Generation of entanglement in the atom–cavity–fibre system via adiabatic passage*

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A scheme, based on the system composed of three atoms separately trapped in three cavities coupled by optical fibres, for entangling two distant atoms via the adiabatic passage is proposed. It is found that the multi-particle W entangled state can also be generated. Moreover, the quantum information sharing can be implemented using this system. These results may be helpful for the implementation of quantum network and useful in quantum cryptography. This scheme is also convenient for operating since only the laser fields applied to the atoms need to be adjusted to accomplish the processes.

Keywords: entanglement generation, quantum information splitting, atom–cavity–fibre system
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1. Introduction

Entanglement between separated subsystems is a crucial ingredient in many quantum information processes, such as quantum teleportation, quantum remote control, distributed quantum computation and so on.[1−7] Therefore, distributing entanglement among different subsystems is one of the rewarding tasks in quantum information. Several schemes, some are based on the detection of leaking photons, some on the cavities driven by the entangled light, some on the direct linking of the cavities for entangling distant atoms, have been proposed[8−11] in recent years.

Here, we only concentrate on the case of entangling distant atoms separately trapped in cavities coupled by the optical fibre. In Ref. [11], a scheme based on performing an adiabatic passage has been proposed, which allows for the reliable transfer of quantum information between two Λ-type atoms separately trapped in two distant cavities coupled by an optical fibre. On the other hand, it is found that the quantum swap and controlled-phase gates can be achieved reliably between two two-level atoms separately trapped in the same system.[12] Inspired by these reports, many quantum information processes, based on this model, have been accomplished. In Ref. [13], the authors have shown that the quantum state transfer and highly reliable quantum swapping, entangling and controlled-Z gates can be deterministically realised between two distant cavities when many atoms resonantly and collectively interact with the local cavity fields without direct interaction between the atoms. In Ref. [14], the authors have shown that an extremely entangled state of two distant atoms can be deterministically generated by both photon emission of the Λ-type atom and photon absorption of the V-type atom. The schemes for entangling distant atoms via adiabatic passage have also been proposed.[15,16] Recently, the schemes based on the same system for the generation of three-dimensional entanglement for two separate atoms have been proposed.[17,18] All these schemes have investigated the systems of atoms separately trapped in two optical cavities coupled by an optical fibre.

In this paper, we consider the system of three atoms separately trapped in three cavities coupled by two optical fibres which can be seen in Fig. 1. Atoms A, B and C with special level structure (see Fig. 1) are trapped in cavities (i), (ii) and (iii), respectively. Entanglement can be achieved between atoms A and C and the information encoded in atom B can be split into two parts encoded in atoms A and C via the adiabatic passage. This scheme is based on performing an adiabatic passage along dark states. Therefore, all the atoms are always in ground states, the influence of atomic spontaneous decay on the fidelity of realising entangled states can be suppressed effectively. It is convenient to operate since only the laser fields ap-

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plied to the atoms need to be adjusted to accomplish the processes.

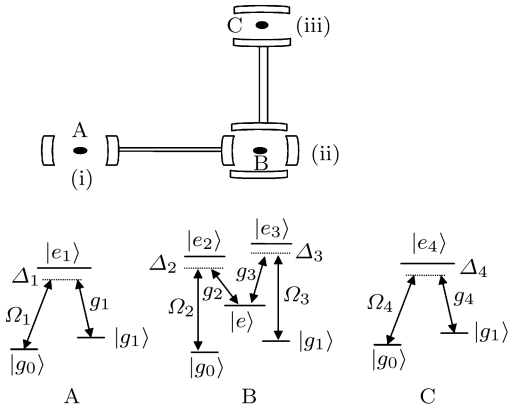


Fig. 1. Experimental setup and the atomic level configuration.

Our paper is organized as follows. In Section 2, the model is introduced. In Section 3, the generation of two-atom maximally entangled state and the multi-particle W entangled state is investigated. In Section 4, the quantum information sharing is investigated. The discussion and conclusions are presented in Section 5.

