Generation of two-mode entanglement between separated cavities

Pengbo Li,[1] Ying Gu,[1,*] Qihuang Gong,[1] and Guangcan Guo[1,2]

[1]*State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University, Beijing 100871, China*
[2]*Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China*
**Corresponding author: ygu@pku.edu.cn*

Received June 20, 2008; revised October 30, 2008; accepted November 7, 2008; posted November 11, 2008 (Doc. ID 97491); published December 24, 2008

We propose a scheme for the generation of two-mode entangled states between two spatially separated cavities. It utilizes a two-level atom sequentially coupling to two high-Q cavities with strong classical driving fields. By suitably choosing the intensities and detunings of the fields and precisely controlling the dynamics, entangled coherent states and Bell states can be produced between the modes of the two cavities. These entangled states should have applications in quantum information processing. © 2008 Optical Society of America

OCIS codes: 270.0270, 270.5585.

1. INTRODUCTION

The preparation of quantum entangled states continues to attract great theoretical and experimental interest. These nonclassical states are utilized not only to test fundamental quantum mechanical principles such as Bell's inequalities [1], but they also play an important role in practical applications of quantum information processing [2] such as quantum computation [3,4], quantum teleportation [5], and quantum cryptography [6]. In quantum optics the generation of various nonclassical states, especially entangled states of electromagnetic fields, is a central topic [7]. In the context of cavity quantum electrodynamics (QED) [8–10], experimental realizations of the entanglement between two different modes sharing a single photon or between two polarized photons in a cavity have been reported [11,12]. In recent years, great effort has been put into preparation of the Schrödinger cat states [13–16], where the extreme cat states are reduced to mesoscopic quantum states with classical counterparts, i.e., coherent states. There are also several other proposals for producing entangled field states between separated cavities [17–21].

In this paper, we propose a scheme for generating two-mode entangled states between two separated cavities. A two-level Rydberg atom is sent sequentially into two spatially separated cavities, with a strong classical field driving it additionally in each cavity. We demonstrate that, by suitably choosing the intensities and detunings of the fields and precisely controlling the dynamics, different entangled states, such as entangled coherent states and Bell states, can be produced between the modes of the two cavities. Especially, this scheme can generate the entangled states $1/\sqrt{2}(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B)$. Up to our knowledge, this is the first proposal for generating these kinds of entangled states between spatially separated cavities. Different from previous proposals for generating entangled field states between distant cavities [17–21], in this proposal only one setup is utilized to produce several different entangled states. The target entangled states can be achieved only through tuning the experimental parameters and controlling the dynamics. Other advantages are that it needs only one Rydberg atom sent through two cavities and that initially the cavity field has only to be in the vacuum state. These entangled states of fields can have both fundamental applications in quantum mechanics and practical applications in quantum information processing. With presently available experimental setups in cavity QED, this protocol could be implemented.

2. GENERATING ENTANGLED COHERENT STATES AND BELL STATES

Consider two distant high-Q cavities and a two-level atom, as sketched in Fig. 1. The atom sequentially couples to the cavities A and B (with frequencies ν_A and ν_B). The ground state of the atom is labeled as $|g\rangle$, and the excited state as $|e\rangle$. In each cavity, the transition $|g\rangle \leftrightarrow |e\rangle$ (transition frequency ω_0) is coupled by the cavity mode with the coupling constants g_A and g_B, respectively. Furthermore, a strong classical field (frequency ω_L^A or ω_L^B) drives the same transition with a Rabi frequency $\Omega_A(\Omega_B)$ in each step. The associated Hamiltonian in each cavity under the dipole and rotating wave approximations is given by (let $\hbar = 1$)

$$H_j = \omega_0\sigma^\dagger\sigma + \nu_j\hat{a}_j^\dagger\hat{a}_j + \Omega_j(e^{-i\omega_L t}\sigma^\dagger + e^{i\omega_L t}\sigma) + g_j(\sigma^\dagger\hat{a}_j + \sigma\hat{a}_j^\dagger), \quad (j = A,B) \tag{1}$$

where $\sigma = |g\rangle\langle e|$ and $\sigma^\dagger = |e\rangle\langle g|$ are the atomic transition operators and $\hat{a}_j$ and $\hat{a}_j^\dagger$ are the annihilation and creation operators with respect to cavity j. To simplify the discussions, we consider first that g_A and g_B are constant in time. However, in Section 3 we will treat them as time-dependent parameters and perform numerical simula-

