Preparation of entanglement between atoms in spatially separated cavities via dissipation

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We propose a scheme to generate a maximally entangled state for two Λ-type atoms trapped in separate optical cavities coupled through an optical fiber based on the combined effect of the unitary dynamics and the dissipative process. Our work shows that the atomic spontaneous emission, cavity decay, and even the fiber loss, which are the three main dissipative factors in the atom-cavity-fibre system, could be used to prepare entanglement, respectively and simultaneously. Originating from an arbitrary state, the desired state could be prepared without precise time control. The robustness of the scheme is numerically demonstrated by considering various parameters.

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1. INTRODUCTION

Quantum entanglement [1, 2] is a fundamental and fascinating quantum effect and has been a key resource for quantum information science (QIS) [3–5]. How to effectively prepare entanglement influences the development of QIS. One traditional obstacle for preparing entanglement is the dissipation that induced by the inevitable coupling between the quantum system and the environment, which would degrade the quantum coherence of the system. The usual methods to deal with the dissipation can be divided into the following categories: quantum error correction [6–8], decoherence-free subspace [9–11], geometric phase [12–15],

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quantum-control technique [16–18] and dissipative dynamics [19–49]. Compared with the other methods, dissipative dynamics has unique characters since the dissipation is used to prepare entanglement so that the preparation process is robust against decoherence. In particular, Kastoryano et al. considered a dissipative scheme for preparing a maximally entangled state of two Λ-type atoms trapped in one optical cavity [30], whose performance is better than that based on the unitary dynamics. Subsequently, this scheme was generalized to coupled cavity system [35], atom-cavity-fiber system [37] and the circuit quantum electrodynamics system [44]. Besides, Zheng et al. proposed a scheme to prepare the maximal entanglement between two atoms coupled to a decaying resonator. The common place of these schemes is that the cavity decay is used as resources for state preparation. On the other hand, Rao and Mølmer, Carr and Saffman consider two schemes [41, 42] to prepare the entanglement of Rydberg atoms via dissipation, respectively. And Shao et al. give two dissipative schemes for three-dimensional entanglement preparation [46, 47], which demonstrates that the atomic spontaneous emission is quite capable of being the powerful resource for entanglement preparation. Furthermore, the scheme proposed in Ref. [49] indicates that the atomic spontaneous emission and cavity decay could be used simultaneously to prepare the desired entanglement for two atoms in one cavity.

To realize the long distance and large-scale quantum information processing, atom-cavity-fiber system is proposed [50, 51] and has been an excellent platform for distributed quantum computation [52, 53], quantum entanglement preparation [54–59], and quantum communication [60]. For these unitary-dynamics-based schemes, atomic spontaneous emission, cavity decay and the fiber loss are three main and undesirable dissipative factors, which would affect the practical applications of the scheme in the QIS.

In this paper, we propose a dissipative scheme to prepare the maximally entanglement of two Λ-type atoms trapped in remote optical cavities coupled through an optical fiber. In our scheme, the atomic spontaneous emission, cavity decay and fiber loss are no longer undesirable but integrant to prepare the stationary state. Our work has the following features: (i) It has no specific requirement of the initial state. (ii) It does not need to control evolution time accurately. Besides, it is robustness on parameter fluctuations. (iii) Different with the other dissipative schemes, the present one shows that, the atomic spontaneous emission, the cavity decay, and the fiber loss, which are the three dissipative factors in the atom-cavity-fiber system, are no longer undesirable, but necessary for the state preparation.
2. FUNDAMENTAL MODEL

