doi:10.3788/gzxb20124111.1342

Entanglement Properties of Photon-added Two-mode Entangled Coherent States and Their Preparations via Cavity Quantum Electrodynamics

WANG Zhong-jie, LI Cong, ZHANG Xiao-dong

(*College of Physics and Electric Information, Anhui Normal University, Wuhu, Anhui* 241000, *China*)

Abstract: Entanglment properties of photon-added two-mode entangled coherent states are analyzed and analytical expression of the concurrence entanglement is obtained. The results show that the concurrence of the photon-added entangled coherent states is very sensitive to the superposition phase. Schemes for preparation of photon-added coherent states and photon-added two-mode entangled coherent states are also proposed. The preparation procession of the photon-added coherent states is that the photon-added coherent states are firstly tansformed into a superposition state of coherent state and vacuum state (the superposition coefficient is associated with amplitude of the coherent state), then by applying the interaction of atom inside high-Q cavity with a classical light, finally added coherent states of cavity field is prepared. Preparation of photon-added two-mode entangled coherent states of cavity fields is based on interaction of the flying atom with two cavity fields.

Key words: Photon-added coherent states; Photon-added entangled coherent states; Cavity quantum electrodynamics

CLCN: O431 **Document Code**: A **Article ID**: 1004-4213(2012)11-1342-5

0 Introduction

In the past years, much attention have been paid to properties and generations of nonclassical states of light fields or atoms owing to their potential practical applications such as precision spectroscopy and quantum computation[1]. Rather recently, a class of so called excited (or photon-added) quantum states have been investigated extensively[2-7]. Many authors studied the various nonclassical properties of these quantum states such as amplitude squeezing and antibunch effects. For example, the author of Ref. [6] investigated amplitude squeezing of the excited even and odd coherent states. They found that squeezing of the field in such states are stronger than those of single excited coherent states. The author of Ref. [7] studied antibunch properties of the photon-added even and odd coherent states. The author of Ref. [8] analyzed amplitude squeezing and sub-Poissonian statistics of excited or photon-added entangled coherent states. The various schemes have been proposed for realization of these quantum states. However, these schemes are realized by interaction of qunturn light field with atoms inside cavity based on perturbation methods[2,8]. Rather recently, the authors of Ref. [5] have proposed a new method to prepare photon-added entangled coherent states by using BBO crystal and single photon detectors.

In this paper, we propose a new unperturbation method to prepare photon-added entangled coherent states which is based on cavity quantum electrodynamics.

1 Entanglement properties of photon-added entangled coherent states

Using the properties of the inverse annihilation operator,

$$a^{-1}|n\rangle=(n+1)^{-1/2}|n+1\rangle \tag{1a}$$

$$aa^{-1}=I, a^{-1}a=I-|0\rangle\langle 0| \tag{1b}$$

Applying the formulae (1a), (1b) and definition of coherent state, we can obtain the photon-added coherent states in the following form of

Foundation item: The Natural Science Foundation of Anhui Province of China (No. 090412060)

First author: WANG Zhong-jie (1962 —), male, Ph. D. degree, mainly focuses on quantum optics and quantum information. Email: wuliwzj@mail.ahnu.edu.cn

Received date: 2012-05-15 **Revised date**: 2012-08-09

$$a^{-1}|\pm\alpha\rangle=\pm\frac{1}{\alpha}(|\pm\alpha\rangle-e^{-|\alpha|^2/2}|0\rangle) \quad (2)$$

It is noted that the photon-added coherent state is a special superposition of coherent state and vacuum state. The superposition coeficient is related to amplitude of the coherent state.

