Generation of W_n state with three atoms trapped in two remote cavities coupled by an optical fibre*

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We propose two schemes for the generation of the W_n state with three atoms separately trapped in two distant cavities coupled by an optical fibre. One is implemented by controlling the interaction time, the other is implemented via the adiabatic passage. The influence of various decoherence processes, such as spontaneous emission of the atoms and photon leakages of the cavities and the optical fibre, on the fidelity is also investigated. It is found that the W_n state can be generated with high fidelity even when these decoherence processes are present.

Keywords: W_n state, adiabatic passage, optical fibre

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1. Introduction

The system, consisting of atoms separately trapped in distant cavities coupled by optical fibres, is very promising for the generation of distributed entanglement in view of the improvement achieved in the control of single atom trapped in optical cavity[1] and the recent realization of microfabricated cavity–fibre systems.[2] So far, a number of schemes for entangling the distant atoms have been proposed based on this system. According to the different methods of implementation, the schemes fall into two types: by controlling the interaction time or via the adiabatic passage. The schemes, implemented through two methods, for the generation of the two-qubit entangled state,[3−6] the two-qutrit entangled state,[7,8] the prototype W state[4,5] and the Greenberger–Horne–Zeilinger (GHZ) state[9,10] have been proposed.

It is well known that there are two types of entangled states for a system of three qubits, the GHZ type and the W type, which can not be converted to each other under stochastic local operation and classical communication (LOCC).[11] The W state is robust against the loss of qubit, since it retains bipartite entanglement if we trace out any one qubit. However, the prototype W state cannot be used for perfect quantum teleportation and superdense coding.[12] Recently, Agrawal and Pati have shown that there exists a variant class of W state named as W_n state (n is an integer),

$$|W_n\rangle = \frac{1}{\sqrt{2n+2}}(\sqrt{n+1}|100\rangle + \sqrt{n}|010\rangle + |001\rangle), \quad (1)$$

which can be used for perfect teleportation and superdense coding.[13] In some cases, more information can be preserved by using the W_n as the quantum channel than by using the GHZ state.[14,15]

In this paper, we investigate the system consisting of one atom trapped in cavity A, the other two atoms trapped in distant cavity B and an optical fibre used to connect the two cavities. Based on this system, we propose two schemes for the generation of the W_n state. One is implemented by controlling the interaction time, the other is implemented via the adiabatic passage. The influence of various decoherence processes, such as spontaneous emission and photon losses of the cavities and the optical fibre, on the fidelity is investigated. We also discuss the experimental feasibilities for our schemes.

Our paper is organized as follows. In Section 2, the model is introduced and the generation of the W_n state by controlling the interaction time is investigated. In Section 3, we present the generation of the W_n state via adiabatic passage. Finally, the conclusions are summarized in Section 4.

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2. Generation of the W_n state by controlling the interaction time

First, we introduce the atom–cavity–fibre system. As shown in Fig. 1(a), atom 1 is trapped in cavity A, atoms 2 and 3 are trapped in cavity B, the cavities are coupled by an optical fibre. The involved atomic level configurations of the three atoms are shown in Fig. 1(b). Under the rotating wave approximation, the interaction Hamiltonian of the atom-cavity–fibre system can be written as ($\hbar = 1$)[16–19]

$$H_{\rm I} = g_1 a_1|e\rangle_1\langle g| + g_2 a_2|e\rangle_2\langle g| + g_3 a_2|e\rangle_3\langle g| + \lambda b(a_1^\dagger + a_2^\dagger) + {\rm h.c.}, \quad (2)$$

where g_1, g_2 and g_3 are the atom–cavity coupling constants. They are assumed to be real numbers. The a_1, a_2 and b are the annihilation operators for the modes of cavities A, B and the optical fibre, respectively. The λ is the cavity–fibre coupling constant and is also assumed to be a real number.

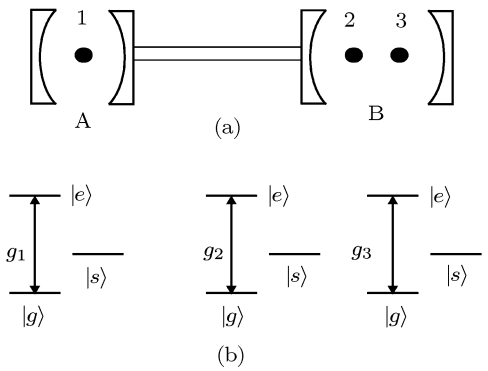


Fig. 1. The setup and the atomic level configurations for the generation of three-qubit W_n state: (a) the setup, (b) the involved atomic level configurations.