We consider the setup described in Fig. 1 where two identical \( \Lambda \)-type atoms are individually trapped into two single mode cavities coupled through an optical fiber with length \( l \). Each atom has two ground states \( |0\rangle \) and \( |1\rangle \) and one excited state \( |e\rangle \) with the corresponding energies \( \omega_0, \omega_1 \) and \( \omega_e \), respectively. The atomic transition \( |1\rangle \leftrightarrow |e\rangle \) is coupled resonantly to the corresponding cavity mode with the coupling constant \( g \). Besides, the transition \( |0\rangle \leftrightarrow |e\rangle \) is driven by the corresponding off-resonance optical laser with detuning \( \Delta \), and Rabi frequency \( \Omega \). The transition between two ground states \( |0\rangle \) and \( |1\rangle \) is coupled resonantly by means of a microwave field with Rabi frequency \( \Omega_{\text{MW}} \). In the short fiber limit \( (l\bar{v})/(2\pi c) \leq 1 \), where \( \bar{v} \) is the decay rate of the cavity fields into a continuum of fiber modes, only one fiber mode interacts with the cavity mode \([51,53]\). For simplicity, we assume the interaction between cavity mode and fiber mode is resonant. Under the rotating wave approximation, the Hamiltonian of the whole system could be written as (setting \( \hbar = 1 \))

\[
H_{\text{a,c,f}} = \sum_{i=A,B} \left( \sum_{j=0,1,e} \omega_j |j\rangle \langle j| + \omega_a a_i^\dagger a_i + (g|e\rangle \langle 1|a_i + \text{H.c.}) \right) + \omega_b b^\dagger b + (\nu b(a_A^\dagger + a_B^\dagger) + \text{H.c.})
\]

\[
H_{\text{cl}} = \Omega \sum_{i=A,B} e^{i\omega t} |0\rangle \langle e| + \text{H.c.},
\]

\[
H_{\text{mw}} = \Omega_{\text{MW}} e^{i\omega_{\text{MW}} t} (|0\rangle_{AA} \langle 1| - |0\rangle_{BB} \langle 1|) + \text{H.c.},
\]

in which \( a_i \) and \( a_i^\dagger \) denote the annihilation and creation operators for the optical mode of cavity \( i \), respectively. \( b \) and \( b^\dagger \) denote the annihilation and creation operator for the fiber mode, respectively. \( \omega_a \) and \( \omega_b \) denote the frequencies of cavity mode and fiber mode, respectively. \( \omega \) and \( \omega_{\text{MW}} \) denote the frequencies of classical laser field and microwave field, respectively. \( \nu \) is the coupling strength between cavity mode and the fiber mode. Then, we define the excitation number operator of the total system \( N_e = \sum_{i=A,B} |e\rangle \langle e| + a_i^\dagger a_i + b^\dagger b \).

Under the weak excitation condition and if the initial state is in the zero excitation subspace, we can safely discard the subspace with excitation number greater than or equal to two.
FIG. 1: Experimental setup and level diagram of Λ-type atoms. $\gamma$, $\kappa$ and $\beta$ denote the atomic spontaneous emission rate, cavity decay rate and fiber loss rate, respectively. Here, we assume the cavity decay rate of the two cavities are the same, and the excited state $|e\rangle$ spontaneously decays into two ground states with branching rate $\gamma/2$.

TABLE I: The eigenstate and corresponding eigenenergy of Hamiltonian $H_{a,c,f}$ in zero excitation subspaces. Here, $|\alpha\beta\rangle|\gamma\delta\epsilon\rangle$ represents that atom in cavity A (B) is in the state $|\alpha\rangle$ ($|\beta\rangle$), optical mode of the cavity A (B) is in the state $|\gamma\rangle$ ($|\delta\rangle$) and of the fiber is in state $|\epsilon\rangle$.

| Eigenstate | Eigenenergy |
|------------|-------------|
| $|00\rangle|000\rangle$ | 0            |
| $|S\rangle|000\rangle$ | $\omega_1$   |
| $|T\rangle|000\rangle$ | $\omega_1$   |
| $|11\rangle|000\rangle$ | $2\omega_1$  |

