemented in the near future.

In summary, based on the STIRAP and f-STIRAP technique, we have proposed several schemes to generate entanglement and transfer quantum state for the spatially separated qubit. In the schemes for creation of atomic entanglement states, the fiber mode, the cavity mode, and the atomic excited states are never appreciably populated, so these schemes are free of the effects of the atomic spontaneous emission, the cavity decay, and the fiber loss. The n-cavity mode W state can also be prepared based on the model. The effects of the experiment parameter error on the proposals are discussed.

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