2. Model

First, we introduce the atom–cavity–fibre system. As shown in Fig. 1, one Λ-type atom A is trapped in the single-mode cavity (i), one five-level atom B is trapped in the double-mode cavity (ii), and another one Λ-type atom C is trapped in the single-mode cavity (iii). The three cavities are connected by two optical fibres. The involved atomic levels and transitions are also shown in Fig. 1. In cavities (i) and (iii), the atom transitions $|g_0\rangle_{\rm A} \leftrightarrow |e_1\rangle_{\rm A}$ and $|g_0\rangle_{\rm C} \leftrightarrow |e_4\rangle_{\rm C}$ are driven by the classical fields with the Rabi frequencies Ω_1 and Ω_4, respectively; the cavity modes a_1 and a_4 drive the atom transitions $|g_1\rangle_{\rm A} \leftrightarrow |e_1\rangle_{\rm A}$ and $|g_1\rangle_{\rm C} \leftrightarrow |e_4\rangle_{\rm C}$ with the coupling constants g_1 and g_4 respectively. In cavity (ii), the atom transitions $|g_0\rangle_{\rm B} \leftrightarrow |e_2\rangle_{\rm B}$ and $|g_1\rangle_{\rm B} \leftrightarrow |e_3\rangle_{\rm B}$ are driven by classical field with Rabi frequencies Ω_2 and Ω_3 respectively; the cavity modes a_2 and a_3 respectively drive the atom transitions $|e\rangle_{\rm B} \leftrightarrow |e_2\rangle_{\rm B}$ and $|e\rangle_{\rm B} \leftrightarrow |e_3\rangle_{\rm B}$. The Δ_i $(i = 1, 2, 3, 4)$ is the detuning of the ith driven classical fields and it is the same with that of the ith coupling quantum fields.

Under the rotating wave approximation and in the interaction picture, the Hamiltonian of the atom–cavity can be written as ($\hbar = 1$)

$$\begin{aligned} H_{\rm I}^{\rm ac} =\ & \Delta_1 |e_1\rangle_{\rm A}\langle e_1| + \Delta_2 |e_2\rangle_{\rm B}\langle e_2| + \Delta_3 |e_3\rangle_{\rm B}\langle e_3| \\ & +\Delta_4 |e_4\rangle_{\rm C}\langle e_4| \\ & +g_1(a_1 |e_1\rangle_{\rm A}\langle g_1| + a_1^+ |g_1\rangle_{\rm A}\langle e_1|) \\ & +\Omega_1(|e_1\rangle_{\rm A}\langle g_0| + |g_0\rangle_{\rm A}\langle e_1|) \\ & +g_2(a_2 |e_2\rangle_{\rm B}\langle e| + a_2^+ |e\rangle_{\rm B}\langle e_2|) \\ & +\Omega_2(|e_2\rangle_{\rm B}\langle g_0| + |g_0\rangle_{\rm B}\langle e_2|) \\ & +g_3(a_3 |e_3\rangle_{\rm B}\langle e| + a_3^+ |e\rangle_{\rm B}\langle e_3|) \\ & +\Omega_3(|e_3\rangle_{\rm B}\langle g_1| + |g_1\rangle_{\rm B}\langle e_3|) \\ & +g_4(a_4 |e_4\rangle_{\rm C}\langle g_1| + a_4^+ |g_1\rangle_{\rm C}\langle e_4|) \\ & +\Omega_4(|e_4\rangle_{\rm C}\langle g_0| + |g_0\rangle_{\rm C}\langle e_4|), \end{aligned} \tag{1}$$

where a_i and a_i^+ $(i = 1, 2, 3, 4)$ are the annihilation and creation operators of the ith cavity mode.