3. PREPARATION OF THE MAXIMALLY ENTANGLED STATE

3.1. Dressed states

To see clearly the roles of the classical laser field, microwave field and dissipative factors, we identify the eigenstates of the Hamiltonian $H_{a,c,f}$ in zero and one excitation subspace and use them as dressed states. In Tables I and II we show the eigenstates and the corresponding eigenvalues with the notations (setting $\omega_0=0.$)

$$|S\rangle \equiv (|01\rangle - |10\rangle)/\sqrt{2}, \quad |T\rangle \equiv (|01\rangle + |10\rangle)/\sqrt{2}, \quad |\varphi\rangle_1 \equiv (|00\rangle|100\rangle - |00\rangle|001\rangle)/\sqrt{2},$$

$$|\varphi\rangle_2 \equiv (|00\rangle|100\rangle + |00\rangle|001\rangle - \sqrt{2}|00\rangle|010\rangle)/2, \quad |\varphi\rangle_3 \equiv (|00\rangle|100\rangle + |00\rangle|001\rangle + \sqrt{2}|00\rangle|010\rangle)/2,$$
| Eigenstate       | Eigenenergy        |
|------------------|--------------------|
| $|\varphi\rangle_1$ | $\omega_o - \omega_1$ |
| $|\varphi\rangle_2$ | $\omega_o - \omega_1 - \sqrt{2}\nu$ |
| $|\varphi\rangle_3$ | $\omega_o - \omega_1 + \sqrt{2}\nu$ |
| $|\varphi\rangle_4$ | $\omega_o + \omega_1$ |
| $|\varphi\rangle_5$ | $\omega_o + \omega_1 - g$ |
| $|\varphi\rangle_6$ | $\omega_o + \omega_1 + g$ |
| $|\varphi\rangle_7$ | $\omega_o + \omega_1 - g_1$ |
| $|\varphi\rangle_8$ | $\omega_o + \omega_1 + g_1$ |
| $|T_1\rangle, |S_1\rangle$ | $\omega_o - \sqrt{g_1^2 - g_3^2}/\sqrt{2}$ |
| $|T_2\rangle, |S_2\rangle$ | $\omega_o + \sqrt{g_1^2 - g_3^2}/\sqrt{2}$ |
| $|T_3\rangle, |S_3\rangle$ | $\omega_o - \sqrt{g_1^2 + g_3^2}/\sqrt{2}$ |
| $|T_4\rangle, |S_4\rangle$ | $\omega_o + \sqrt{g_1^2 + g_3^2}/\sqrt{2}$ |

$|\varphi\rangle_4 \equiv (|e1\rangle|000\rangle + |1e\rangle|000\rangle - \frac{g}{\nu}|11\rangle|010\rangle)/\sqrt{2 + (\frac{g}{\nu})^2}$,

$|\varphi\rangle_5 \equiv (|11\rangle|001\rangle + |e1\rangle|000\rangle - |1e\rangle|000\rangle - |11\rangle|100\rangle)/2$,

$|\varphi\rangle_6 \equiv (|11\rangle|100\rangle + |e1\rangle|000\rangle - |1e\rangle|000\rangle - |11\rangle|001\rangle)/2$,

$|\varphi\rangle_7 \equiv (|e1\rangle|000\rangle + |1e\rangle|000\rangle + \frac{2\nu}{g}|11\rangle|010\rangle - \frac{g_1}{g}|11\rangle|001\rangle - \frac{g_1}{g}|11\rangle|100\rangle)/\sqrt{2 + (\frac{g}{\nu})^2}$,

$|\varphi\rangle_8 \equiv (|e1\rangle|000\rangle + |1e\rangle|000\rangle + \frac{2\nu}{g}|11\rangle|010\rangle + \frac{g_1}{g}|11\rangle|001\rangle + \frac{g_1}{g}|11\rangle|100\rangle)/\sqrt{2 + (\frac{g}{\nu})^2}$,

$|T_1\rangle \equiv \left[ \frac{\sqrt{g_1^2 - g_3^2}(g^2 + g_3^2)}{2\sqrt{2}g^2}(|01\rangle|100\rangle + |10\rangle|001\rangle) - \frac{g_2^2 + g_3^2}{2g\nu}(|01\rangle|010\rangle + |10\rangle|010\rangle) \right. $