0740-3224/09/010189-5/$15.00

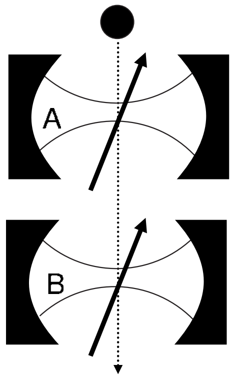

Fig. 1. Proposed experimental setup. A two-level atom sequentially couples to two distant cavities A and B, driven by a strong classical field.

tions to verify the analytical results.

The Hamiltonian of Eq. (1) can be changed to a reference frame rotating with the driving field frequency ω_L,

$$H_j^L = \Delta\sigma^\dagger\sigma + \delta_j\hat{a}_j^\dagger\hat{a}_j + \Omega_j(\sigma^\dagger + \sigma) + g_j(\sigma^\dagger\hat{a}_j + \sigma\hat{a}_j^\dagger), \quad (j = A,B) \tag{2}$$

with $\Delta=\omega_0-\omega_L$ and $\delta_j=\nu_j-\omega_L$. In the following we set $\Delta=0$ for simplicity. We now switch to a new atomic basis $|\pm\rangle=1/\sqrt{2}(|g\rangle\pm|e\rangle)$. In the interaction picture with respect to $H_0^j=\delta_j\hat{a}^\dagger\hat{a}_j+\Omega_j(\sigma^\dagger+\sigma)$, we obtain the following Hamiltonian:

$$H_j^I = \frac{g_j}{2}(|+\rangle\langle+|-|-\rangle\langle-|+e^{2i\Omega_j t}|+\rangle\langle-|-e^{-2i\Omega_j t}|-\rangle\langle+|)\hat{a}_j e^{-i\delta_j t} + \text{H.c.} \tag{3}$$

The Hamiltonian of Eq.(3) is the starting point in the following discussions, from which we show that several kinds of entangled states of the two distant cavities can be generated through different approximations. Though this scheme requires no complicated setups, entangled coherent states and Bell states can be generated only through tuning the experimental parameters and precisely controlling the dynamics.

Entangled coherent states—We first show how to produce the entangled coherent states between the two cavities. Assuming that $\Omega_A(\Omega_B)\gg\{g_A,\delta_A(g_B,\delta_B)\}$, this strong driving condition can allow one to realize a rotating-wave approximation and neglect the fast oscillating terms. Now H_j^I reduces to

$$\begin{aligned} H_j^I &= \frac{g_j}{2}(|+\rangle\langle+|-|-\rangle\langle-|)(\hat{a}_j e^{-i\delta_j t} + \hat{a}_j^\dagger e^{i\delta_j t}) \\ &= \frac{g_j}{2}(\sigma^\dagger + \sigma)(\hat{a}_j e^{-i\delta_j t} + \hat{a}_j^\dagger e^{i\delta_j t}). \end{aligned} \tag{4}$$

If we choose $\delta_j=0$, this Hamiltonian corresponds to the simultaneous realization of Jaynes–Cummings (JC) [22] and anti-Jaynes–Cummings (AJC) interaction in each cavity. The evolution operator for the system is given by

$$\begin{aligned} U_j(t) &= e^{-iH_j^I t} = e^{-ig_j t/2(\sigma^\dagger+\sigma)(\hat{a}_j+\hat{a}_j^\dagger)} \\ &= \hat{D}(\alpha_j)|+\rangle\langle+| + \hat{D}(-\alpha_j)|-\rangle\langle-|, \end{aligned} \tag{5}$$