Initially, we assume the system is in the state

$$|\Psi(0)\rangle = \frac{1}{\sqrt{2}}(|s\rangle_1 + |e\rangle_1)|g\rangle_2|g\rangle_3|00\rangle_{\rm c}|0\rangle_{\rm f}, \quad (3)$$

where $|00\rangle_{\rm c}$ and $|0\rangle_{\rm f}$ denote that the cavities and the optical fibre are in the vacuum states, respectively. In the domination of the Hamiltonian (2), the state $|s\rangle_1|g\rangle_2|g\rangle_3|00\rangle_{\rm c}|0\rangle_{\rm f}$ will not evolve with time. The reason is that this state is decoupled from the Hamiltonian, i.e., $H_{\rm I}|s\rangle_1|g\rangle_2|g\rangle_3|00\rangle_{\rm c}|0\rangle_{\rm f} = 0$. While the state $|e\rangle_1|g\rangle_2|g\rangle_3|00\rangle_{\rm c}|0\rangle_{\rm f}$ will evolve into the state $|\psi(t)\rangle = \sum_{i=1}^{6} c_i|\phi_i\rangle$, where

$$\begin{aligned}
|\phi_1\rangle &= |egg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f},\\
|\phi_2\rangle &= |ggg\rangle_{123}|10\rangle_{\rm c}|0\rangle_{\rm f},\\
|\phi_3\rangle &= |ggg\rangle_{123}|00\rangle_{\rm c}|1\rangle_{\rm f},\\
|\phi_4\rangle &= |ggg\rangle_{123}|01\rangle_{\rm c}|0\rangle_{\rm f},\\
|\phi_5\rangle &= |geg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f},\\
|\phi_6\rangle &= |gge\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}. \quad (4)
\end{aligned}$$

During the process, the system state evolves in the domination of the Schrödinger equation,

$$\mathrm{i}\frac{\partial}{\partial t}|\psi(t)\rangle = H_{\rm I}|\psi(t)\rangle, \quad (5)$$

where $H_{\rm I}$ is given by Eq. (2). Here we assume that $g_1 = g$, $g_2 = \sqrt{n}g/\sqrt{n+1}$, $g_3 = g/\sqrt{n+1}$ (n is an integer) and $r = \lambda/g$. Associating Eqs. (4) and (5), we can obtain

$$\begin{aligned}
c_1 &= \frac{1}{2(1+2r^2)}\cos(\sqrt{1+2r^2}gt) + \frac{1}{2}\cos(gt) + \frac{r^2}{1+2r^2},\\
c_2 &= \frac{\mathrm{i}}{2\sqrt{1+2r^2}}\sin(\sqrt{1+2r^2}gt) - \frac{1}{2}\sin(gt),\\
c_3 &= \frac{r}{(1+2r^2)}\cos(\sqrt{1+2r^2}gt) - \frac{r}{1+2r^2},\\
c_4 &= \frac{\mathrm{i}}{2}\sin(gt) - \frac{\mathrm{i}}{2\sqrt{1+2r^2}}\sin(\sqrt{1+2r^2}gt),\\
c_5 &= \frac{\sqrt{n}}{\sqrt{n+1}}c, \quad c_6 = \frac{1}{\sqrt{n+1}}c, \quad (6)
\end{aligned}$$

where

$$c = [\cos(\sqrt{1+2r^2}gt) + 2r^2 - (1+2r^2)\cos(gt)]/2(1+2r^2).$$

According to the above equations, when $gt = (2l+1)\pi$ ($l = 0, 1, 2, \ldots$) and $\sqrt{1+2r^2} = 2m$ ($m = 1, 2, 3, \ldots$), we can get that $c_1 = c_2 = c_3 = c_4 = 0$, $c_5 = \sqrt{n}/\sqrt{n+1}$, and $c_6 = 1/\sqrt{n+1}$. Then the system is in the state

$$|\Psi\rangle = \frac{1}{\sqrt{2(1+n)}}(\sqrt{n+1}|sgg\rangle_{123} + \sqrt{n}|geg\rangle_{123} + |gge\rangle_{123})|00\rangle_{\rm c}|0\rangle_{\rm f}. \quad (7)$$