$\left. - \frac{\sqrt{g_1^2 - g_3^2}}{\sqrt{2}g}(|01\rangle|001\rangle + |10\rangle|100\rangle) + (|0e\rangle|000\rangle + |e0\rangle|000\rangle) \right]/\sqrt{2}(g_3^4 + g^2g_3^2 - 2g_3^2\nu^2)$,

$|S_1\rangle \equiv \left[ \frac{\sqrt{g_1^2 - g_3^2}(g^2 + g_3^2)}{2\sqrt{2}g^2}(|01\rangle|100\rangle - |10\rangle|001\rangle) - \frac{g_2^2 + g_3^2}{2g\nu}(|01\rangle|010\rangle - |10\rangle|010\rangle) \right.$
\[ |T_2 \rangle \equiv \left[ -\frac{\sqrt{g_1^2 - g_3^2}}{\sqrt{2g}} (|01\rangle|00\rangle - |10\rangle|10\rangle) + (|0e\rangle|00\rangle - |e0\rangle|00\rangle) \right] / \sqrt{2(g_1^4 + g_2^2 g_3^2 - 2g_3^2 \nu^2) g^2}, \]

\[ |S_2 \rangle \equiv \left[ -\frac{\sqrt{g_1^2 - g_3^2}}{\sqrt{2g}} \left( (|01\rangle|10\rangle + |10\rangle|01\rangle) - \frac{g_2^2 + g_3^2}{2g^2} (|01\rangle|01\rangle + |10\rangle|10\rangle) \right) \right] / \sqrt{2(g_1^4 + g_2^2 g_3^2 - 2g_3^2 \nu^2) g^2}, \]

\[ |T_3 \rangle \equiv \left[ \frac{\sqrt{g_1^2 + g_3^2}}{\sqrt{2g^2}} (|01\rangle|10\rangle + |10\rangle|01\rangle) + \frac{g_3^2 - g_2^2}{2g^2} (|01\rangle|01\rangle + |10\rangle|10\rangle) \right] / \sqrt{2(g_1^4 + g_2^2 g_3^2 - 2g_3^2 \nu^2) g^2}, \]

\[ |S_3 \rangle \equiv \left[ \frac{\sqrt{g_1^2 + g_3^2}}{\sqrt{2g^2}} (|01\rangle|10\rangle - |10\rangle|01\rangle) + \frac{g_3^2 - g_2^2}{2g^2} (|01\rangle|01\rangle - |10\rangle|10\rangle) \right] / \sqrt{2(g_1^4 + g_2^2 g_3^2 + 2g_3^2 \nu^2) g^2}, \]

\[ |T_4 \rangle \equiv \left[ \frac{\sqrt{g_1^2 + g_3^2}}{\sqrt{2g^2}} (|01\rangle|10\rangle + |10\rangle|01\rangle) + \frac{g_3^2 - g_2^2}{2g^2} (|01\rangle|01\rangle + |10\rangle|10\rangle) \right] / \sqrt{2(g_1^4 - g_2^2 g_3^2 + 2g_3^2 \nu^2) g^2}, \]

\[ |S_4 \rangle \equiv \left[ \frac{\sqrt{g_1^2 + g_3^2}}{\sqrt{2g^2}} (|01\rangle|10\rangle - |10\rangle|01\rangle) + \frac{g_3^2 - g_2^2}{2g^2} (|01\rangle|01\rangle - |10\rangle|10\rangle) \right] / \sqrt{2(g_1^4 - g_2^2 g_3^2 + 2g_3^2 \nu^2) g^2}, \]