with $\hat{D}(\alpha_j)=e^{\alpha_j\hat{a}_j^\dagger-\alpha_j^*\hat{a}_j}$, and $\alpha_j=-ig_jt/2$. Assume that at the time $t=0$ the system is prepared in the ground state $|g\rangle|0\rangle_A|0\rangle_B=1/\sqrt{2}(|+\rangle+|-\rangle)|0\rangle_A|0\rangle_B$, i.e., the atom stays in $|g\rangle$, and the two cavities are in the vacuum states. The atom enters cavity A and undergoes the dynamics of Eq. (5). The evolved state after a time t_A will be

$$\frac{1}{\sqrt{2}}(|+\rangle|\alpha\rangle_A + |-\rangle|-\alpha\rangle_A)|0\rangle_B, \tag{6}$$

where $\alpha=-ig_At_A/2$. This microscopic–mesoscopic entangled state is the so-called Schrödinger cat state. After an interaction time t_A in cavity A, the atom enters cavity B. It will also undergo the evolution according to Eq. (5). After a time t_B, the system consisting of the two cavities and the atom will become

$$\frac{1}{\sqrt{2}}(|+\rangle|\alpha\rangle_A|\beta\rangle_B + |-\rangle|-\alpha\rangle_A|-\beta\rangle_B), \tag{7}$$

with $\beta=-ig_Bt_B/2$. Expression (7) describes a tripartite entangled state involving one microscopic and two mesoscopic systems. If we measure the atomic state in the bare basis $\{|g\rangle,|e\rangle\}$, the entangled coherent states of the fields can be generated:

$$\mathcal{N}_{AB}^{\pm}(|\alpha\rangle_A|\beta\rangle_B \pm |-\alpha\rangle_A|-\beta\rangle_B), \tag{8}$$

where $\mathcal{N}_{AB}^{\pm}$ is the normalized factor. It is known that these states can act as an important tool in the field of quantum information such as quantum teleportation and quantum computing with coherent states [13–16]. Here, utilizing flying atoms, we propose to generate the entangled coherent states between two distant resonators.

Bell states—We then show that using the interaction described by Eq. (3) one can generate the Bell states [1] $1/\sqrt{2}(|0\rangle_A|1\rangle_B\pm|1\rangle_A|0\rangle_B)$ and $1/\sqrt{2}(|0\rangle_A|0\rangle_B\pm|1\rangle_A|1\rangle_B)$. If we choose $\delta_j=2\Omega_j$ and $|\delta_j|\gg g_j$, then we can bring the Hamiltonian (3) to the JC interaction in the $|\pm\rangle$ atomic dressed basis

$$H_j^{JC} = \frac{g_j}{2}(|+\rangle\langle-|\hat{a}_j + |-\rangle\langle+|\hat{a}_j^\dagger). \tag{9}$$

Assume that at $t=0$, the system stays in $|+\rangle|0\rangle_A|0\rangle_B$. Then after an interaction time $t_A=\pi/(2g_A)$ in cavity A, the system will evolve into

$$\frac{1}{\sqrt{2}}(|+\rangle|0\rangle_A - i|-\rangle|1\rangle_A)|0\rangle_B. \tag{10}$$

Subsequently, the atom enters cavity B and undergoes the dynamics of Eq. (9). Then the atom-field state will be

$$\frac{1}{\sqrt{2}}(\cos(g_Bt/2)|+\rangle|0\rangle_B - i\sin(g_Bt/2)|-\rangle|1\rangle_B)|0\rangle_A - \frac{i}{\sqrt{2}}|-\rangle \times|1\rangle_A|0\rangle_B. \quad (11)$$

If the interaction time $t_B=\pi/g_B$ or $3\pi/g_B$ is taken, the final states will be

$$\frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B \pm |1\rangle_A|0\rangle_B)|-\rangle, \quad (12)$$

where a common phase factor $-i$ or i has been discarded. Clearly, at this time the atomic state has been factorized out and the modes of two distant cavities end up in the Einstein–Podolsky–Rosen (EPR) pair states [23]:

$$\frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B \pm |1\rangle_A|0\rangle_B). \quad (13)$$

These are maximally entangled states of two qubits stored in the modes of two distant cavities.