The photon-added two-mode entangled states is defined as

$$|\varphi\rangle=\frac{1}{\sqrt{N_\phi}}a_1^{-1}a_2^{-1}(|\alpha\rangle_1|\alpha\rangle_2+e^{i\phi}|-\alpha\rangle_1|-\alpha\rangle_2) \quad (3)$$

where $N_\phi=2[(1-e^{-|\alpha|^2})^2\pm(e^{-2|\alpha|^2}-e^{-|\alpha|^2})^2]/|\alpha|^4(\alpha\neq 0)$ is a normalized constant, Applying Eq. (2), we can obtain another form of the photon-added two-mode odd and even entangled states

$$|\varphi\rangle=\frac{1}{\sqrt{N_\phi}\alpha^2}[(|\alpha\rangle_1-e^{-|\alpha|^2/2}|0\rangle_1)(|\alpha\rangle_2-e^{-|\alpha|^2/2}|0\rangle_2)+e^{i\phi}[(|-\alpha\rangle_1-e^{-|\alpha|^2/2}|0\rangle_1)\cdot(|-\alpha\rangle_2-e^{-|\alpha|^2/2}|0\rangle_2) \quad (4)$$

The photon-added entangled states are important in the understanding of properties of some special light fields. Here it is interesting to discuss entanglement properties of this type of states, specially effect of the superposition phase of photon-added entangled coherent states on the entanglement properties. We define the normalized orthogonal basic vectors[9]

$$|+\rangle=\cos\frac{\gamma}{2}|\uparrow\rangle-e^{i\phi/2}\sin\frac{\gamma}{2}|\downarrow\rangle \quad (5a)$$

$$|-\rangle=e^{-i\phi/2}\sin\frac{\gamma}{2}|\uparrow\rangle+\cos\frac{\gamma}{2}|\downarrow\rangle \quad (5b)$$

With

$$|\uparrow\rangle=(|\alpha\rangle-e^{-|\alpha|^2/2}|0\rangle)/\sqrt{N} \quad (5c)$$

$$|\downarrow\rangle=[(|-\alpha\rangle-e^{-|\alpha|^2/2}|0\rangle)+e^{-|\alpha|^2}(|\alpha\rangle-e^{-|\alpha|^2/2}|0\rangle)]/\sqrt{M} \quad (5d)$$

$$\cos\gamma=\frac{\cos(\phi/2)}{\sqrt{\cos^2(\phi/2)+e^{2|\alpha|^2}-1}} \quad (5e)$$

$$\sin\gamma=\frac{\sqrt{e^{2|\alpha|^2}-1}}{\sqrt{\cos^2(\phi/2)+e^{2|\alpha|^2}-1}} \quad (5f)$$

$$N=1-e^{-|\alpha|^2},\ M=(1-e^{-|\alpha|^2})(1-e^{-2|\alpha|^2}) \quad (5g)$$

The photon-added entangled state (to see Eq. (4)) is then represented in the form

$$|\varphi\rangle=C_+|+\rangle_1|+\rangle_2+C_-|-\rangle_1|-\rangle_2 \quad (6a)$$

With

$$C_+=\frac{Ne^{i\phi/2}}{\alpha^2\sqrt{N_\phi}}[\cos(\phi/2)+\frac{(1-e^{-2|\alpha|^2})(1-i\sin(\phi)/2)+\cos^2(\phi/2)e^{-2|\alpha|^2}}{\sqrt{\cos^2(\phi/2)+e^{2|\alpha|^2}-1}}] \quad (6b)$$

$$C_-=\frac{Ne^{i3\phi/2}}{\alpha^2\sqrt{N_\phi}}[\cos(\phi/2)-i\sin(\phi/2)\cdot(1-e^{-|\alpha|^2})-\frac{(1-e^{-2|\alpha|^2}\sin^2(\phi/2))}{\sqrt{\cos^2(\phi/2)+e^{2|\alpha|^2}-1}}] \quad (6c)$$