where \( g_1^2 = g^2 + 2\nu^2 \), \( g_2^2 = g^2 - 2\nu^2 \) and \( g_3^2 = \sqrt{g^4 + 4\nu^4} \), and \( |T \rangle \) is the maximally entanglement we want to prepare for the two distributed atoms.
FIG. 2: Level configuration and the transitions of the states in the dressed state picture. Microwave field causes resonant transitions among states $|11\rangle|000\rangle$, $|S\rangle|000\rangle$ and $|00\rangle|000\rangle$. Classical laser field cause resonant transitions between states $|00\rangle|000\rangle$ and $|T_4\rangle$. The other transitions between state in zero excitation subspace and that in one excitation caused by classical laser field are non-resonant with different detunings. Dissipative factors, i.e., atomic spontaneous emission, cavity decay and fiber loss, are critical to translate the state $|T_4\rangle$ into the desired state. we use the notations

$$
\Omega_1 = \sqrt{2}g_\nu\Omega/\sqrt{g_3^4 + g_2^2g_3^2 - 2\nu^2g_3^2}
$$

and

$$
\Omega_2 = \sqrt{2}g_\nu\Omega/\sqrt{g_3^4 - g_2^2g_3^2 + 2\nu^2g_3^2}
$$

for simplicity.

3.2. Roles of the microwave field and the classical laser field

Under the dressed state picture, Hamiltonian $H_{mw}$ can be rewritten as

$$
H_{mw} = \sqrt{2} \Omega_{MW} e^{i\omega_{MW}t} (|S\rangle|000\rangle\langle000| - |00\rangle|000\rangle\langle000|) + \text{H.c.} \quad (5)
$$

Similarly, $H_{cl}$ can be rewritten as

$$
H_{cl} = \frac{\sqrt{2}g_\nu\Omega}{\sqrt{g_3^4 + g_2^2g_3^2 - 2\nu^2g_3^2}} e^{i\omega_{MW}t} |00\rangle\langle000| (\langle T_1 | + \langle T_2 |) + \frac{\sqrt{2}g_\nu\Omega}{\sqrt{g_3^4 - g_2^2g_3^2 + 2\nu^2g_3^2}} e^{i\omega_{MW}t} |00\rangle\langle000| (\langle T_3 | + \langle T_4 |)
$$

$$
+ \frac{\sqrt{2}\Omega_2}{g_1} e^{i\omega_{MW}t} |T_4\rangle|000\rangle \langle\varphi_4| + \frac{g\Omega}{\sqrt{2}g_1} e^{i\omega_{MW}t} |T_4\rangle|000\rangle (\langle \varphi_7 | + \langle \varphi_8 |) + \frac{\Omega}{\sqrt{2}} e^{i\omega_{MW}t} |S\rangle|000\rangle (\langle \varphi_5 | + \langle \varphi_6 |) + \text{H.c.} \quad (6)
$$

In the interaction picture with respect to the Hamiltonian $H_{a,c,f}$ that expressed by the eigenvectors and eigenvalues in zero and one excitation subspace, Eqs. (5) and (6) can be
transformed to

\[ H_{mw} = \sqrt{2} \Omega_{MW} (|S⟩⟨000⟩|000⟩⟨11⟩ − |00⟩⟨00⟩|S⟩⟨S|) + H.c. \]  

(7)

and

\[
H_{cl} = \frac{\sqrt{2}g \nu \Omega}{\sqrt{g_3^2 + g_2^2 g_3^2 - 2 \nu^2 g_3^2}} \left[ e^{i(ω - ω_c + \sqrt{g_1^2 - g_3^2})t} |000⟩⟨000| + e^{i(ω - ω_c - \sqrt{g_1^2 - g_3^2})t} |000⟩⟨000| \right] \\
+ \frac{\sqrt{2}g \nu \Omega}{g_1} e^{i(ω - ω_c)t} |T⟩⟨000| φ_2⟩ + \frac{g \Omega}{\sqrt{2}g_1} \left[ e^{i(ω - ω_c - g_1)t} |T⟩⟨000| φ_7⟩ + e^{i(ω - ω_c + g_1)t} |T⟩⟨000| φ_8⟩ \right] \\
+ \frac{Ω}{\sqrt{2}} \left[ e^{i(ω - ω_c + g)t} |S⟩⟨000| φ_5⟩ + e^{i(ω - ω_c - g)t} |S⟩⟨000| φ_6⟩ \right] + H.c. \]  

