CHIN. PHYS. LETT. Vol. 31, No. 2 (2014) 024206

Distributed Qutrit–Qutrit Entanglement through Laser-Driven Resonant Interaction *

WU Huai-Zhi(吴怀志), YANG Zhen-Biao(杨贞标)**
Lab of Quantum Optics, Department of Physics, Fuzhou University, Fuzhou 350002

(Received 10 October 2013)

We propose to deterministically realize the qutrit–qutrit maximal entanglement for two atoms held in separate cavities coupled by an optical resonator. We study such a system in the resonant regime and show that the laser-driven resonant dynamics allow for the fast and robust creation of qutrit–qutrit entanglement.

PACS: *42.81.Qb*, *42.50.Dv*, *42.50.Pq*, *03.67.Lx* DOI: 10.1088/0256-307X/31/2/024206

Entanglement is a subtle non-local correlation between parts of a quantum system without classical analogues. An entangled state shared by separate subsystems plays an important role for the test of quantum nonlocality.[1−3] Moreover, it is also a valuable resource for many protocols in quantum communication and computation.[4] Entangled quantum states come in many flavors, such as Bell,[2] Einstein–Podolsky–Rosen,[1] Greenberger–Horne–Zeilinger[3] and W states,[5] generally depending on the dimensionality and tensor product structure of the Hilbert spaces involved. All these states have different qualities and are suitable for different roles in quantum information protocols.[4] Thus a strong motivation has been raised for the study of entanglement and its correlative applications. Though the fields of quantum communication and computation have been mainly built on the concept of qubits (two-dimensional systems), the exploration of qubits (multiple systems with Hilbert spaces of dimension d) has attracted much attention in the recent years. Entangled qubits possess some interesting properties that account for their usefulness: they violate local realism more strongly than entangled qubits;[6] quantum cryptographic protocols where qubits are replaced with qubits are both more secure and faster (in that more information may be sent, on average, per sent particle).[7]

Schemes have been proposed for realization of qutrit–qutrit entanglement. Typical examples can be found in the cases that explore the matter–light interaction,[9−15] for which two atoms held in a single cavity are engineered in a maximal qutrit–qutrit entanglement. In order to be used for quantum communication protocols,[16,17] such an entanglement should be generated between distant atoms, like atoms trapped in different cavities. In this case, separate atoms may be addressed individually in a more convenient way (as compared with the cases where atoms are confined in a single cavity). Distributed atomic entanglement requires a way to coherently mediate the interaction between the separate atoms. Schemes have also been proposed for engineering distributed qutrit–qutrit entanglement[18−21] based on the prototype of two distant atoms interacting with the local cavity modes that are coupled through an optical resonator (say, an optical fiber).[22−24] Notice that the scheme in Refs. [19,20] employs the dispersive interaction for suppressing the excitation of either atoms or photons, thus the operation time is relatively long. Notice also that both the schemes based on the adiabatic passage[18] and quantum Zeno dynamic[15] employ the weak laser driving as to guarantee the system's state evolution confined in the specific ('dark state' or 'Zeno') subspace, they thus also suffer from a slow operation process.

In this Letter, we make an alternative and propose to rapidly engineer qutrit–qutrit entanglement based on the system composed of two distant atoms held in separate cavities that are coupled by an optical resonator. In the scheme, the resonant interaction between the distant atoms as well as between the cavities is driven by moderate laser fields, thus guarantees a relatively faster operation process, as compared to the previous ones in Refs. [18-21], due to the fact that one of the methods for reducing the quantum decoherence effect is to cut down the operation time. In this context, the scheme might be favorable for the complicated coherent control in quantum communication and computation. We will then move on to study the influences of imperfections and dissipation.

Our setup is schematically shown in Fig. 1(a). Two distant atoms are individually held in two double-mode cavities (A and B), which are connected by the third optical resonator. The linking resonator can be either the third cavity coupling the two distant cavi-

*Supported by the National Basic Research Program of China under Grant No 2012CB921601, the National Natural Science Foundation of China under Grant Nos 11247283, 11305037, 11347114, and 11374054, the Natural Science Foundation of Fujian Province under Grant No 2013J01012, and the Fund from Fuzhou University.
**Corresponding author. Email: zbyang@fzu.edu.cn
© 2014 Chinese Physical Society and IOP Publishing Ltd

ties (like in a photonic crystal), or a 'short' (in a sense which will be specified shortly) optical fiber. For simplicity, we will henceforth refer to the linking resonator as to the 'fiber'.