In order to study the dynamics of entanglement of the state described by Eq. (3), we employ the concurrence as a entanglement measure. The concurrence is defined as

$$C(\rho)=\max\{0,\sqrt{\lambda_1}-\sqrt{\lambda_2}-\sqrt{\lambda_3}-\sqrt{\lambda_4}\} \quad (7)$$

where $\rho=|\varphi\rangle\langle\varphi|$ is density operator, $\lambda_i(\lambda_1\geqslant\lambda_2\geqslant\lambda_3\geqslant\lambda_4)$ are the eigenvalues of the operator $\rho(\sigma_y\otimes\sigma_y)\rho^*(\sigma_y\otimes\sigma_y)$. The concurrence is easily computed as

$$C(\rho)=2|C_+C_-| \quad (8)$$

Fig. 1 shows the evolution of the concurrence with the parameter α with different superposition phase. When the superposition phase $0\leqslant\phi<\pi/2$, the concurrence $C(\rho)$ always increases up to saturation value with the parameter α increasing. But the maximun of $C(\rho)$ will decreases when the superposition phase ϕ increases. When the superposition phase $\pi/2<\phi\leqslant\pi$, $C(\rho)$ increases up to the maximum and then decreases with the parameter α increasing. This means that the concurrence of the photon-added entangled coherent states is very sensitive to the superposition phase. On the other hand, we also see that the maximum concurrence ($C(\rho)=1$) of the photon-added entangled coherent states will be exsit only if $\phi=0$.

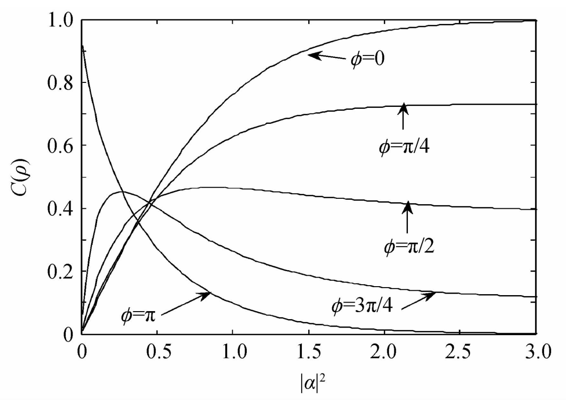

Fig. 1 The evolution of the concurrence of the photon-added entangled coherent states with the parameter α

2 Preparation of photon-added coherent states

In previous work, we proposed a method to prepare the photon-added coherent state based on the trapped ions. Here we propose a scheme for generation of the photon-added coherent state based on the cavity fields. Let us consider a three-level atom interacting with a single-mode cavity field and driven by a classical field. The atomic states are denoted by $|g\rangle$, $|e\rangle$, and $|i\rangle$. The transition frequency between the states $|e\rangle$ and $|i\rangle$ is highly detuned from the cavity frequency, and thus the state $|i\rangle$ is not affected during the atom-cavity interaction. The Hamiltonian ($\hbar=1$) is

$$H=\frac{\omega_0}{2}\sigma_z+\omega_c a^+a+g(\sigma_+a+\sigma_-a^+)+\Omega(\mathrm{e}^{\mathrm{i}\phi}\sigma_+\mathrm{e}^{-\mathrm{i}\omega t}+\mathrm{e}^{-\mathrm{i}\phi}\sigma_-\mathrm{e}^{\mathrm{i}\omega t}) \quad (9)$$

where $\sigma^+=|e\rangle\langle g|$, $\sigma^-=|g\rangle\langle e|$, $\sigma_z=|e\rangle\langle e|-|g\rangle\langle g|$, $|e\rangle$, $|g|\rangle$ being the excited and ground states of the atom, a^+ and a are the creation and annihilation operators for the cavity mode, g is the atom-cavity coupling strength, and Ω and ϕ is the Rabi frequency and phase of the classical field, respectively. We assume that $\omega_0=\omega$, $\phi=\pi/2$. Then the interaction Hamiltonian, in the interaction picture, is

$$H_{\mathrm{I}}=g(\mathrm{e}^{-\mathrm{i}\delta t}\sigma_+a+\mathrm{e}^{\mathrm{i}\delta t}\sigma_-a^+)+\mathrm{i}\Omega(\sigma_+-\sigma_-) \quad (10)$$