Thus we obtain the three atoms in the entangled state $(\sqrt{n+1}|sgg\rangle_{123} + \sqrt{n}|geg\rangle_{123} + |gge\rangle_{123})/\sqrt{2(n+1)}$, which is separated from the cavity fields and the optical fibre mode. This state is equal to $(\sqrt{n+1}|100\rangle_{123} + \sqrt{n}|010\rangle_{123} + |001\rangle_{123})/\sqrt{2(n+1)}$ by using the asymmetric coding[20] for the atomic qubits, i.e., qubit 1 is encoded in the basis vector states $|g\rangle_1$ and $|s\rangle_1$, while qubits 2 and 3 are encoded in the subspaces spanned by the state $\{|g\rangle_2, |e\rangle_2\}$ and $\{|g\rangle_3, |e\rangle_3\}$, respectively. The W_n state is generated ideally.

However, the ideal condition may not be satisfied exactly in practical situations. We plot Fig. 2 to investigate the influence of the deviation of the cavity–fibre coupling constant on the fidelity, which is defined as $F = |\langle\Psi|\Psi(t)\rangle|^2$. From Fig. 2(a), it can be noticed that the fidelity is stable against the deviation of the ratio coefficient r from the condition $r = \sqrt{1.5} \simeq 1.225$. From Fig. 2(b), it can be noted that the fidelity becomes more stable with the increase of r. When $r \geq 10$, the minimum value of the fidelity is always larger than 0.995. This means that the condition $\sqrt{1+2r^2} = 2m$ $(m = 1, 2, 3, \ldots)$ can be approximately neglected when $\lambda \geq 10g$. Moreover, Figure 3 is plotted to investigate the influence of the deviation of the atom–cavity coupling constants on the fidelity.

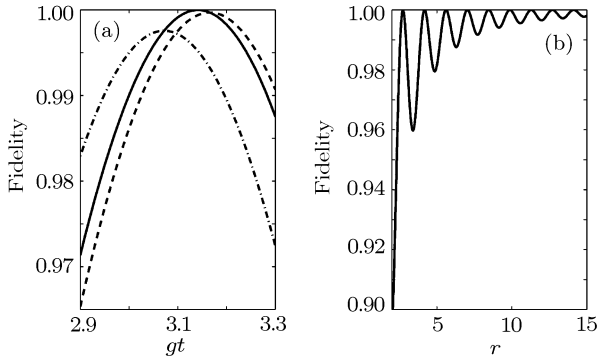


Fig. 2. (a) Fidelity for the generated W_n state of three atoms versus the scale time gt for $r = 1.2$ (dashed line), $r = 1.22$ (solid line) and $r = 1.3$ (dashed–dot line). (b) The fidelity for the generated W_n state of three atoms when $gt = \pi$.

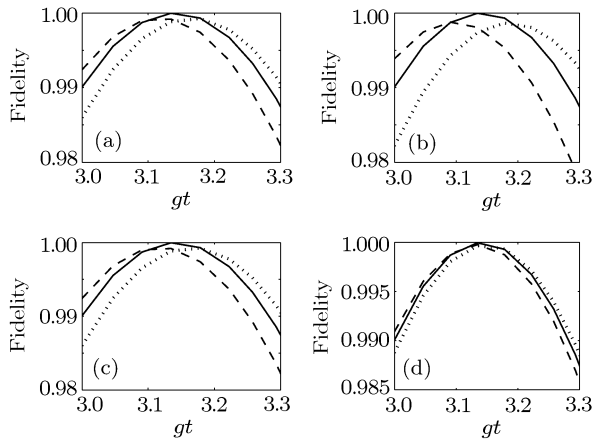


Fig. 3. Fidelity of the generated W_n state versus the scale time gt with $r = \sqrt{1.5}$. (a) and (b) refer to relative variations of -5% (dot line), 0 (solid line) and $+5\%$ (dashed line) in g_2 for $n = 1$ and $n = 10$, respectively. (c) and (d) refer to relative variations of -5% (dot line), 0 (solid line) and $+5\%$ (dashed line) in g_3 for $n = 1$ and $n = 5$, respectively.

We can see that the fidelity is stable against the deviation. The larger the n is, the greater the influence of the deviation of parameter g_2 is and the less the influence of the deviation of parameter g_3 becomes. The reason is that the population of state $|geg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}$ increases, while that of the state $|gge\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}$ decreases, with the increasing n in the ideal state $|\Psi\rangle$.