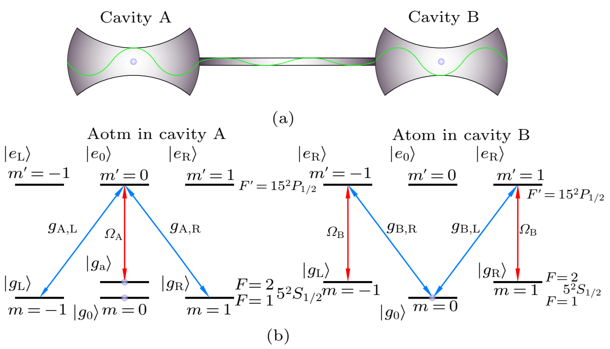

Fig. 1. (Color online) The setup and the atom level configuration for realizing qutrit–qutrit entanglement. (a) Two atoms are trapped in double-mode cavities A and B, respectively. The cavities are coupled by an optical resonator. (b) The involved atomic transitions for each atom in the local cavity.

The coupling of the fiber modes to the cavity modes in the Schrödinger interaction picture may be modelled by the Hamiltonian $H_{\rm I}^{\rm cf}=\sum_{n=1}^{\infty}\sum_{k={\rm L,R}}\Delta_{n,k}b_{n,k}^{+}b_{n,k}+\nu_{n,k}\{b_{n,k}[a_{{\rm A},k}^{+}+(-1)^{n}e^{i\varphi_{\rm f}}a_{{\rm B},k}^{+})]+{\rm H.c.}\}$ ($\hbar=1$ is used throughout this work), where $\Delta_{n,k}$ is the frequency difference of the nth polarized fiber mode and the cavity mode with the corresponding polarization (subscripts L and R denote, respectively, σ^{+}-circular and σ^{-}-circular polarization), $b_{n,k}$ and $a_{{\rm A},k}$ ($a_{{\rm B},k}$) are the annihilation operators for the polarized modes of the fiber and of cavity A (B), $\nu_{n,k}$ is the corresponding coupling strength, and the phase $\varphi_{\rm f}$ is due to the propagation of the field through the fiber of length L: $\varphi=2\pi\omega L/c$.[23] In the short fiber limit $2L\overline{\nu}/(2\pi c)\ll 1$,[23] where $\overline{\nu}$ is the decay rate of the cavity fields into a continuum of the fiber modes, only the resonant modes $b_{\rm L}$ and $b_{\rm R}$ of the fiber are excited and coupled to the cavity modes. In this case, the interaction Hamiltonian $H_{\rm I}^{\rm cf}$ describing the cavity–fiber coupling can be rewritten as $H_{\rm I}^{\rm cf}=\sum_{k={\rm L,R}}\nu_{k}[b_{k}(a_{{\rm A},k}^{+}+a_{{\rm B},k}^{+})+{\rm H.c.}]$,[23] where the phase $(-1)^{n}e^{i\varphi_{\rm f}}$ has been absorbed into the annihilation and creation operators of the polarized modes of cavity B. In this work, the state of the photon modes for cavity A (B) or the fiber is taken to be $|ii'\rangle$, with i (i') denoting i σ^{+}- (i' σ^{-}-) photons.

The atoms have three excited states ($|e_{\rm L}\rangle$, $|e_{0}\rangle$, and $|e_{\rm R}\rangle$) and four ground states ($|g_{\rm L}\rangle$, $|g_{\rm a}\rangle$, $|g_{0}\rangle$, and $|g_{\rm R}\rangle$), which could be the Zeeman sub-levels of alkali atoms in the excited- and ground-state manifold. We consider here a possible implementation with ^{87}Rb, whose relevant atomic levels are shown in Fig. 1.(b). We only illustrate the involved state transition by starting from the initial state $|g_{\rm a}\rangle_{\rm A}|g_{0}\rangle_{\rm B}$. Each atom is assumed to be coupled (resonantly) to an external π-polarized laser field and both σ^{+}- and σ^{-}-polarized photon modes of the local cavity. Due to the different initial states for the two atoms, the involved transitions for each atom are asymmetric. In cavity A, the transitions $|g_{\rm a}\rangle\rightarrow|e_{0}\rangle$ and $|e_{0}\rangle\rightarrow|g_{\rm L}\rangle$ ($|g_{\rm R}\rangle$) are coupled to the π-polarized laser field and the σ^{+}-circular (σ^{-}-circular) polarized cavity mode, respectively. In cavity B, the transitions $|g_{0}\rangle\rightarrow|e_{\rm L}\rangle$ ($|e_{\rm R}\rangle$) and $|e_{k}\rangle\rightarrow|g_{k}\rangle$ are coupled to the σ^{+}-circular (σ^{-}-circular) polarized cavity mode and the π-polarized laser field, respectively. We first assume that the frequencies for the laser and cavity fields are selected in such a way that additional transitions can not occur.