where $\delta=\omega_c-\omega_0$ is the detuning between the atomic transition frequency and cavity frequency, here we set $\delta=0$. We make a unitary transformation $H_{\mathrm{I}}^{'}=TH_{\mathrm{I}}T^+=\mathrm{e}^{-\mathrm{i}\pi\sigma_x/4}H_{\mathrm{I}}\mathrm{e}^{\mathrm{i}\pi\sigma_x/4}$, the transformed interaction Hamiltonian is represented as

$$H_{\mathrm{I}}^{'}=\mathrm{i}\,\frac{g}{2}(a-a^+)\sigma_z+\frac{g}{2}(a+a^+)\sigma_x+\Omega\sigma_z \quad (11)$$

Making the rotating wave approximation, which is equivalent to the transformation $\mathrm{e}^{-\mathrm{i}2\Omega t\sigma_z}H_{\mathrm{I}}^{'}\mathrm{e}^{-\mathrm{i}2\Omega t\sigma_z}$, the transformed interaction Hamiltonian $H_{\mathrm{I}}^{'}$ becomes

$$H_{\mathrm{I}}^{'}=\mathrm{i}\,\frac{g}{2}(a-a^+)\sigma_z+\frac{g}{2}(\sigma_+\mathrm{e}^{\mathrm{i}2\Omega t}+\sigma_-\mathrm{e}^{-\mathrm{i}2\Omega t})+\Omega\sigma_z \quad (12)$$

Assuming that $2\Omega\rangle\rangle g$, we can neglect the oscillating fast terms. Then $H_{\mathrm{I}}^{'}$ reduces to

$$H_{\mathrm{I}}^{'}=\mathrm{i}\,\frac{g}{2}(a-a^+)\sigma_z+\Omega\sigma_z \quad (13)$$

Proceeding to making the anti-transformation, $H_{\mathrm{I}}=T^+H_{\mathrm{I}}^{'}T$, we can obtain

$$H_{\mathrm{I}}=\mathrm{i}\,\frac{g}{2}(a-a^+)\sigma_y+\Omega\sigma_y \quad (14)$$

The evolution operator for interaction Hamiltonian (8) is given by

$$U_{\mathrm{I}}(t)=\mathrm{e}^{-\mathrm{i}tH_I}=\mathrm{e}^{-\mathrm{i}\Omega t\sigma_y}\mathrm{e}^{gt(a-a^+)\sigma_y/2}=\frac{1}{2}\mathrm{e}^{\mathrm{i}\Omega t}D(\beta)\cdot(1-\sigma_y)+\frac{1}{2}\mathrm{e}^{-\mathrm{i}\Omega t}D(-\beta)(1+\sigma_y) \quad (15)$$

where $D(i\beta)$ is the displacement operator, $D(i\beta)=\mathrm{e}^{\mathrm{i}gt(a+a^+)/2}$, $\beta=gt/2$. Now we assume that at initial time the cavity field is prepared in the coherent state, the atom is in the ground state $|g\rangle$, i.e., the initial state of the system $|\psi(0)\rangle=|g\rangle|\alpha\rangle$. In order to prepare the photon-added coherent state, we first apply a beam of classical laser to drive resonantly the atom with the evolution operator $U_1=\mathrm{e}^{-\mathrm{i}\varepsilon t\sigma_x}$. The state of the system after interaction time t_1 can be represented as follows

$$|\psi_1(t_1)\rangle=U_1|\psi(0)\rangle=[\cos(\vartheta)|g\rangle-i\sin(\vartheta)|e\rangle]|i\alpha\rangle_f \quad (16)$$

where $\vartheta=\varepsilon t_1$. Next we can select the interaction time t_2 of the atom with cavity field to satisfy $\alpha=gt_2/2=\beta$. After the interaction time t, the evolution of the state vector of the system is given by Eq. (15)