(8)

Equation (7) shows that Hamiltonian \( H_{mw} \) causes resonant transitions among states \(|11⟩|000⟩, |S⟩|000⟩ \) and \(|00⟩|000⟩), as we shall see later, which is exactly the reason why the scheme is independent of the initial states. From Eq. (8), one can see that classical laser field causes interactions between the states in zero excitation subspace and that in one excitation subspace, and the detuning of the interaction could be adjusted through choosing the values of \( ω, ω_c, g \) and \( ν \) according to the requirement of the scheme. For example, if one choose \( ω_c - ω = -\sqrt{g_1^2 + g_3^2}/\sqrt{2}, |00⟩|000⟩ \) would couple resonantly to \(|T_4⟩\), while other terms in Eq. (8) would undergo non-resonant interactions with different detunings.

### 3.3. Roles of the dissipative factors

Dissipation, which can occur via the atomic spontaneous emission, cavity decay and fiber loss, is an integral component of the current state preparation scheme. The states in one excitation subspace would be transformed to the corresponding states in zero excitation subspace via dissipation. Fascinatingly, it is easy to find that the first and the third term of the state \(|T_4⟩\) would be transformed to the state \(|T⟩|000⟩\) (have not considered the normalization factor) via the cavity decay. Besides, the second term and the fourth term of \(|T_4⟩\) would also be converted to \(|T⟩|000⟩\) via the fiber loss and the atomic spontaneous emission \(|e⟩ → |1⟩\), respectively. Since \(|T⟩|000⟩\) is the product state of the atomic maximally entangled state, the cavity mode vacuum state and the fiber mode vacuum state, the scheme would be considered successful if \(|T⟩|000⟩\) is prepared. Therefore, to prepare the desired state, it is better
FIG. 3: (a)(c)(e) Populations of the states in zero subspace with the initial state $|11\rangle|000\rangle$. (b)(d)(f) Fidelities of the desired state with the initial state $|11\rangle|000\rangle$. In subfigures (a) and (b), the parameters are chosen as $\Omega = 0.008g, \Omega_{MW} = 0.25\Omega, \nu = g$. And the dissipative factors are chosen as $\beta = 0.1g, \kappa = 0$, and $\gamma = 0$. The inset of subfigure (b) is plotted with the dissipative factors $\kappa = 0, \gamma = 0$, and $\beta$ varies from 0 to 0.1$g$ at the time $8 \times 10^3/g$. In subfigures (c) and (d), the parameters are chosen as $\Omega = 0.008g, \Omega_{MW} = 0.2\Omega, \nu = g$. And the dissipative factors are chosen as $\beta = 0, \kappa = 0.1g$, and $\gamma = 0$. The inset of subfigure (d) is plotted with the dissipative factors $\beta = 0, \gamma = 0$, and $\kappa$ varies from 0 to 0.1$g$ at the time $1.6 \times 10^4/g$. In subfigures (e) and (f), the parameters are chosen as $\Omega = 0.008g, \Omega_{MW} = 0.2\Omega, \nu = g$. And the dissipative factors are chosen as $\beta = 0, \kappa = 0$, and $\gamma = 0.1g$. The inset of subfigure (f) is plotted with the dissipative factors $\beta = 0, \kappa = 0$, and $\gamma$ varies from 0 to 0.1$g$ at the time $1.6 \times 10^4/g$.

if other undesired states in zero excitation subspace could be coupled resonantly to $|T_4\rangle$ in one excitation subspace directly or indirectly.
3.4. Preparation process