In the following, we investigate the influence of atomic spontaneous emission and photon leakages out of the cavities and the fibre on the fidelity. The master equation of motion for the density matrix of the whole system can be written as[17,21,22]

$$\begin{aligned}\dot{\rho} = &-{\rm i}[H,\rho] + \sum_{j=1}^{3}\frac{\Gamma_j}{2}(2\sigma_j^-\rho\sigma_j^+ - \sigma_j^+\sigma_j^-\rho - \rho\sigma_j^+\sigma_j^-)\\ &+\sum_{l=1}^{2}\frac{\kappa_l}{2}(2a_l\rho a_l^\dagger - a_l^\dagger a_l\rho - \rho a_l^\dagger a_l)\\ &+\frac{\gamma}{2}(2b\rho b^\dagger - b^\dagger b\rho - \rho b^\dagger b),\end{aligned} \tag{8}$$

where Γ_j is the spontaneous emission rate of atom j for the state $|e\rangle_j$, $\sigma_j^- = |g\rangle_j\langle e|$, κ_l and γ are the decay rates for photons in the modes of cavities and fibre, respectively.

For simplicity, we assume that $\Gamma_j = \Gamma$ $(j = 1, 2, 3)$ and $\kappa_l = \kappa$ $(l = 1, 2)$. We solve Eq. (8) numerically and plot the fidelity versus gt in Fig. 4. From the figure, we note that the curve of $n = 1$ coincides with that of $n = 99$ and the maximal fidelity 0.984 can be achieved for the case that $\Gamma = \kappa = \gamma = 0.01g$ and $\lambda = \sqrt{1.5}g$. Moreover, the W_n state can be generated with high fidelity even in the weak cavity–fibre coupling regime if the condition $\sqrt{1+2r^2} = 2m$ $(m = 1, 2, 3, \ldots)$ is exactly fulfilled.

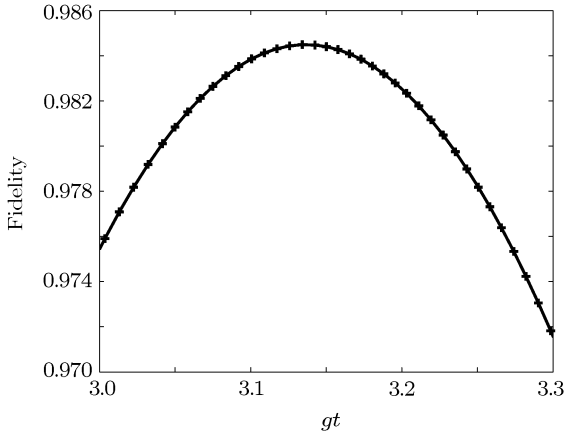


Fig. 4. Fidelity of the generated W_n state versus scale time gt for $\Gamma = \kappa = \gamma = 0.01g$ and $\lambda = \sqrt{1.5}g$, with $n = 1$ (solid line) and $n = 99$ ('+ 'line).

Finally, we briefly discuss the experimental feasibility of the present scheme. The atomic configuration

could be realized by choosing the appropriate energy level of the Cs atom.[20] Based on the recent experiments in realizing the high-Q cavity and the strong atom–cavity coupling, the condition $\kappa \leq 0.01g$ can be satisfied.[23−26] As for the strong couplings between fibre and cavities, a nearly perfect fibre–cavity coupling (with efficiency larger than 99.9%) can be realized by fibre–taper coupling to high-Q Si microspheres.[27,28] Along with the progress of the fibre–cavity coupling and the strong atom–cavity coupling techniques, we believe that the W_n state can be generated with high fidelity based on our scheme.

3. Generation of the W_n state via adiabatic passage

In this section, we present the scheme for the generation of the W_n state via the adiabatic passage. The setup is the same as that introduced in Section 2. The involved atomic levels and the involved transitions are shown in Fig. 5. Here, we can take Cs atom to meet the requirements of the level structure.[10,29]

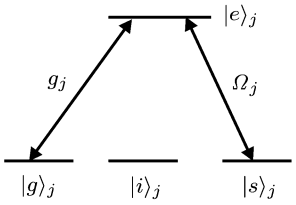


Fig. 5. The atomic level configurations for the generation of three-qubit W_n state via the adiabatic passage.