In the large detuning regime, i.e. $(\Omega_i/\Delta_i, g_i/\Delta_i) \ll 1$ $(i = 1, 2, 3, 4)$, the excited states of the atoms are only virtually excited in the process of atom-field interaction. Therefore, the excited states can be adiabatically eliminated[18−20] and the effective interaction Hamiltonian can be written as

$$\begin{aligned} H_{\rm eff}^{\rm ac} =\ & g_1'(a_1 |g_0\rangle_{\rm A}\langle g_1| + a_1^+ |g_1\rangle_{\rm A}\langle g_0|) \\ & +g_2'(a_2 |g_0\rangle_{\rm B}\langle e| + a_2^+ |e\rangle_{\rm B}\langle g_0|) \\ & +g_3'(a_3 |g_1\rangle_{\rm B}\langle e| + a_3^+ |e\rangle_{\rm B}\langle g_1|) \\ & +g_4'(a_4 |g_0\rangle_{\rm C}\langle g_1| + a_4^+ |g_1\rangle_{\rm C}\langle g_0|), \end{aligned} \tag{2}$$

where $g_i' = g_i\Omega_i/\Delta_i$ $(i = 1, 2, 3, 4)$. In the above equation, we have assumed that the stark shifts are corrected by re-tuning the laser frequencies.[21−23]

On the other hand, in the short fibre limit $(2l\bar{\nu})/(2\pi c) \ll 1$, where l is the length of the fibre and $\bar{\nu}$ is the decay rate of the cavity field into a continuum of fibre modes, the interaction Hamiltonian of cavity–fibre can be written as[12,13,24]

$$\begin{aligned} H_{\rm I}^{\rm cf} =\ & \nu_1[b_1(a_1^+ + a_2^+) + b_1^+(a_1 + a_2)] \\ & +\nu_2[b_2(a_3^+ + a_4^+) + b_2^+(a_3 + a_4)]. \end{aligned} \tag{3}$$

In the interaction picture, the total Hamiltonian of the atom–cavity–fibre system is given by

$$\begin{aligned} H_{\rm I} =\ & H_{\rm eff}^{\rm ac} + H_{\rm I}^{\rm cf} \\ =\ & g_1'(a_1 |g_0\rangle_{\rm A}\langle g_1| + a_1^+ |g_1\rangle_{\rm A}\langle g_0|) \\ & +g_2'(a_2 |g_0\rangle_{\rm B}\langle e| + a_2^+ |e\rangle_{\rm B}\langle g_0|) \\ & +g_3'(a_3 |g_1\rangle_{\rm B}\langle e| + a_3^+ |e\rangle_{\rm B}\langle g_1|) \\ & +g_4'(a_4 |g_0\rangle_{\rm C}\langle g_1| + a_4^+ |g_1\rangle_{\rm C}\langle g_0|) \\ & +\nu_1[b_1(a_1^+ + a_2^+) + b_1^+(a_1 + a_2)] \\ & +\nu_2[b_2(a_3^+ + a_4^+) + b_2^+(a_3 + a_4)]. \end{aligned} \tag{4}$$

3. Generation of entangled states

In this section, we show that a maximally entangled state of the atoms A and C can be deterministically generated in an ideal situation via adiabatic passage. Also, the scheme can be generalised to the generation of the multi-particle W entangled state.

It is easy to verify that the following states

$$|D_0\rangle = |g_1eg_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\,, \tag{5}$$

$$\begin{aligned}|D_1\rangle = A_1\big(&\nu_1 g_2'\,|g_0eg_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\\ &-g_1'g_2'\,|g_1eg_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|10\rangle_{\rm f}\\ &+\nu_1 g_1'\,|g_1g_0g_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\big),\end{aligned} \tag{6}$$

$$\begin{aligned}|D_2\rangle = A_2\big(&\nu_2 g_3'\,|g_1eg_0\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\\ &-g_3'g_4'\,|g_1eg_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|01\rangle_{\rm f}\\ &+\nu_2 g_4'\,|g_1g_1g_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\big)\end{aligned} \tag{7}$$