If the parameters satisfy \( \omega_c - \omega = -\sqrt{g_1^2 + g_2^2/\sqrt{2}}, \) |00⟩|00⟩ would couple resonantly to |\( T_4 \rangle \) while the other terms in Eq. (8) underdo non-resonant interactions with different detunings. First, consider the initial state |11⟩|00⟩. As shown in Sec. 3.2, |11⟩|00⟩ would be transformed to |S⟩|00⟩ through the intermediate state |S⟩|00⟩. Since |00⟩|00⟩ couples resonantly to |\( T_4 \rangle \), the initial state |11⟩|00⟩ would be transformed to |\( T_4 \rangle \) via dissipation finally. The process could be expressed as |11⟩|00⟩ \( \xrightarrow{H_{mw}} \) |S⟩|00⟩ \( \xrightarrow{H_{mw}} \) |00⟩|00⟩ \( \xrightarrow{H_{cl}} \) |\( T_4 \rangle \). Similarly, if the initial state is |S⟩|00⟩ or |00⟩|00⟩, it would also be converted to the desired state finally. Besides, since |01⟩|00⟩ or |10⟩|00⟩ could be regarded as a superposition of the states |S⟩|00⟩ and |\( T_4 \rangle \) and |S⟩|00⟩ would be transformed to |\( T_4 \rangle \) finally, the desired state could also be achieved if the initial state is |01⟩|00⟩ or |10⟩|00⟩.

In the above analysis, for simplicity we only consider the dissipative channel |e⟩ \( \rightarrow \) |1⟩ when we study the roles of the atomic spontaneous emission. Nevertheless, the atomic spontaneous emission has another possibilities, |e⟩ \( \rightarrow \) |0⟩. By the time that happens, the second and the fourth terms of the state |\( T_4 \rangle \) would be converted to |00⟩|00⟩, which is coupled resonantly to the state |\( T_4 \rangle \) through the classical laser field and thus has little or no effect on the state preparation. The detailed level configuration and the transformed process of the whole scheme is shown in Fig. 2.

4. DISCUSSION

With the dissipation being included, the dynamics of the system in Lindblad form could be described by the master equation

\[
\dot{\rho} = i[\rho, H] + \sum_j \left[ L_j \rho L_j^\dagger - \frac{1}{2}(L_j^\dagger L_j \rho + \rho L_j^\dagger L_j) \right],
\]

where \( L_j \) is the so-called Lindblad operator. Specifically, the corresponding Lindblad operators in the current scheme associated with atomic spontaneous emission, cavity decay, and fiber loss can be expressed as

\[
L_{\gamma_1} = \sqrt{\gamma/2}|0\rangle_A \langle 0|_A, \quad L_{\gamma_2} = \sqrt{\gamma/2}|1\rangle_A \langle 1|_A, \quad L_{\gamma_3} = \sqrt{\gamma/2}|0\rangle_B \langle 0|_B, \quad L_{\gamma_4} = \sqrt{\gamma/2}|1\rangle_B \langle 1|_B, \quad L_{\kappa_1} = \sqrt{\kappa} a_A, \quad L_{\kappa_2} = \sqrt{\kappa} a_B, \quad \text{and} \quad L_{\beta} = \sqrt{\beta} b.
\]

To verify the feasibility of the scheme, we solve the master equation numerically in zero and one excitation subspace. For the purpose of studying the effect of each of the dissipative
FIG. 4: Fidelity of the desired state with the initial state $|11\rangle|000\rangle$ at the time $1.5 \times 10^4/g$. The parameters are chosen as $\Omega = 0.008g$, $\Omega_{\text{MW}} = 0.25\Omega$, and $\nu = g$. (a) The dissipative factors $\beta$ and $\kappa$ vary from 0 to 0.06$g$, and $\gamma$ is set to zero. (b) The dissipative factors $\beta$ and $\gamma$ vary from 0 to 0.06$g$, and $\kappa$ is set to zero. (c) The dissipative factors $\gamma$ and $\kappa$ vary from 0 to 0.06$g$, and $\beta$ is set to zero.