The transition $|g\rangle_1 \leftrightarrow |e\rangle_1$ is coupled to the mode of cavity A with the coupling constant g_1. The transitions $|g\rangle_2 \leftrightarrow |e\rangle_2$ and $|g\rangle_3 \leftrightarrow |e\rangle_3$ are coupled to the modes of cavity B with the coupling constants g_2 and g_3, respectively. The transitions $|s\rangle_j \leftrightarrow |e\rangle_j$ $(j = 1, 2, 3)$ are driven by the classical fields with Rabi frequencies Ω_j. The interaction Hamiltonian can be written as $(\hbar = 1)$

$$\begin{aligned} H_{\rm II} =\ & g_1 a_1 |e\rangle_1\langle g| + \Omega_1 |e\rangle_1\langle s| + \lambda b(a_1^\dagger + a_1^\dagger) \\ & + \sum_{j=2}^{3}(g_j a_j |e\rangle_j\langle g| + \Omega_j |e\rangle_j\langle s|) + \text{h.c.} \end{aligned} \quad (9)$$

We assume that $\Omega_2 = \Omega_3 = \Omega$, $g_1 = g$, $g_2 = \sqrt{n}g/\sqrt{n+1}$ and $g_3 = g/\sqrt{n+1}$. For an initial state $|sgg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}$, the state evolution remains in the subspace spanned by the basis state vectors

$$\begin{aligned} |\varphi_1\rangle &= |sgg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_2\rangle &= |egg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_3\rangle &= |ggg\rangle_{123}|10\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_4\rangle &= |ggg\rangle_{123}|00\rangle_{\rm c}|1\rangle_{\rm f}, \\ |\varphi_5\rangle &= |ggg\rangle_{123}|01\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_6\rangle &= |geg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_7\rangle &= |gsg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_8\rangle &= |gge\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}, \\ |\varphi_9\rangle &= |ggs\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}. \end{aligned} \quad (10)$$

There is a dark state

$$\begin{aligned} |D\rangle =\ & \frac{1}{N}[g\Omega|\varphi_1\rangle - \Omega_1\Omega(|\varphi_3\rangle - |\varphi_5\rangle) \\ & - \frac{\Omega_1 g}{\sqrt{n+1}}(\sqrt{n}|\varphi_7\rangle + |\varphi_9\rangle)], \end{aligned} \quad (11)$$

where N is the normalization factor. It is noted that all the three atoms are in the ground states and the fibre is in the vacuum state, so the effects of spontaneous emission and the decay of the fibre can be ignored safely. Moreover, if the condition $g \gg \Omega_1, \Omega$ is always satisfied, the population of the cavity modes in excited states is negligible.

Now we show how to generate the W_n state. We suppose that the condition $g \gg \Omega_1, \Omega$ is always satisfied. Initially, we suppose that $\Omega \gg \Omega_1$. Under this condition, we have $|D\rangle \sim |\varphi_1\rangle$. Then the initial state of the system can be prepared as

$$|\Phi(0)\rangle = \frac{1}{\sqrt{2}}(|i\rangle_1 + |s\rangle_1)|gg\rangle_{23}|00\rangle_{\rm c}|0\rangle_{\rm f}. \quad (12)$$

The state $|igg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}$ does not change under the time evolution dominated by the Hamiltonian (9), because it is decoupled from that Hamiltonian. Then we slowly increase Ω_1 and decrease Ω until $\Omega \ll \Omega_1$. The state $|\varphi_1\rangle$ is adiabatically evolved into $(\sqrt{n}|\varphi_7\rangle + |\varphi_9\rangle)/\sqrt{n+1}$. The final state of the system can be written as

$$\begin{aligned} |\Phi\rangle =\ & \frac{1}{\sqrt{2(n+1)}}(\sqrt{n+1}|igg\rangle_{123} \\ & + \sqrt{n}|gsg\rangle_{123} + |ggs\rangle_{123})|00\rangle_{\rm c}|0\rangle_{\rm f}. \end{aligned} \quad (13)$$

The three atoms are in the entangled state $(\sqrt{n+1}|igg\rangle_{123} + \sqrt{n}|gsg\rangle_{123} + |ggs\rangle_{123})/\sqrt{2(n+1)}$, which is separated from the cavity fields and the optical fibre mode. This state is equal to $(\sqrt{n+1}|100\rangle_{123} + \sqrt{n}|010\rangle_{123} + |001\rangle_{123})/\sqrt{2(n+1)}$ by using the asymmetric coding[20] for the atomic qubits, i.e., qubit 1 is encoded in the basis vector states $|g\rangle_1$ and $|i\rangle_1$, while qubits 2 and 3 are encoded in the subspaces spanned by the state $\{|g\rangle_2, |s\rangle_2\}$ and $\{|g\rangle_3, |s\rangle_3\}$, respectively.