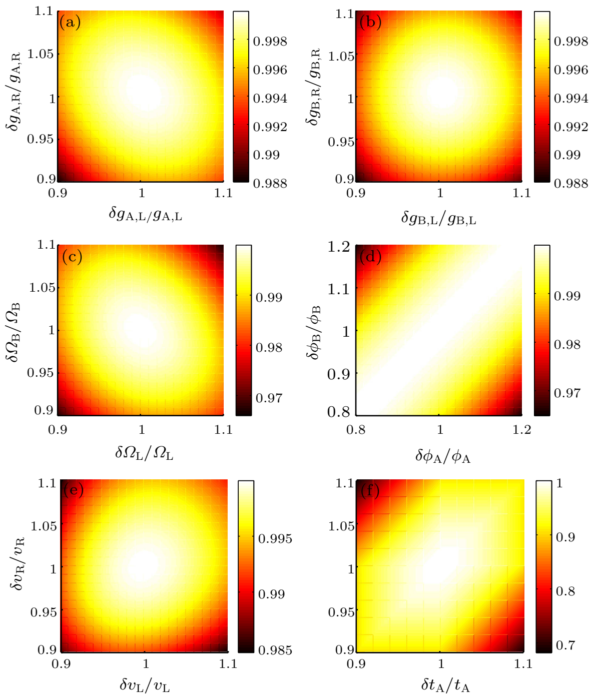

Fig. 2. (Color online) The fidelity of the qutrit–qutrit entanglement versus kinds of errors (all the parameters plotted are dimensionless). (a) F vs $\frac{\delta g_{\rm A,L}}{g_{\rm A,L}}$ and $\frac{\delta g_{\rm A,R}}{g_{\rm A,R}}$; (b) F vs $\frac{\delta g_{\rm B,L}}{g_{\rm B,L}}$ and $\frac{\delta g_{\rm B,R}}{g_{\rm B,R}}$; (c) F vs $\frac{\delta\Omega_{\rm L}}{\Omega_{\rm L}}$ and $\frac{\delta\Omega_{\rm R}}{\Omega_{\rm R}}$; (d) F vs $\frac{\delta\phi_{\rm A}}{\phi_{\rm A}}$ and $\frac{\delta\phi_{\rm B}}{\phi_{\rm B}}$; (e) F vs $\frac{\delta v_{\rm L}}{v_{\rm L}}$ and $\frac{\delta v_{\rm R}}{v_{\rm R}}$; and (f) F vs $\frac{\delta t_{\rm A}}{t_{\rm A}}$ and $\frac{\delta t_{\rm B}}{t_{\rm B}}$ ($t_{\rm A}$ and $t_{\rm B}$ are the required times for each atom interacting with the local cavity fields, respectively).