FIG. 5: Fidelity of the desired state with the initial state $|11\rangle|000\rangle$. The parameters are chosen as $\Omega = 0.008g$, $\Omega_{\text{MW}} = 0.25\Omega$, and $\nu = g$. The dissipative factors are set as $\beta = \kappa = \gamma$.

factors, we would first consider one factor at a time. Then, the combined effect of the dissipative factors would be considered. In Figs. 3(a) and 3(b), we plot the populations and the fidelity of the scheme when the dissipative factors satisfy $\beta = 0.1g$, $\kappa = 0$, and $\gamma = 0$. The results show that the desired state could be prepared with the fidelity more than 94% when the evolution time equals $10^4/g$. The inset in Fig. 3(b) shows that when $\kappa = \gamma = 0$, the fiber loss is critical for the state preparation since the fidelity would be zero if the fiber loss is not exist. Similarly, numerical results in Figs. 3(c) and 3(d), and 3(e) and 3(f) indicate that the cavity decay and atomic spontaneous emission could also be utilized as resources to prepare the maximal entanglement with high fidelity, respectively. In Fig. 4, we plot the fidelity when two out of the three dissipative factors are considered at the same time. The result gives a further verification that each of the dissipative factors could be utilized to
FIG. 6: (a) Fidelity of the desired state versus the relative fluctuations of $\Omega$ and $\Omega_{MW}$ with the initial state $|11\rangle|000\rangle$ at the time $2 \times 10^4/g$. The notations $d\Omega$ and $d\Omega_{MW}$ in the axis labels denote the deviations of $\Omega$ and $\Omega_{MW}$, respectively. The parameters are chosen as $\Omega = 0.008g$, $\Omega_{MW} = 0.002g$, and $\nu = g$. (b) Fidelity of the desired state versus $\nu$ and evolution time with the initial state $|11\rangle|000\rangle$. The parameters are chosen as $\Omega = 0.008g$ and $\Omega_{MW} = 0.002g$. Both figures are plotted with the dissipative factors $\beta = \kappa = \gamma = 0.04g$

prepare the entanglement.

In Fig. 5, we plot the fidelity when the three dissipative factors are considered at the same time. One can see from Fig. 5(a) that the fidelity increases as the dissipative factors increases. However, as shown in Fig. 5(b), further increase of the dissipative factors would decrease the performance of the scheme. In fact, like most of the dissipative schemes, the present one is based on the combined effect of the unitary dynamics and the dissipative process. When the values of the dissipative factors are set to zero, the scheme would not succeed. As the dissipative factors increases, the role of the dissipative process becomes evident and the fidelity increases. Nevertheless, further increase of the dissipative factors would lead to an adverse effect on the unitary dynamics and thus decrease the overall performance of the scheme. Besides, in Fig. 6(a) we plot the fidelity versus the fluctuations of $\Omega$ and $\Omega_{MW}$, which shows that the scheme is robust on the variation of $\Omega$ and $\Omega_{MW}$ since the fidelity remains higher than 80% even when the relative errors of these two factors reach 50% simultaneously. And Figure 6(b) indicates that the scheme is robust on the variation of the coupling strength between the cavity mode and the fiber mode.

In contrast with the unitary-dynamics-based schemes [54–59, 61], the dissipative factors take on a new role in the present scheme since it constitutes a vital passage from the state in
one excitation subspace to the desired state in the zero excitation subspace. Different from the dissipative scheme \cite{37} based on the effective operator formula \cite{30} in the atom-cavity-fiber system, the current one shows that the spontaneous emission and the fiber loss could also be utilized to prepare the distributed entanglement.

5. CONCLUSION

In conclusion, we have designed an alternative scheme to prepare the distributed entanglement in the atom-cavity-fiber system via dissipation. The scheme is based on the combined effect of the unitary dynamics and the dissipative process introduced by atomic spontaneous emission, the cavity decay, and the fiber loss. The effects of the dissipative factors have been examined individually or simultaneously by the numerical simulations. All of the experimental requirements of our scheme is feasible under the current technology.

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