Now we consider the case of generating the entangled states $1/\sqrt{2}(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B)$ between the two cavities. If we choose $\delta_A=2\Omega_A$ and $|\delta_A|\gg g_A$, then we can realize the JC interaction in cavity A, which is described by Eq. (9). However, in cavity B we need the AJC interaction, which requires the relations $\delta_B=-2\Omega_B$ and $|\delta_B|\gg g_B$ be chosen to neglect the fast oscillating terms. Then we can bring the Hamiltonian (3) to the AJC interaction in the $|\pm\rangle$ atomic dressed basis

$$H_B^{AJC} = \frac{g_B}{2}(|-\rangle\langle+|\hat{a}_B + |+\rangle\langle-|\hat{a}_B^\dagger). \quad (14)$$

The brief idea of producing the target entangled states is as follows. We send a Rydberg atom prepared in state $|+\rangle$ into cavity A. Then at $t=0$, the total system is in state $|+\rangle|0\rangle_A|0\rangle_B$. At the stage of the atom interacting with cavity A, the system is governed by the interaction of Eq. (9). Then after an interaction time $t_A=\pi/2g_A$ in cavity A, the atom-field state will be the same as Eq. (10). Subsequently, the atom enters cavity B and undergoes the dynamics of Eq. (14). Then the atom-field state will be

$$\frac{1}{\sqrt{2}}|-\rangle|0\rangle_A|0\rangle_B - \frac{i}{\sqrt{2}}(\cos(g_Bt/2)|-\rangle|0\rangle_B - i\sin(g_Bt/2)|+\rangle|1\rangle_B) \times|1\rangle_A. \quad (15)$$

If the interaction time $t_B=\pi/g_B$ or $3\pi/g_B$ is taken, the final states will be

$$\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B \mp |1\rangle_A|1\rangle_B)|+\rangle. \quad (16)$$

The atomic state has been factorized out, and the modes of two distant cavities end up in the following entangled states:

$$\frac{1}{\sqrt{2}}(|0\rangle_A|0\rangle_B \pm |1\rangle_A|1\rangle_B). \quad (17)$$

These states are also maximally entangled states. Together with states in expression (13), they form the well-known Bell states. Up to our knowledge, this is the first proposal for producing these Bell states of expression (17) between separated cavities. Hence, these states should have applications in quantum information processing, such as entanglement distribution, teleportation, distributed quantum computation and quantum communication [2]. In particular, since cavities are the promising quantum nodes for quantum information processing, the produced entanglement between distant cavities may provide some applications in quantum networks [24].

3. PRACTICAL CONSIDERATIONS

It is necessary to analyze the proposal requirements and discuss some practical issues associated with it. The decoherence in a cavity QED system comes from spontaneous emission of the atomic excited states and damping of the cavity fields [8–10]. To eliminate the effects of these decoherence processes on the generated entangled states, the preparation time should be much smaller than the decay time of the atomic excited states and the cavity modes, i.e., the conditions $T\kappa \ll 1$, $T\gamma \ll 1$ are required for producing the entangled states with high fidelities, where κ and γ represent the decay rates of the cavity mode and atomic excited states, respectively. Therefore, realizing this protocol for entangled field states requires that the atom and two cavity modes not decay during this process. One can control the interaction time of the Rydberg atom with the two cavities in the experiments and implement this proposal in the strong coupling regime to meet the requirements [9].