In the interaction picture, the Hamiltonian describing the atom–cavity coupling in the rotating wave approximation can be written as $H_{\rm I}^{\rm ac}=\sum_{k={\rm L,R}}(g_{{\rm A},k}a_{{\rm A},k}|e_{0}\rangle_{\rm A}\langle g_{k}|+\Omega_{\rm A}e^{i\phi_{\rm A}}|e_{0}\rangle_{\rm A}\langle g_{\rm a}|+g_{{\rm B},k}a_{{\rm B},k}|e_{k}\rangle_{\rm B}\langle g_{0}|+\Omega_{\rm B}e^{i\phi_{\rm B}}|e_{k}\rangle_{\rm B}\langle g_{k}|+{\rm H.c.}]$,[25–27] where $g_{x,k}$ ($x=$A, B) is the coupling strength of the atom with the polarized photon mode in cavity x and satisfies $g_{x,k}=g_{0}C_{m,m'}$ (with g_{0} and $C_{m,m'}$ being the atom–cavity coupling constant and Clebsch–Cordan coefficient, respectively), Ω_{x} and ϕ_{x} are Rabi frequency and phase of the laser field, and H.c. denotes Hermitian conjugate. We define the excitation number operator $N_{\rm e} = |g_{\rm a}\rangle_{\rm A}\langle g_{\rm a}| + |e_0\rangle_{\rm A}\langle e_0| + \sum_{k={\rm L,R}}(|e_k\rangle_{\rm B}\langle e_k| + |g_k\rangle_{\rm B}\langle g_k| + b_k^+ b_k + \sum_{x={\rm A,B}} a_{x,k}^+ a_{x,k})$. It is obvious that the excitation number operator $N_{\rm e}$ commutes with the Hamiltonian $H_{\rm I} = H_{\rm I}^{\rm cf} + H_{\rm I}^{\rm ac}$, thus the total excitation number is conserved during the dynamics evolution of the entire system.

We suppose that the system is initially in the state $|\psi(0)\rangle = \frac{1}{\sqrt{3}}(|g_0\rangle_{\rm A} + \sqrt{2}|g_{\rm a}\rangle_{\rm A})|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2} \equiv \frac{1}{\sqrt{3}}(|\phi_0\rangle + \sqrt{2}|\phi_1\rangle)$. Preparation of this initial state can be achieved by optical pumping or stimulated Raman adiabatic passage with two lasers applied to the atom in cavity A, one resonant with the transition from $F=1$ to $F'=1$, the other coupling levels $F=2$ and $F'=1$.[28] The state $|\phi_0\rangle \equiv |g_0\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$ will not evolve, as it is completely decoupled from the Hamiltonian. However, the state $|\phi_1\rangle \equiv |g_{\rm a}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$ will evolve in the single-excitation subspace $\{|\phi_1\rangle, \ldots, |\phi_i\rangle, \ldots, |\phi_12\rangle\}$,[29] where $|\phi_2\rangle = |e_0\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_3\rangle = |g_{\rm L}\rangle_{\rm A}|g_0\rangle_{\rm B}|10\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_4\rangle = |g_{\rm L}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|10\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_5\rangle = |g_{\rm L}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|10\rangle_{\rm c2}$, $|\phi_6\rangle = |g_{\rm L}\rangle_{\rm A}|e_{\rm L}\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_7\rangle = |g_{\rm L}\rangle_{\rm A}|g_{\rm L}\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_8\rangle = |g_{\rm R}\rangle_{\rm A}|g_0\rangle_{\rm B}|01\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_9\rangle = |g_{\rm R}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|01\rangle_{\rm f}|00\rangle_{\rm c2}$, $|\phi_{10}\rangle = |g_{\rm R}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|01\rangle_{\rm c2}$, $|\phi_{11}\rangle = |g_{\rm R}\rangle_{\rm A}|e_{\rm R}\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$, and $|\phi_{12}\rangle = |g_{\rm R}\rangle_{\rm A}|g_{\rm R}\rangle_{\rm B}|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$. The time evolution of the entire system is governed by the Schrödinger equation $i\frac{\partial}{\partial t}|\psi(t)\rangle = H_{\rm I}|\psi(t)\rangle$, where state vector $|\psi(t)\rangle$ at time t can be expressed as $|\psi(t)\rangle = \frac{1}{\sqrt{3}}(|\phi_0\rangle + \sqrt{2}\sum_{i=1}^{12} C_i|\phi_i\rangle)$.

By setting $g_{\rm A} \equiv g$, $g_{\rm B} = \sqrt{2}g$, $v = 1.56g$, $\Omega_{\rm A} = \Omega_{\rm B} = 1.1g$, $\phi_{\rm A} = \phi_{\rm B}$, and $t = 3.51/g$, we obtain a qutrit–qutrit maximal entanglement (in the sense that the local Von Neumann entropy is maximal)

$$|\psi_{\rm q}\rangle = \frac{1}{\sqrt{3}}(|g_0\rangle_{\rm A}|g_0\rangle_{\rm B} + |g_{\rm L}\rangle_{\rm A}|g_{\rm L}\rangle_{\rm B} + |g_{\rm R}\rangle_{\rm A}|g_{\rm R}\rangle_{\rm B}), \tag{1}$$

leaving the cavities and fiber in vacuum state (i.e., $|00\rangle_{\rm c1}|00\rangle_{\rm f}|00\rangle_{\rm c2}$). Let us stress that the laser-driven resonant interaction discussed here possesses the advantage of requiring a very short interaction time. Compared with the schemes through adiabatic passage,[18] virtual-excitation processes,[19,20] or even quantum Zeno dynamics,[21] the time required in the present scheme is shortened by at least an order of magnitude.