$$|\psi(t)\rangle=U_I(t)|\psi_1(t_1)\rangle=\frac{1}{2}\{[\mathrm{e}^{\mathrm{i}\Omega t_2}(\cos\vartheta-\sin\vartheta)|0\rangle+\mathrm{e}^{-\mathrm{i}\Omega t_2}(\cos\vartheta+\sin\vartheta)|-2\alpha\rangle]|g\rangle-\mathrm{i}[\mathrm{e}^{\mathrm{i}\Omega t_2}(\sin\vartheta-\cos\vartheta)|0\rangle+\mathrm{e}^{-\mathrm{i}\Omega t_2}(\cos\vartheta+\sin\vartheta)|-2\alpha\rangle]|e\rangle\} \quad (17)$$

Next we make measurement on the electric state of the atom. If detection result is the ground state $|g\rangle$ of the atom, we then obtain

$$|\psi'\rangle=\frac{1}{2}\sin(\vartheta+\pi/4)\mathrm{e}^{-\mathrm{i}\Omega t_2}[|-2\alpha\rangle-\mathrm{e}^{\mathrm{i}2\Omega t_2}\cot(\vartheta+\pi/4)|0\rangle] \quad (18)$$

Selecting the parameter ϑ to satisfy $\cot(\vartheta+\pi/4)=\mathrm{e}^{-|\alpha|^2}$ and $\Omega t_2=2m\pi$, m is large integer, we can obtain the normalized state vector

$$|\psi'\rangle=\frac{1}{\sqrt{N}}(|-2\alpha\rangle-\mathrm{e}^{-|\alpha|^2}|0\rangle) \quad (19)$$

It is easily seen that Eq. (13) is a photon-added coherent state.

3 Preparation of photon-added entangled state

In the following we propose a new scheme for generation of the photon-added two-mode entanglement state. Let's consider two distant identical high-Q light cavities1, 2. The three-level flying atom can cross from cavity 1 to cavity 2, as shown in Fig. 2. The atomic states are denoted by $|g\rangle$, $|e\rangle$ (here $|g\rangle$ and $|e\rangle$ are assumed to be degenerated), and $|i\rangle$. The transition frequency between the states $|g\rangle$, $|e\rangle$ and $|i\rangle$ is highly detuned from the cavity field frequency, thus the state $|i\rangle$ is not affected during the atom - cavity

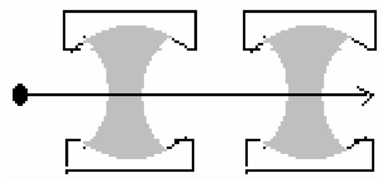

Fig. 2 Schematic diagram of generation of the photon-added two-mode entanglement state

interaction. The Hamiltonian describing the interaction of the flying atom with cavity field 1(2) is given by ($\hbar=1$)

$$H=H_0+H_I \tag{20a}$$

$$H_0=\omega a^+a+\omega_g|g\rangle\langle g|+\omega_g|e\rangle\langle e|+\omega_f|f\rangle\langle f| \tag{20b}$$

$$H_I^{1(2)}=\{\Omega_{1(2)}a_{1(2)}|f\rangle\langle g|+\Omega_{1(2)}a_{1(2)}|f\rangle\langle e|+H.c\} \tag{20c}$$

where $a_{1(2)}$ is the annihilation operators for the cavity mode, $\Omega_{1(2)}$ is the atom 1(2)-cavity effect coupling constant. Under condition of the large detuning, $\delta_{1(2)}=\omega_f-\omega_{1(2)}\rangle\rangle\Omega$, the effective interaction Hamiltonian can be obtained as

$$H_{1\mathrm{eff}}^{1(2)}=-k_{1(2)}a_{1(2)}^+a_{1(2)}(|e\rangle\langle g|+|g\rangle\langle e|+1) \tag{21}$$

where $k_{1(2)}=|\Omega_{1(2)}|^2/\delta_{1(2)}$, In the following we set $k_1=k_2=k$. The evolution operator for $H_{1\mathrm{eff}}^{1(2)}$ is represented as