As the atom moves through the two cavities, it encounters the time-dependent atom-field coupling constants. To be more realistic, we consider a Gaussian profile for the atom-field interaction, $g_A(t)=g_Ae^{-(vt-vt_1)^2/w_A^2}$, $g_B(t)=g_Be^{-(vt-vt_2)^2/w_B^2}$, where v is velocity of the atom, and w_A and w_B are the waists of the cavity modes. In this case, when taking into account the temporal variation of the coupling constants, we can use an effective interaction time $T_i \simeq w_i/v$ [9] to consider the issue. However, we will integrate the time-dependent expressions to obtain the exact interaction time in the next paragraph. So the interaction time of the atom with each cavity could be precisely adjusted by controlling the motion of the atom. Typically, in experiments with a microwave cavity the interaction time is adjusted by sending the atom through the cavity at a well-controlled velocity [9]. Generating the Bell states requires that $T_Ag_A/T_Bg_B=1/2$. If the coupling strengths are the same, the interaction time in each cavity differs by a factor of $T_A/T_B=1/2$. One could first adjust the atomic velocity to satisfy the interaction time T_A and, in cavity 2, reduce the atomic velocity to satisfy the interaction time T_B [19]. Alternatively, one could consider equal interaction time and adjust the coupling strengths to $g_A/g_B=1/2$ through the cavity volume $g \propto 1/\sqrt{V}$, which can be implemented in the experiments with two different cavities.

In order to verify the model for generating Bell states, we numerically solve the Schrödinger equation with the effective Hamiltonian of Eq. (9) from the initial state $|+\rangle|0\rangle_A|0\rangle_B$. Figure 2(a) displays the time-dependent cou-

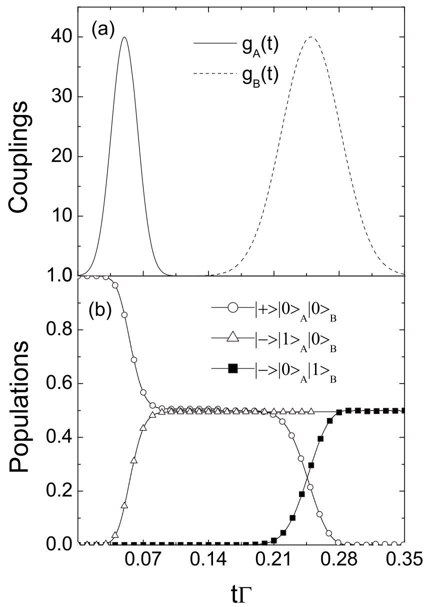

Fig. 2. (a) Time-dependent coupling strengths $g_A(t)$, $g_B(t)$. The parameters are $g_A \simeq g_B = 40\Gamma$, $w_A/v = 0.02\Gamma^{-1}$, $w_b/v = 0.045\Gamma^{-1}$, $t_1 = 0.05\Gamma^{-1}$, and $t_2 = 0.25\Gamma^{-1}$. (b) Coherent evolution of the system with the effective Hamiltonian [Eq. (9)] from the initial state $|+\rangle|0\rangle_A|0\rangle_B$.

pling strengths $g_A(t)$ and $g_B(t)$. Here the cavity modes are assumed to be a Gaussian profile, $g_A(t) = g_A e^{-(vt-vt_1)^2/w_A^2}$, $g_B(t) = g_B e^{-(vt-vt_2)^2/w_B^2}$. The parameters are taken as $g_A \simeq g_B = 40\Gamma, w_A/v = 0.02\Gamma^{-1}$, $w_b/v = 0.045\Gamma^{-1}$, $t_1 = 0.05\Gamma^{-1}$, and $t_2 = 0\Gamma^{-1}$. Γ^{-1} is a characteristic time, with the value $\Gamma \sim 10\kappa \simeq 2\pi$ KHz for microwave cavity QED [9]. The coupling strengths are also satisfied: $\int_0^{T_A} g_A(t)\mathrm{d}t = \pi/2$, $\int_{T_A+t_f}^{T_A+t_f+T_B} g_B(t)\mathrm{d}t = \pi$, where t_f is the free flight time between the cavities. Figure 2(b) shows the dynamics of the system with the time-dependent cavity couplings $g_A(t)$ and $g_B(t)$. One can see from Fig. 2(b) that, for $t = T_A$, the system is completely transferred to the state $1/\sqrt{2}(|+\rangle|0\rangle_A - i|-\rangle|1\rangle_A)|0\rangle_B$. At the end of the process the two cavities end up in the entangled state $1/\sqrt{2}(|0\rangle_A|1\rangle_B + |1\rangle_A|0\rangle_B)$.