In the above analysis, the system is assumed to operate under ideal conditions. In the real experiments, the potential errors include: (i) the mismatch of the coupling rate $g_{x,k}$ and Ω_x ($x = A$, B; $k = L$, R) for the atoms with the local cavity and laser fields, as $g_{x,k}$ and Ω_x are dependent on atomic position and might fluctuate; (ii) the mismatch of the phase ϕ_x due to noise in the phases of the laser fields; (iii) the mismatch of the coupling rate v_k for the cavity and fiber modes, as v_k is decided by manufactured technology and might be imprecise; (iv) polarization errors due to unstable magnetic fields, which leads to mismatches in parameters related to polarization; and (v) timing error, due to the finite switching rates of the interactions.

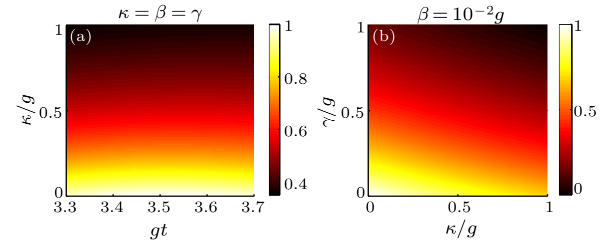

Fig. 3. (Color online) The fidelity of the qutrit–qutrit maximal entanglement versus the dimensionless parameters (a) gt and κ/g ($\kappa = \beta = \gamma$ is set); (b) κ/g and γ/g ($\beta = 0.01g$ is set).

In order to check out how the mentioned errors influence the generation of the entanglement, we define the following fidelity as a measure of the reliability of the qutrit–qutrit maximal entanglement

$$F = \langle\psi_{\rm q}|{\rm Tr}_{\rm c_1,f,c_2}[\rho(t)]|\psi_{\rm q}\rangle, \tag{2}$$

where $\rho(t) \equiv |\psi(t)\rangle\langle\psi(t)|$ is the state of the entire system at an arbitrary time (governed by Eq. (3) which takes no account of dissipation), and ${\rm Tr}_{\rm c_1,f,c_2}$ denotes the partial trace over the field degrees of freedom. We first assume 'perfect interaction', and take the case $g_{\rm A,L} = g_{\rm A,R} \equiv g$, $g_{\rm B,L} = g_{\rm B,R} \equiv \sqrt{2}g$, $\Omega_x = 1.1g$, $\phi_{\rm A} = \phi_{\rm B}$, and $v_k \equiv 1.56g$ as a reference, under such conditions qutrit–qutrit maximal entanglement is obtained at the reference time $t = T_0$ ($gT_0 = 3.51$). We then set the errors in the parameters $g_{x,k}$, Ω_x, ϕ_x, v_k and t_k to be $\delta_{g_{x,k}}$, δ_{Ω_x}, δ_{ϕ_x}, δ_{v_k} and δ_{t_k} ($x=$A, B; $k=$L, R), respectively. In Fig. 2, the fidelity is plotted versus all these kinds of errors. Notice that these fidelity plots display a number of symmetries, which trivially reflect the choices of the error parameters and the symmetry of the system under exchange of the two atoms with the cavities and fiber. Moreover, we find that the fidelity is very robust against errors in the parameters $g_{x,k}$, Ω_x, ϕ_x, and ν_k. A deviation $\delta_{g_{x,k}} \simeq 10\% g_{x,k}$, $\delta_{\Omega_x} \simeq 10\%\Omega_x$, $\delta_{\phi_x} \simeq 10\%\phi_x$, or $\delta_{\nu_{x,k}} \simeq 10\%\nu_{x,k}$ will cause only a reduction of smaller than (or, approximately) 1% in the fidelity. We note that the influence of the timing error δ_{t_k} on the fidelity is a bit more serious, as compared with that of the other errors. However, we find that a deviation $\delta_{t_k} \simeq 5\%\delta_{t_k}$ will cause only a reduction of smaller than 3% in the fidelity.