are eigenstates of the Hamiltonian described by Eq. (4) with zero eigenvalue. A_1 and A_2 are the normalisation factors. The symbol $|0000\rangle_{\rm c}$ represents the vacuum states of the cavity modes a_1, a_2, a_3 and a_4; and $|00\rangle_{\rm f}$ represents the vacuum states of the optical fibre modes $b_1$and b_2, while $|10\rangle_{\rm f}$ denotes the mode b_1 in the one photon state and b_2 in the vacuum state. The energy gap ΔE between the dark states $|D_1\rangle$, $|D_2\rangle$ and their closest bright state is g. The adiabatic transferring time should be larger than $1/g$.[25]

Initially, suppose $g_1' \gg g_2'$ and $g_4' \gg g_3'$. Under this condition, we have $|D_1\rangle \sim |g_1g_0g_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}$, $|D_2\rangle \sim |g_1g_1g_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}$. The initial state of the system is prepared in the state of

$$\begin{aligned}&|\psi_0\rangle\\ &= \frac{1}{\sqrt{2}}\,|g_1\rangle_{\rm A}\left(|g_0\rangle_{\rm B}+|g_1\rangle_{\rm B}\right)|g_1\rangle_{\rm C}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\,.\end{aligned} \tag{8}$$

We slowly increase g_2', g_3' by increasing Ω_2, Ω_3 and decrease g_1', g_4' by decreasing Ω_1, Ω_4 until $g_1' \ll g_2'$ and $g_4' \ll g_3'$ provided that the condition ν_1, $\nu_2 \gg g_1'$, g_2', g_3', g_4' is fulfilled all the time. The state $|g_1g_0g_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\left(|g_1g_1g_1\rangle_{\rm ABC}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\right)$ is adiabatically transferred into the state $|g_0g_1\rangle_{\rm AC}\,|e\rangle_{\rm B}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\left(|g_1g_0\rangle_{\rm AC}\,|e\rangle_{\rm B}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\right)$ along the dark state $|D_1\rangle\left(|D_2\rangle\right)$. The final state can be given by

$$\frac{1}{\sqrt{2}}(|g_0g_1\rangle_{\rm AC}+|g_1g_0\rangle_{\rm AC})\,|e\rangle_{\rm B}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}\,, \tag{9}$$

which is the maximally entangled state of atoms A and C.

From Eqs. (5)–(7), it can be noted that the cavity modes are unpopulated during the whole operation process. Therefore, the loss of the cavity photon can be ignored. Furthermore, the spontaneous emission of the excited state can be omitted as an approximation, because the entanglement comes out from the dark states. For simplicity, set $\Delta_i = \Delta$, $g_i = g(i = 1,2,3,4)$, $\Omega_1 = \Omega_4 = \Omega$, $\Omega_2 = \Omega_3 = \Omega'$ and $\nu_1 = \nu_2$. Suppose the conditions $(\Omega/\Delta, \Omega'/\Delta, g/\Delta) \ll 1$ are fulfilled throughout the whole procedure. And assume that $\nu \gg g, g'$, which means that the transmission time of photon through the fibre becomes much shorter than the interaction time of atoms and cavity modes, so the loss of fibre photon can be almost ignored. When $\nu_1 = \nu_2 = \nu = 100g$, $g_1' = g_4' = g$ and $g_2' = g_3' = g'$, the fidelity of the state can reach 0.995 for $g' = 10g$. And the fidelity of the state can reach 0.99 for $\nu = 50g$ and $g' = 7g$.