We now discuss the effect of some imperfections in the experiments on the final states. For generating Bell states, the interaction time of the atom with each cavity must be precisely controlled. In the experiments, fluctuations of the parameters will induce some imperfections to the produced entangled states. To quantify the final states prepared in this protocol, we exploit the fidelity $F = \langle\psi_B|\rho_f|\psi_B\rangle$, where $|\psi_B\rangle$ refers to the ideal Bell states, and ρ_f is the final density matrix of the cavity modes. Here we give an example to estimate the fidelity for the state of expression (13) when taking into account the fluctuation of the interaction time. Assume that the interaction time T_a or T_B takes a deviation of δt from the ideal value owing to some experimental fluctuations such as the velocity fluctuation of the atom. Figure 3 plots the fidelity as a function of the parameter $\delta t/t$. One can see that under relatively small fluctuations of the interaction time, the fidelity is still very close to unity. When the fluctuation of the interaction time $\delta t/t$ is larger than 10%, the fidelity will reduce to 0.98.

Finally, we consider some experimental matters. For a potential experimental system and set of parameters in microwave resonators [9], the promising atomic candidate could be Rydberg atoms with much longer radiative time. Resonators stable beyond 100 ms have been reported recently [25]. The radiative lifetime for Rydberg atoms is about $T_a \sim 30$ ms [9]. We choose the single-photon dipole-coupling strength as $g_A \sim g_B = g/(2\pi) \sim 50$ kHz [9]. Then, for generating entangled coherent states, the preparation time is about $T \sim 0.06$ ms with averaged photon number $|\alpha|^2 = |\beta|^2 = 25$ in each cavity. In the case of producing Bell states, the preparation time is about $T \sim 0.02$ ms. Therefore, the time needed to complete the procedure is much shorter than the decay time of the atom and the cavities. These results are in line with the current experimental setups.

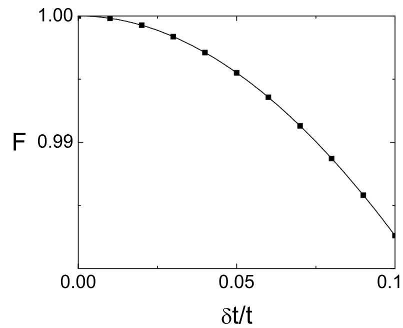

Fig. 3. Variation of the fidelity versus $\delta t/t$. Parameters are chosen as in Fig. 2.

4. CONCLUSION

In conclusion, we have proposed a scheme for the generation of two-mode entangled states between two separated cavities. It relies on a two-level atom sequentially coupling to two high-Q cavities with a strong classical driving field. We demonstrate that, by suitably choosing the intensities and detunings of the fields and precisely controlling the dynamics, entangled coherent states as well as Bell states can be produced between the two cavity modes. With presently available experimental setups in cavity QED, the realization of this proposal is feasible.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (NSFC) under grants 10674009, 10874004, 10521002, and 10434020 and by the National Key Basic Research Program No.2006CB921601. P. L. acknowledges useful discussions with Hongyan Li.

REFERENCES

1. J. S. Bell, "On the Einstein–Podolsky–Rosen paradox," Physics (Long Island City, N.Y.) **1**, 195–290 (1965).
2. M. A. Nielsen and I. L. Chuang, *Quantum Computation and Quantum Information* (Cambridge U. Press, 2000).
3. P. W. Shor, "Algorithms for quantum computation: discrete logarithms and factoring," in *Proceedings of the 35th Annual Symposium on Foundations of Computer Science* (IEEE, 1994), p. 116.
4. L. K. Grover, "Quantum mechanics helps in searching for a needle in a haystack," Phys. Rev. Lett. **79**, 325–328 (1997).
5. C. H. Bennett, G. Brassard, C. Crepeau, R. Jozsa, A. Peres, and W. K. Wootters, "Teleporting an unknown quantum