In all the above arguments, we have ignored the influences of dissipation in the system. Here we take into account the dissipation due to atomic spontaneous emission and photon leakage from the cavities and fiber. The master equation of motion for the density matrix of the entire system can be expressed as

$$\begin{aligned}\dot{\rho} =& -i[H_{\rm I},\rho] + \sum_{x={\rm A,B}}\Big[\sum_{k={\rm L,R}}\frac{\beta}{2}(2b_k\rho b_k^\dagger - b_k^\dagger b_k\rho \\ & -\rho b_k^\dagger b_k) + \frac{\gamma}{2}\sum_{\sigma={\rm L,R},\pi}(2A_{x,\sigma}\rho A_{x,\sigma}^\dagger - A_{x,\sigma}^\dagger A_{x,\sigma}\rho \\ & -\rho A_{x,\sigma}^\dagger A_{x,\sigma}) \\ & +\sum_{k={\rm L,R}}\frac{\kappa}{2}(2a_{x,k}\rho a_{x,k}^\dagger - a_{x,k}^\dagger a_{x,k}\rho - \rho a_{x,k}^\dagger a_{x,k})\Big],\end{aligned} \quad (3)$$

where $A_{x,\sigma} = \sum_{y,z}|y\rangle_x\langle y;i\sigma|z\rangle_x\langle z|$ ($y = g_{\rm L}$, g_0, $g_{\rm R}$; $z = e_{\rm L}$, e_0, $e_{\rm R}$) is the atomic lowering operator, with ${}_x\langle y;i\sigma|z\rangle_x$ being the Clebsch–Gordian coefficient (i.e., $C_{m,m'}$) for the dipole transition $|e\rangle \to |g\rangle$ with polarizaition $\sigma =$ L, R, π; γ, β and κ stand, respectively, for spontaneous emission rate and for the fiber and cavity decay rates (assumed for simplicity to be equal for the two cavities and for the two polarized modes). The contribution of the thermal photons has been neglected, as is reasonable at optical frequencies. The master Eq. (3) is numerically solved in the subspace $\forall \in \{\forall_{\rm full},\ |g_{\rm L}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{c_1}|00\rangle_{fib}|00\rangle_{c_2},\ |g_{\rm R}\rangle_{\rm A}|g_0\rangle_{\rm B}|00\rangle_{c_1}|00\rangle_{\rm fib}|00\rangle_{c_2}\}$. In Fig. 3(a), the fidelity of the qutrit–qutrit maximal entanglement is plotted versus the dimensionless parameters gt and κ/g ($\kappa = \beta = \gamma$ is set). While in Fig. 3(b), the fidelity (at $T_0 = \frac{3.51}{g}$) is plotted versus the dimensional parameters κ/g and γ/g ($\beta = 0.01g$ is set). In the calculations, we still set $g_{\rm A,L} = g_{\rm A,R} \equiv g$, $g_{\rm B,L} = g_{\rm B,R} \equiv \sqrt{2}g$, $\Omega_x = 1.1g$, $\phi_{\rm A} = \phi_{\rm B}$, and $v_k \equiv 1.56g$. From Fig. 3(a), we note that the fidelity is almost unaffected by the three decay rates κ, β and γ when $\kappa = \beta = \gamma \le 10^{-3}g$, and is 0.986 when $\kappa = \beta = \gamma = 10^{-2}g$, larger than the one (<0.87) obtained in Ref. [19]. We note that, for the previous scheme through the adiabatic passage,[18] the decay rate $\kappa \equiv 10^{-2}g$ alone degraded the fidelity down to $F = 0.95$. The great improvement is of course due to the reduction in the interaction time. Apparently, the fidelity decreases rapidly when the three decay rates κ, β and γ become larger; it is about 0.875 when $\kappa = \beta = \gamma = 10^{-1}g$, and almost is spoiled when $\kappa = \beta = \gamma = g$. For the available parameters $(g,\kappa,\gamma)/2\pi = (12,\ 1.5,\ 1.5)$ MHz, the condition with $\beta = 0.01g$ might be enough to estimate the fiber's loss.[30] In such a case, the operation time is 47 ns, and the fidelity is 0.8686.