$$U_1^{1(2)}(t)=\mathrm{e}^{\mathrm{i}kta_{1(2)}^+a_{1(2)}(\sigma_x+1)} \tag{22}$$

with $\sigma_x=|e\rangle\langle g|+|g\rangle\langle e|$. After the flying atom crosses from cavity 1 to cavity 2, the evolution operator corresponding to such a process can be represented as

$$U_1(t)=U_1^2(t)U_1^1(t)=\frac{1}{2}[\mathrm{e}^{\mathrm{i}2kta_2^+a_2)}\mathrm{e}^{\mathrm{i}2kta_1^+a_1)}\cdot(1+\sigma_x)+(1-\sigma_x)] \tag{23}$$

where we have assume that the interaction time of the flying atom with cavity 1(2) is the same.

Now we assume that at initial time the flying atom is in the ground state $|g\rangle$ and each of the two cavity fields is prepared in the photon-added coherent state. So the initial state for the system is represented as

$$|\psi(0)\rangle=(|\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_1)(|\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)|g\rangle \tag{24}$$

Selecting $kt=\pi/2$, we can obtain the state of the system

$$|\psi_1\rangle=U_I|\psi(0)\rangle=\frac{1}{2}\{[(|-\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_1)\cdot(|-\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)+(|\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_1)\cdot(|\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)]|g\rangle-[(|\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}\cdot|0\rangle_1)(|\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)-(|-\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}\cdot|0\rangle_1)(|-\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)]|e\rangle\} \tag{25}$$

Next we make measurement on the atom. If detection result is the ground state $|g\rangle$ of the atom, we then obtain the photon-added two-mode even entanglement state

$$|\psi_2'\rangle=[(|-\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_1)(|-\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)+|\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_1)\cdot(|\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)] \tag{26}$$

If detection result is the excited state $|e\rangle$ of the atom, we then obtain the photon-added two-mode odd entanglement state

$$|\psi_2'\rangle=[(|-\alpha\rangle_1-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_1)(|-\alpha\rangle_2-\mathrm{e}^{-|\alpha|^2/2}|0\rangle_2)-|\alpha\rangle_1-e^{-|\alpha|^2/2}|0\rangle_1)\cdot(|\alpha\rangle_2-e^{-|\alpha|^2/2}|0\rangle_2)] \tag{27}$$

4 Discussion

We now give a brief discussion on the experiment realization[15]. For the Rydberg Rb atoms with pricipal quantum numbers 50 and 51, the radiative time is $T_a=2\times10^{-2}$ s, and coupling strength with cavity field is $g=2\pi\times24$ kHz. The Rabi frequency of atoms acting with the classical field $\Omega=\varepsilon=2\pi\times120$ kHz$=5$ g and the velocity of atoms$v=4\times10^2$ m/s can be selected. A cavity with the quality factor $Q=1.0\times10^8$ and with cavity field frequency $\nu=50$ GHz is experimentally achievable (photon lifetime $T_p=3.0\times10^{-4}$ s). The initial average photon number of the cavity field $\bar{n}=14.4$ ($|\alpha|=1.2\pi$) is set. We can evaluate the required time for preparation of photon-added coherent states, which is $t_1+t_2=(1.0\times10^{-6}+0.5\times10^{-4})\mathrm{s}\approx0.5\times10^{-4}$ s. It should be noticed that this time can be much shorter if the initial average photon number $\bar{n}$ is much smaller. Therefore, the present scheme might be realizable. On the other hand, for preparation of photon-added coherent states, from Eq. (17) we see that if detection result on the atom is the excitation state $|e\rangle$, we can also obtain the photon-added coherent state. Therefore, the success probability for this scheme is 100%. For preparation of photon-added two-mode entangled coherent states, from Eq. (25) we see that the success probability is 100%. In addition, the method presented here can be also used to prepare the photon-added three-mode entangled coherent states.