Furthermore, the multi-particle W state can be deterministically generated in an ideal situation. As shown in Fig. 1, suppose that N_1 Λ-type atoms are trapped in the single-mode cavity (i) and N_2 Λ-type atoms are trapped in the single-mode cavity (iii). The atoms trapped in the same cavity 'see' the same field, while the spatial separation between each two of them is big enough to omit the atomic dipole–dipole interaction. In the short fibre limit and with the adiabatic approximation, the total interaction Hamiltonian of the atom–cavity–fibre system can be written as[13,16]

$$\begin{aligned}H_{\rm I} = {}& H_{\rm I}^{\rm cf} + H_{\rm eff}^{\rm ac}\\ &+g_1'\left(a_1\left(\sum_{i=1}^{N_1}|g_0\rangle_i\langle g_1|\right)+a_1^+\left(\sum_{i=1}^{N_1}|g_1\rangle_i\langle g_0|\right)\right)\\ &+g_2'(a_2\,|g_0\rangle_{\rm B}\langle e| + a_2^+\,|e\rangle_{\rm B}\langle g_0|)\\ &+g_3'(a_3\,|g_1\rangle_{\rm B}\langle e| + a_3^+\,|e\rangle_{\rm B}\langle g_1|)\\ &+g_4'\left(a_4\left(\sum_{i=1}^{N_2}|g_0\rangle_i\langle g_1|\right)+a_4^+\left(\sum_{i=1}^{N_2}|g_1\rangle_i\langle g_0|\right)\right)\\ &+\nu_1[b_1(a_1^+ + a_2^+) + b_1^+(a_1+a_2)]\\ &+\nu_2[b_2(a_3^+ + a_4^+) + b_2^+(a_3+a_4)].\end{aligned} \tag{10}$$

Suppose

$$\begin{aligned}|\varphi_0\rangle_{\rm A} &= |g_1g_1g_1\cdots\rangle_{1,2\cdots N_1}\,,\\ |\varphi_0\rangle_{\rm C} &= |g_1g_1g_1\cdots\rangle_{1,2\cdots N_2}\,,\\ |\varphi_1\rangle_{\rm A} &= |\{g_0,1\}\{g_1,(N_1-1)\}\rangle_{1,2\cdots N_1}\,,\\ |\varphi_1\rangle_{\rm C} &= |\{g_0,1\}\{g_1,(N_2-1)\}\rangle_{1,2\cdots N_2}\,;\end{aligned} \tag{11}$$

$|\{g_0,1\}\{g_1,(N_1-1)\}\rangle_{1,2\cdots N_1}$denotes the symmetric and normalised state of N_1 atoms where one of them is in the state $|g_0\rangle$ and the rest (N_1-1) of them are in the state $|g_1\rangle$. Initially, the system is in the state

$$|\psi_0\rangle = \frac{1}{\sqrt{N_1+N_2}}|\varphi_0\rangle_{\rm A}(\sqrt{N_1}\,|g_0\rangle_{\rm B} + \sqrt{N_2}\,|g_1\rangle_{\rm B})\,|\varphi_0\rangle_{\rm C}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}. \quad (12)$$

And the conditions $g_1' \gg g_2'$ and $g_4' \gg g_3'$ are fulfilled. Under the condition that ν_1, $\nu_2 \gg g_1'$, g_2', g_3', g_4', we adiabatically increase g_2', g_3' by increasing Ω_2, Ω_3; and decrease g_1', g_4' by decreasing Ω_1, Ω_4 until $g_1' \ll g_2'$ and $g_4' \ll g_3'$. Finally, the initial state adiabatically evolves into the following state:

$$\frac{1}{\sqrt{N_1+N_2}}\big(\sqrt{N_1}\,|\varphi_1\rangle_{\rm A}\,|\varphi_0\rangle_{\rm C} + \sqrt{N_2}\,|\varphi_0\rangle_{\rm A}\,|\varphi_1\rangle_{\rm C}\big)\,|e\rangle_{\rm B}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}. \quad (13)$$

The N_1 atoms in cavity (i) and the N_2 atoms in cavity (iii) are in the (N_1+N_2)- qubit W state

$$|\varphi\rangle_{\rm AC} = |\{g_0,1\}\{g_1,(N_1+N_2-1)\}\rangle_{1,2\cdots(N_1+N_2)}. \quad (14)$$