From Fig. 3(b), it can be seen that the decay rates $\kappa \equiv 10^{-1}g$, $\beta \equiv 10^{-1}g$, and $\gamma \equiv 10^{-1}g$ alone lead to the fidelity larger than 0.9766, 0.9788, and 0.9155, respectively. Thus the influences of the dissipation due to the photon leakage from the cavities and fiber is slighter than that due to the atomic spontaneous emission. Note that these consequences are superior to the previous ones via the virtual excitation processes in Ref. [20].

In summary, we have proposed a resonant scheme, different from all the previous ones (i.e., via adiabatic passage or dispersive interaction), for the deterministic generation of qutrit–qutrit entanglement for a pair of atoms held in separate cavities connected by an optical fiber or optical resonator. In the scheme, the fast operation for the qutrit–qutrit entanglement offsets the deficiency due to strong excitations in the cavities, fiber and atoms, making the effects of dissipation superior to those of the virtual scheme. In this aspect, the proposed resonant strategy is thus very important for the topic of complicated quantum control where the reduction in the operation time is one of the main purposes. In addition, the scheme is very favorable as it proves to be rather robust against the possible errors in system parameters. The scheme could find potential applications in multidimensional quantum alphabets for distributed quantum information processing.

References

[1] Einstein A, Podolsky B and Rosen N 1935 *Phys. Rev.* **47** 777
[2] Bell J S 1965 *Physics* (Long Island City N. Y.) **1** 195
[3] Greenberger D M, Horne M, Shimony A and Zeilinger A 1990 *Am. J. Phys.* **58** 1131
[4] Horodecki R, Horodecki P, Horodecki M and Horodecki K 2009 *Rev. Mod. Phys.* **81** 865
[5] Dür W, Vidal G and Cirac J I 2000 *Phys. Rev.* A **62** 062314
[6] Kaszlikowski D et al 2000 *Phys. Rev. Lett.* **85** 4418
Collins D et al 2002 *Phys. Rev. Lett.* **88** 040404
[7] Bechmann-Pasquinucci H and Tittel W 2000 *Phys. Rev.* A **61** 062308
Bourennane M et al 2001 *Phys. Rev.* A **64** 012306
Walborn S P et al 2006 *Phys. Rev. Lett.* **96** 090501
[8] Dada A C et al 2011 *Nat. Phys.* **7** 677
[9] Zou X B, Pahlke K and Mathis W 2003 *Phys. Rev.* A **67** 044301
[10] Zheng S B 2003 *Phys. Rev.* A **68** 035801
[11] Lin X M et al 2005 *Chin. Phys. Lett.* **22** 1318
[12] Zheng S B 2007 *Phys. Lett.* A **370** 110
[13] Yang Z B, Wu H Z and Zheng S B 2010 *Chin. Phys.* B **19** 094205
[14] Chen L B et al 2011 *Opt. Commun.* **284** 5020
[15] Li W A and Huang G Y 2011 *Phys. Rev.* A **83** 022322
[16] DiVincenzo D P 2000 *Fortschr. Phys.* **48** 771
[17] Kimble H J 2008 *Nature* **453** 1023
[18] Ye S Y, Zhong Z R and Zheng S B 2008 *Phys. Rev.* A **77** 014303
[19] Lü X Y et al 2008 *Phys. Rev.* A **78** 032305
[20] Yang Z B et al 2010 *J. Phys.* B **43** 085506
[21] Li W A 2011 *Opt. Commun.* **284** 2245
[22] Pellizzari T 1997 *Phys. Rev. Lett.* **79** 5242
[23] Serafini A, Mancini S and Bose S 2006 *Phys. Rev. Lett.* **96** 010503
[24] Yin Z Q and Li F L 2007 *Phys. Rev.* A **75** 012324
[25] Wu Y 1996 *Phys. Rev.* A **54** 1586
[26] Yang X, Wu Y and Li Y 1997 *Phys. Rev.* A **55** 4545
[27] Wu Y and Yang X 2005 *Phys. Rev.* A **71** 053806
[28] Wilk T, Webster S C, Kuhn A and Rempe G 2007 *Science* **317** 488
[29] Yang Z B et al 2009 *Phys. Rev.* A **80** 012305
[30] Gordon K J et al 2004 *IEEE J. Quantum Electron.* **40** 900