However, the condition $g \gg \Omega_1, \Omega$ may not be ideally satisfied in practice. Then the cavity modes may be excited and decay to the state $|ggg\rangle_{123}|00\rangle_{\rm c}|0\rangle_{\rm f}$. These processes would decrease the fidelity of the generated W_n state. As a concrete numerical example, we suppose that $\Omega_1 = \Omega_0 \exp[-(t-T)/2\tau^2]$, $\Omega = \Omega_0 \exp(-t^2/2\tau^2)$, where T is the adiabatic operating time, $\Omega_0 = g/4$ and $\tau = 40/g$.[5,30,31] The minimal energy gap is $\Delta E_{\rm min} \approx 0.1g$ for λ ranging from g to $50g$. For this case, setting $g = 1$ GHz, the adiabatic operating time is about $T \geq 10/0.1g = 100$ ns.[32] As shown in Fig. 6(a), the population of the state $(\sqrt{n}|\varphi_7\rangle + |\varphi_9\rangle)/\sqrt{n+1}$ finally approaches 1. That is

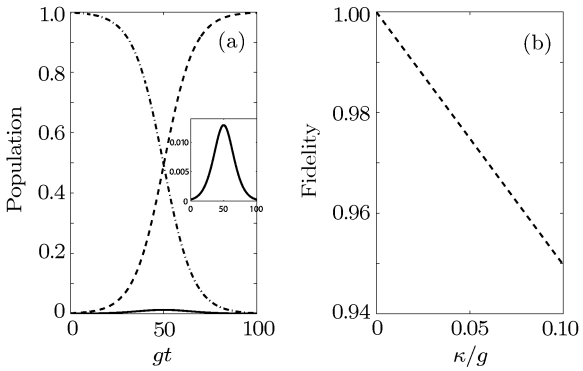


Fig. 6. (a) Time evolution of the populations. The P_1 represents the population of the state $|\varphi_1\rangle$ (dashed-dot line), the P_2 represents the population of the state $(\sqrt{n}|\varphi_7\rangle + |\varphi_9\rangle)/\sqrt{(n+1)}$ (dashed line) and the P_3 represents the population of the state $(|\varphi_3\rangle - |\varphi_5\rangle)/\sqrt{2}$ (solid line). The P_3 is enlarged in the inset. (b) Fidelity of the generation of the tripartite W_n state.

to say that a reliable generation of the W_n state can be achieved. The probability of the state $|\varphi_1\rangle$ evolving into the state $(|\varphi_3\rangle - |\varphi_5\rangle)/\sqrt{2}$ is

$$\varepsilon = \kappa \int_0^T \frac{2(\Omega_1 \Omega)^2}{(g\Omega_1)^2 + 2(\Omega_1\Omega)^2 + (g\Omega)^2} {\rm d}t, \qquad (14)$$

where κ is the decay rate of the cavities. The final state of the atoms is approximately given by

$$\rho = |\psi'\rangle_{123}\langle\psi'| + \frac{\varepsilon}{2}|ggg\rangle_{123}\langle ggg|, \qquad (15)$$

where $|\psi'\rangle = [\sqrt{n+1}|igg\rangle_{123} + \sqrt{1-\varepsilon}(\sqrt{n}|gsg\rangle_{123} + |ggs\rangle_{123})]/\sqrt{2(n+1)}$. Figure 6(b) shows the influence of the cavity decay on the fidelity. It is noted that the fidelity would be larger than 0.95 if $\kappa < 0.1g$.

4. Conclusions

In conclusion, we have proposed two schemes for generating a three-qubit W_n state with three atoms separately trapped in two distant cavities mediated by an optical fibre. For the first scheme, the W_n state can be deterministically generated at appropriate time if the ratio of the atom–cavity coupling constant to the cavity–fibre coupling constant satisfies a certain condition. By numerically solving the master equation, we show that the three-qubit W_n state can be generated with high fidelity even with atomic spontaneous decay and photon leakages out of the cavities and the optical fibre. For the second scheme, the W_n state of the three atoms can be generated via adiabatic passage. During the whole procedure, since all the atoms are always in the ground states and the fibre modes are always in the vacuum state, the influence of the atomic spontaneous emission and the decay of fibre on the fidelity can be suppressed effectively. The state can be generated with high fidelity when $\kappa < 0.1g$. The experimental feasibilities for our schemes are also discussed. We believe that our schemes can be realized with the achieved progress in experiment.

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