The entanglement can be generated via the adiabatic passage only by adjusting the laser fields. It is convenient to operate in experiment and the distance between atoms A and C to be entangled is increased, compared with the previous schemes.[14−16] The scheme can be generalised into the case of multiparticle state. This system can be considered as an ingredient of the quantum network.[7]

4. Quantum information sharing

In this section, we investigate the quantum information sharing[26−28] which is achieved by splitting the original information based on our model. Assume that Alice and Charlie possess respectively the atoms A and C, and Bob possess a qubit encode in atom B, which is in an unknown state,

$$|\phi\rangle_{\rm B} = \alpha\,|g_0\rangle_{\rm B} + \beta\,|g_1\rangle_{\rm B}, (|\alpha|^2 + |\beta|^2 = 1). \quad (15)$$

Then the initial state of the system is

$$|\psi_0\rangle = |g_1\rangle_{\rm A}(\alpha\,|g_0\rangle_{\rm B} + \beta\,|g_1\rangle_{\rm B})\,|g_1\rangle_{\rm C}\,|0000\rangle_{\rm c}\,|00\rangle_{\rm f}. \quad (16)$$

With the same operations in Section 3, finally the atoms A and C are in the state

$$\alpha\,|g_0g_1\rangle_{\rm AC} + \beta\,|g_1g_0\rangle_{\rm AC}, (|\alpha|^2 + |\beta|^2 = 1). \quad (17)$$

Neither Alice nor Charlie can recover the original qubit only by local operations on their own atom. In order to reconstruct the original qubit the two particles should be brought together or through measurement and classical communication. For example, if Alice and Charlie agree to let Alice possess the final qubit, thus Charlie measures his atom with the basis $\{(|g_0\rangle_{\rm C}+|g_1\rangle_{\rm C})/\sqrt{2}, (|g_0\rangle_{\rm C}-|g_1\rangle_{\rm C})/\sqrt{2}\}$ and sends the measurement outcome to Alice through the classical communication. Then Alice performs the operation I or σ_z on her qubit according to Bob's measurement outcome to reconstruct the original qubit. This is very useful in maintaining information security.

With the result achieved in the last section, this scheme can be generalised straightforwardly to the case of splitting the quantum information into many shares.

5. Discussion and conclusions

In conclusion, we have proposed a scheme to generate the entanglement between two remote atoms trapped separately in two cavities coupled to the third one by optical fibres. The scheme can be generalised to the case of many particles. These results are helpful for implementing the quantum network and this system can be used to split the quantum information into two or more shares to achieve the information sharing which is useful in quantum cryptograph.

This scheme has the following merits. By taking advantage of the adiabatic passage, it is insensitive to the small fluctuation of some of the parameters.[12,29] The effect caused by the photon loss out of the cavities can be efficiently suppressed, since the cavity modes are never excited throughout the whole procedure. The influence of atomic spontaneous decay can be suppressed effectively because the atoms are always in the ground states. Assuming ν_1, $\nu_2 \gg g_1'$, g_2', g_3', g_4' means that the transmission time of photon through the fibre becomes much shorter than the interaction time of the atoms with the cavity fields. Therefore, the loss of the fibre photon has little effect on the evolution of the system. And this scheme is easy to operate since only the Rabi frequencies need to be adjusted.

Finally, we give some brief discussion of the experimental feasibility. The two Λ-type atoms and the five-level atom can be realised by choosing the hyperfine-split levels for the D lines of alkali-metal atoms such as ^{87}Rb atom.[16,18,30] The single-mode

cavity and the double-mode cavity can be realised in experiment.[31,32] A nearly perfect fibre-cavity coupling (with an efficiency larger than 99.9%) can be realised by fibre-taper coupling to high-Q silica microspheres.[33] The strong coupling between the cavity and the fibre i.e., ν_1, $\nu_2 \gg g_1'$, g_2', g_3', g_4', such as $\nu = 100g$, $\nu = 50g$, can be obtained.[33−35] Under this condition, the fidelity of the system prepared by using our scheme can reach 0.99. With the achieved progress in experiment, we believe that the entanglement of atoms with high fidelity and the sharing of quantum information can be realised by our scheme.