state via dual classical and Einstein–Podolsky–Rosen channels," Phys. Rev. Lett. **70**, 1895–1899 (1993).
6. A. K. Ekert, "Quantum cryptography based on Bell's theorem," Phys. Rev. Lett. **67**, 661–663 (1991).
7. M. O. Scully and M. S. Zubairy, *Quantum Optics* (Cambridge U. Press, 1997).
8. H. J. Kimble, "Strong interactions of single atoms and photons in cavity QED," Phys. Scr., T **76**, 127–137 (1998).
9. J. M. Raimond, M. Brune, and S. Haroche, "Manipulating quantum entanglement with atoms and photons in a cavity," Rev. Mod. Phys. **73**, 565–582 (2001).
10. H. Mabuchi and A. C. Doherty, "Cavity quantum electrodynamics: coherence in context," Science **298**, 1372–1377 (2002).
11. A. Rauschenbeutel, P. Bertet, S. Osnaghi, G. Nogues, M. Brune, J. M. Raimond, and S. Haroche, "Controlled entanglement of two field modes in a cavity quantum electrodynamics experiment," Phys. Rev. A **64**, 050301(R) (2001).
12. T. Wilk, S. C. Webster, A. Kuhn, and G. Rempe, "Single-atom single-photon quantum interface," Science **317**, 488–490 (2007).
13. M. Brune, E. Hagley, J. Dreyer, X. Maitre, A. Maali, C. Wunderlich, J. M. Raimond, and S. Haroche, "Observing the progressive decoherence of the meter in a quantum measurement," Phys. Rev. Lett. **77**, 4887–4890 (1996).
14. C. Monroe, D. M. Meekhof, B. E. King, and D. J. Wineland, "A Schrödinger cat superposition state of an atom," Science **272**, 1131–1136 (1996).
15. G. S. Agarwal and R. R. Puri, "Quantum theory of propagation of elliptically polarized light through a Kerr medium," Phys. Rev. A **40**, 5179–5186 (1989).
16. E. Solano, G. S. Agarwal, and H. Walther, "Strong-driving-assisted multipartite entanglement in cavity QED," Phys. Rev. Lett. **90**, 027903 (2003).
17. D. E. Browne and M. B. Plenio, "Robust generation of entanglement between two cavities mediated by short interactions with an atom," Phys. Rev. A **67**, 012325 (2003).
18. J. Larson and E. Andersson, "Cavity-state preparation using adiabatic transfer," Phys. Rev. A **71**, 053814 (2005).
19. R. G. Maraver, K. Eckert, R. Corbalan, and J. Mompart, "Cavity-quantum-electrodynamics entangled photon source based on two truncated Rabi oscillations," J. Opt. Soc. Am. B **24**, 257–265 (2007).
20. J. Shu, X. B. Zou, Y. F. Xiao, and G. C. Guo, "Generating four-mode multiphoton entangled states in cavity QED," Phys. Rev. A **74**, 044301 (2006).
21. P. B. Li, Y. Gu, Q. H. Gong, and G. C. Guo, "Effective generation of polarization-entangled photon pairs in a cavity-QED system," Phys. Lett. A **372**, 5959–5963 (2008).
22. E. T. Jaynes and F. W. Cummings, "Comparison of quantum and semiclassical radiation theories with application to the beam maser," Proc. IEEE **51**, 89–109 (1963).
23. A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?" Phys. Rev. **47**, 777–780 (1935).
24. H. J. Kimble, "The quantum internet," Nature (London) **453**, 1023–1030 (2008).
25. S. Kuhr, S. Gleyzes, C. Guerlin, J. Bernu, U. B. Hoff, S. Delglise, S. Osnaghi, M. Brune, J.-M. Raimondb, S. Haroche, E. Jacques, P. Bosland, and B. Visentin, "Ultrahigh finesse Fabry–Perot superconducting resonator," Appl. Phys. Lett. **90**, 164101 (2007).