5 Conclusion

In conclusion, we have proposed the schemes to prepare the photon-added coherent state and the photon-added entangled coherent states. The schemes are not only based on the unperturbation interaction of atom with cavity fields but also can be realized experimentally.

References

[1] SORENSEN A, MOLMER K. Entanglement and quantum computation with ions in thermal motion[J]. *Physical Review A*, 2000, **62**(2): 022311-022320.

[2] AGARWAL G S, TARA K. Nonclassical properties of states generated by the excitations on a coherent state[J]. *Physical Review A*, 1991, **43**(1): 492-497.

[3] DODONOV V V, KORENNOY Y A, MAN'KO V I , *et al*. Nonclassical properties of states generated by the excitations of even/odd coherent state of light[J]. *Quantum and Semiclass Optics*, 1996, **8**(3): 413-427.
[4] XIN Z Z, DUAN Y B, ZHANG H M, *et al*. Excited two photon coherent state of the radiation field[J]. *Journal of Physics B*, 1996, **29**(19): 4493-4506.
[5] DAI Q, JING H. Photon-added entangled coherent state[J]. *International Journal of Theoretical Physics*, 2008, **47**(10): 2716-2721.
[6] LU Hong, GUO Guang-can. Nonclassical properties of states generated by the superposition of excited coherent states[J]. *Acta Physica Sinica*, 1999, **48**(9): 1644-1649.
[7] YANG Qing-yi, WEI Lian-fu, DING Liang-en. Boson inverse operators and associated even and odd coherent states[J]. *Acta Physica Sinica*, 2003, **52**(6): 1390-1395.
[8] TAO Meng-xian, LU Hong, SHE Wei-long. Statistical properties of photon-added entangled coherent states[J]. *Acta Physica Sinica*, 2002, **51**(9): 1996-2005.
[9] XIA Yun-jie, GAO De-ying. Entangled coherent states and their nonclassical effects[J]. *Acta Physica Sinica*, 2007, **56**(7): 3703-3708.
[10] WANG Zhong-jie, ZHANG Xiao-dong, LI Cong. Properties and generation of photon-added Schrödinger cat states[J]. *Communication in Theoretical Physics*, 2012, **57**(3): 459-462.
[11] WANG Zhong-jie, ZHANG Kan, FAN Chao-yang. Scheme for teleportation of unknown single qubit state via continuous variables entangling channel[J]. *Chinese Physics*, 2010, **19**(11): 110311-110314.
[12] ZHENG S B, GUO G C. Teleportation of an unknown atomic state through the Raman atom-cavity-field interaction [J]. *Physics Letters A*, 1997, **232**: 171-174.
[13] JAMES D F. Quantum computation with hot and cold ions: an assessment of proposed schemes [J]. *Fortschritte der Physics*, 2000, **48**(9-11): 823-837.
[14] ZHENG S B, GUO G C. Efficient scheme for two-atom entanglement and quantum information processing in cavity QED[J]. *Physical Review Letters*, 2000, **85**(11): 2392-2395.

增光子二模纠缠相干态的纠缠特性及其通过腔量子电动力学的制备

王中杰,李聪,张晓东
(安徽师范大学 物理与电子信息学院,安徽 芜湖 241000)

摘 要:分析了增光子二模纠缠相干态的纠缠特性,得到共生纠缠度的解析表示式.结果表明:增光子二模纠缠相干态的共生纠缠度与叠加态的相位有非常灵敏的关系.提出了一种制备增光子相干态和增光子二模纠缠相干态的方法,其制备过程为首先把增光子相干态转化为相干态与真空态一种特殊的叠加态(叠加系数与相干态振幅有关),再通过位于高Q腔内的原子与经典激光场的相互作用,从而实现增光子相干态的制备.通过一个飞行原子先后与两个光腔中光场相互作用可以实现增光子二模纠缠相干态的制备.

关键词:增光子相干态;增光子二模纠缠相干态;腔量子电动力学