References

[1] Bennett C H, Brassard G, Crépeau C, Jozsa R, Peres A and Wootters W K 1993 *Phys. Rev. Lett.* **70** 1895

[2] Bennett C H, Di Vincenzo D P, Shor P W and Smolin J A 2001 *Phys. Rev. Lett.* **87** 077902

[3] Wang A M 2007 *Phys. Rev.* A **75** 062323

[4] Chen L B, Jin R B and Lu H 2009 *Chin. Phys.* B **18** 30

[5] Murao M, Jonathan D, Plenio M B and Vedral V 1999 *Phys. Rev.* A **59** 156

[6] Li Y L, Feng J, Meng X G and Liang B L 2007 *Acta Phys. Sin.* **56** 5591 (in Chinese)

[7] Kimble H J 2008 *Nature* **453** 1023

[8] Duan L M and Kimble H J 2003 *Phys. Rev. Lett.* **90** 253601

[9] Kraus B and Cirac J I 2004 *Phys. Rev. Lett.* **92** 013602

[10] Busch J, Kyoseva E S, Trupke M and Beige A 2008 *Phys. Rev.* A **78** 040301(R)

[11] Pellizzari T 1997 *Phys. Rev. Lett.* **79** 5242

[12] Sersfini A, Mancini S and Bose S 2006 *Phys. Rev. Lett.* **96** 010503

[13] Yin Z Q and Li F L 2007 *Phys. Rev.* A **75** 012324

[14] Peng P and Li F L 2007 *Phys. Rev.* A **75** 062320

[15] Chen L B, Ye M Y, Lin G W, Du Q H and Lin X M 2007 *Phys. Rev.* A **76** 062304

[16] Song J, Xia Y and Song H S 2007 *J. Phys.* B: *At. Mod. Opt. Phys.* **40** 4503

[17] Ye S Y, Zhong Z R and Zheng S B 2008 *Phys. Rev.* A **77** 014303

[18] Lü X Y, Liu J B, Ding C L and Li J H 2008 *Phys. Rev.* A **78** 032305

[19] Lougovski P, Solano E and Walther H 2005 *Phys. Rev.* A **71** 013811

[20] Klimov A B 2000 *Phys. Rev.* A **61** 063802

[21] Santos M F, Solano E and de Matos Filho R L 2001 *Phys. Rev. Lett.* **87** 093601

[22] Biswas A and Agarwal G S 2004 *Phys. Rev.* A **69** 062306

[23] Solano E 2005 *Phys. Rev.* A **71** 013813

[24] van Enk S J, Kimble H J, Cirac J I and Zoller P 1999 *Phys. Rev.* A **59** 2659

[25] Duan L M, Cirac J I and Zoller P 2001 *Science* **292** 1695

[26] Cleve R, Gottesman D and Lo H K 1999 *Phys. Rev. Lett.* **83** 648

[27] Hillery M, Bužek V and Berthiaume A 1999 *Phys. Rev.* A **59** 1829

[28] Zheng S B 2006 *Phys. Rev.* A **74** 054303

[29] Zheng S B 2005 *Phys. Rev. Lett.* **95** 080502

[30] Wu Y and Yang X 2004 *Phys. Rev.* A **70** 053818

[31] Cho J, Angelakis D G and Bose S 2008 *Phys. Rev. Lett.* **101** 246809

[32] Ji A C, Xie X C and Liu W M 2007 *Phys. Rev. Lett.* **99** 183602

[33] Spillane S M, Kippenberg T J, Painter O J and Vahala K J 2003 *Phys. Rev. Lett.* **91** 043902

[34] Barclay P B, Srinivasan K and Painter O 2006 *Appl. Phys. Lett.* **89** 131108

[35] Trupke M, Hinds E A, Eriksson S and Curtis E A 2005 *Appl. Phys. Lett.* **87** 211106